Ocean Deoxygenation: Drivers and Consequences
· Past · Present · Future ·

INTERNATIONAL CONFERENCE KIEL GERMANY

3 – 7 September 2018
03.09. – 07.09.2018
AUDIMAX | Kiel University
Christian-Albrechts-Platz 2
Ocean Deoxygenation Conference 2018
Bus stop: ‘Universität’

Wednesday 05.09. | 16:30
AUDIMAX | Frederik-Paulsen-Hörsaal
Public event and discussion
see more on Page 16

Sunday 02.09. | 16:00
Ship ‘MS Koi’
Registration and Ice-Breaker
see more on Page 13
Bus stop: ‘Seegarten’

Thursday 06.09. | 19:00
Norwegenkai
Conference Dinner
see more on Page 17
Bus stop: ‘Hauptbahnhof’

Tuesday 04.09. | 18:30
Halle 400
Early Career Scientists Event
see more on Page 14
Bus stop: ‘KVG Betriebshof Werftstraße’

KIEL

CENTRAL STATION
‘Hauptbahnhof’ or ‘Hbf’, main train station and main bus stop for changing busses

10 Minutes

15 Minutes

5 Minutes
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The distribution of oxygen in the ocean is controlled by physical, biogeochemical and biological processes. Both the supply and consumption of oxygen are sensitive to climate change in ways that are not fully understood. Recent observations suggest that the oxygen content of the ocean is declining (ocean deoxygenation) and that oxygen minimum zones and coastal hypoxia sites are expanding with tremendous effects on the ocean’s ecosystems and living organisms.

**This conference will:**
- focus on the past, present and future state of oxygen in the ocean on global, regional and local scales
- analyse mechanisms and feedbacks critical to identifying natural and anthropogenic causes of oxygen variability
- determine impacts on biogeochemical cycles and ecosystems

**Conference sessions will cover the following topics:**
- Prediction and Monitoring
- Ecosystem Impacts
- Ventilation and Oxygen Supply
- Microbial Communities and their Impact on Biogeochemical Cycles in Oxygen Minimum Zones
- Major Upwelling Systems
- Physiological Effects of Oxygen and Interactions with Multiple Stressors
- Impacts on Fisheries / Socioeconomics
- Coastal Systems: From Understanding to Management
- Ocean Deoxygenation – How the Past can Inform the Future
- Biogeochemical Cycles: Feedbacks and Interactions

The conference features 30 keynote speakers and 325 conference participants from 35 countries contributing with 147 oral presentations and 67 posters. Social activities include the Ice-Breaker on a charter ship with which the conference participants will discover the Kiel Fjord, a special evening for early career scientists, as well as the Conference Dinner that will take place in the terminal of the ferry to Norway. Further, the conference will organise a public event presenting the highlights of the Collaborative Research Centre SFB 754 and a workshop for local teachers on Ocean Deoxygenation.
Welcome

Dear attendee of the Ocean Deoxygenation Conference 2018,

it is my great pleasure to welcome you to our Kiel conference on ocean deoxygenation. Within the past decade, ocean deoxygenation has become an increasing threat to marine life and its role in the Earth system. Deoxygenation disrupts the biogeochemical and ecological functioning of marine ecosystems, and may even contribute to accelerate climate change. With rising anthropogenic pressures on the Earth system, it is important that we understand and document the causes and consequences of, and feedbacks and risks associated with, deoxygenation. Having enjoyed the stimulating deoxygenation conferences in Toulouse in 2011, in Liège in 2014 and at the London Royal Society in 2016, I am delighted to see you here in Kiel now to further advance the science in a collaborative international effort.

The conference is hosted by the Kiel-based Collaborative Research Centre SFB 754 ‘Climate-Biogeochemistry Interactions in the Tropical Ocean’. It was initiated by Doug Wallace more than a decade ago. I have been extremely lucky to move to Kiel just when this joint effort of Kiel University and the GEOMAR Helmholtz Centre for Ocean Research Kiel took off. Substantial funding by the German Research Foundation with more than 30 million Euros over the 12-year period 2008-2019, dedicated support by the GEOMAR directorate, and open-minded and fruitful collaboration with our international partners in Peru, Cape Verde and elsewhere have made it possible to make significant contributions towards identifying and monitoring ocean deoxygenation and to substantially improve our understanding of the relevant mechanisms and possible impacts.

Our conference brings together scientific communities from a wide range of disciplines, international research programs and geographical regions. We wish to provide an environment that stimulates open exchange of ideas and fosters creativity. We are committed to safeguard good scientific practice, equality and diversity, and to support early career scientists. The success of this conference will rely not only on the excellent work of the organising team, whom I sincerely thank for having made all this possible, but also on your enthusiasm to jointly move the field forward, to develop, ask and eventually answer the relevant research questions.

I look forward to engaging with you and wish you all a great week in Kiel and a successful and rewarding conference!

Prof. Dr. Andreas Oschlies
Speaker SFB 754
Practical Information

**Getting around**

**Bus**
You can use the following busses from Kiel Central Station (‘Hauptbahnhof’ / ‘Hbf’) to the Audimax (get-off at ‘Universität’ or ‘Universität/Westring’):

- **50, 60S** and **81** in the direction ‘Botanischer Garten’,
- **61** in the direction ‘Suchsdorf’
- **62** in the direction ‘Projensdorf’,
- **91** in the direction ‘Holtenau-Friedrichsort’

>> Bus map online: [www.netzplan-kiel.de](http://www.netzplan-kiel.de) (only in German)

A single bus ticket costs 2.60 €. You can purchase the ticket with the bus driver and it is valid for two hours. You can change busses as long as they continue the trip in the same direction. For rides with no more than 5 stops (including the start), you can purchase a short distance ticket for 1.80 €. You can only get these tickets from the bus driver. A four-ticket-combi costs 9.20 € (not available from the bus driver but from KVG Service Shops), and 7.80 € is required for a day-ticket within the city zone. Some hotels provide free bus passes for the duration of the stay.

**NOTE:** Conference participants can ask for a Kiel public transport (KVG-Kiel) ticket when they register. Costs are already included in the conference fee. The ticket will be valid on all KVG busses during the conference week.

**Bike**

It is easy to get to the conference venue ‘Audimax’ and the locations of the social events by bike from the city centre and from the northern and western outskirts of the city.

- **Fahrradverleih Kiel** – e.g. simple City bike 22,50 € / 7 days.
  [www.fahrradverleih-kiel.de](http://www.fahrradverleih-kiel.de)
- **Radstation Kiel** – located at the right hand side of the main entrance of the train station at the ‘Umsteiger’. Price for a simple bike: 40 € / week. Booking by phone preferred: +49 431 2377 790, radstation@bruecke-sh.de

**Taxi**

A taxi ride from the city centre to the university costs approximately 10 €. Tell the driver to take you to the Audimax / main building of the university (‘Universitätshochhaus’) at the crossing Westring and Olshausenstraße.

- **Mare Taxi GmbH** +49 431 77070
- **Taxi Kiel** +49 431 680101
- **City Taxi Kiel GmbH** +49 431 7068068

**Emergency numbers**

Police 110 // Ambulance 112
University Emergency number +49 431 880 - 222
University security +49 431 880 - 1888 or +49 431 880 - 2315
Conference Information

- The Ocean Deoxygenation Conference 2018 will take place from Monday, 3rd Sept. to Friday, 7th Sept. 2018 in the Audimax on the Campus of Kiel University.

- **Registration** will already start during the Ice-Breaker event on Sunday, 16:00, on the vessel ‘MS Koi’ leaving from the pier behind the Satori Speicher, Kiel.

- **Participation** at the Ocean Deoxygenation Conference 2018 requires registration. Attendees of the conference are kindly requested to wear their name badges. Should you lose your name badge, please contact the registration desk.

- Please contact the Conference Organising Team for parking spots in front of the Audimax in case of parking needs due to mobility impairment.

- A **weekly public transport ticket** for Kiel will be available at the registration desk for those who indicated their demand during registration.

- The **conference fee includes** coffee breaks and lunches (Monday-Friday), the Ice-Breaker on Sunday with finger-food and beverages, and the Conference Dinner on Thursday evening (buffet and beverages). Participation at the Early Career Scientists Event (dinner incl. beverages served) is free of costs. Participation is only possible upon registration prior to the conference.

- **Coffee breaks** and **lunch breaks** are taking place in the foyer of the Audimax.

- **Child Care**: In cooperation with the CAU Family Service we will offer child care free of charge during the conference for participants who have contacted us in advance.

- **Wifi**: Wireless internet will be available at the conference location using Eduroam. If you have no Eduroam access you can get a guest account at the registration desk.

Presenter guidelines

- **Presenters** are asked to upload and check their files until 13:30 on the day their presentation is scheduled at the latest. Uploading is possible between 30 min. before start of the daily conference programme and 13:30 at the conference registration office, or during the lunch-breaks and afternoon coffee breaks in the lecture room where the presentation will take place. Technical assistance will be available. Please note that we cannot accept personal computers / laptops for presentations.

- **Posters** should be already set up on Monday, 3rd Sept, in the tent in front of the Audimax, as the poster area will be open throughout the meeting. The general poster session is scheduled on Wednesday, 18:00 - 20:30. Conference staff will assist you in hanging up the posters.

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**German | English**

Hörsaal = Lecture hall
WC = toilet
Hauptbahnhof/Bhf. = central railway station

Kieler Förde = Kiel Fjord
Fischbrötchen = bread roll with fish
Bier = beer
Environmentally-friendly & sustainable conference

The Conference Organising Team worked hard on reducing environmental impacts caused by a conference of this size. However, with this many participants there will always be negative effects on the environment – e.g. unavoidable CO₂ emissions caused by travelling, more food and rubbish, etc. Therefore, nothing is perfect, but we tried with the following measures to minimize the ecological footprint the conference is causing and being socially responsible:

- We asked all catering companies supporting the conference venues to avoid any plastic, such as disposable cutlery, dishes and unnecessary packaging and wrappings.

- The serviettes used for all conference events are compostable, FSC-labelled, and received the Nordic Ecolabel.

- By using the water bottles each conference participant receives at the registration, you reduce dirty dishes and extra cleaning, as well as save energy used for producing beverage bottles.

- In order to minimize our carbon footprint, we want to offset the conference emissions by supporting emission saving projects. At the time of printing this booklet (beginning of August) we are working on compensating emissions from: mobility (flights, train- and car rides and public transportation of all participants), accommodation, energy, heating, air-conditioning, catering, waste disposal. This is done in cooperation with Atmosfair, a German non-profit organisation. More information will be provided during the conference.

- We use sea lyme grass (Leimus Arenarius) particularly cultured for the protection of the North German coast line for the decoration on the tables during the breaks. After the conference, the lyme grass will be handed over to the POSIMA project of the Department of Geography, Kiel University, in cooperation with the German Ministry for Environment, Nature Conservation and Nuclear Safety and the agency Project Management Jülich (www.posima.de). Eventually, all lyme grass we used for decoration will protect around 10 m² of coastline, supporting species diversity, reducing sand transport and enhancing CO₂ fixation.

- Think global – act local. We tried to use as many local partners and regional products as possible. This also includes the food provided by the caterers.

- Posters and signs not used after the conference will be sponsored to local Kindergartens for arts and crafts.

- We try our best to separate and recycle the waste and garbage produced during the conference.

- The abstract booklet is printed on 100 % recycled paper, awarded with the ecolabel Blue Angel and climate-neutral. For the name tags we chose PEFC-certified paper.
Conference Coordination & Organisation

Head of Conference Organisation Team and Conference Coordination:
  Dr. Chris Schelten (SFB 754 Scientific Coordinator)
Conference Coordination: Dr. Anja Wenzel
Conference Scientific Advice: Dr. Lothar Stramma (SFB 745 Scientific Secretary)
Conference Software & Payment Support: Dr. Carsten Schirnack, Claas Faber
  (Kiel Data Management Team)
Administrative Support: Monika Peschke
Public Event Support & Teacher Workshop:
  Dr. Sally Soria-Dengg (SFB 754 Outreach Coordinator)
Event Management: Helen Degner-Schmidt
Graphic Design: Rita Erven, Wladimir Haase (Student Assistant)
Early Career Scientists Event Support: Dr. Judith Meyer, Dr. Tim Stöven (SFB 754 Postdocs)
Poster Awards Coordination Support: Dr. Frédéric Le Moigne (SFB 754 Scientist)
Trainee: Marco Geiger

Student support: Clara Beckmann, Benjamin Claassen, Michael Eitner, Gabriela Escobar Sanchez, Theresa Fett, Conny Gamarra Chu, Juliane Heinrich, Zerlina Hofmann, Clara Igelmann, Alejandra Beatriz Irigoyen Rios, Felix Kapulla, Melanie Karrasch, Ole Kelting, Lasse Klein, Tabea Löblein, Lara Lowe, Mirjam Michel, Marie Möller, Sonia Morón, Laura Niewendick, Kristina Parplies, Julia Raab, Tim-Niklas Reck, Linnea Rulle, Sebastian Steffen, Ina Stoltenberg, Marvin Suhr, Scarlett Vorwerk

Thanks to the CIESM 2016 conference organisation team: particularly Christiane Loorz & Martina Hars; Frédéric Le Moigne and Mark Hopwood for managing the conference Twitter account; GEOMAR purchasing department: particularly Stefan Fischer & Michael Mix; GEOMAR finance department: particularly Dennis Clausen & Oxana Schlüter; the team of the GEOMAR travel department; the Hausmeister Team West; Sabine Bohnes (GEOMAR Personal Office); Kiel Data Management Team; GEOMAR Data Computing Center: particularly Sven Kabusse & Martin Matthies; Harald Vogt. Thanks to Sigi Keiser for proofreading – and everyone else we did not mention but who supported us with advise, physical and mental power!
Collaborative Research Centre 754
‘Climate – Biogeochemistry Interactions in the Tropical Ocean’

SFB 754

The Collaborative Research Center (SFB 754) addresses the relatively newly recognized threat of ocean deoxygenation, its possible impact on tropical oxygen minimum zones and implications for the global climate-biogeochemistry system.

The overall goal of the SFB 754 is to improve understanding of the coupling of tropical climate variability and circulation with the ocean’s oxygen and nutrient balance, to quantitatively evaluate the nature of oxygen-sensitive tipping points, as well as to assess consequences for the ocean’s future.

The key questions of the SFB 754 are:

- How does subsurface dissolved oxygen in the tropical ocean respond to variability in ocean circulation and ventilation?
- What are the sensitivities and feedbacks linking low or variable oxygen levels and key nutrient source and sink mechanisms? In the benthos? In the water column?
- What are the magnitudes and time scales of past, present and likely future variations in oceanic oxygen and nutrient levels? On the regional scale? On the global scale?

Addressing the SFB 754 goals requires multi-disciplinary studies. Therefore, the SFB 754 builds upon wide-ranging expertise at Kiel University, GEOMAR Helmholtz Centre for Ocean Research Kiel and the Max Planck Institute for Marine Microbiology in Bremen, and studies topics such as biological, chemical and physical oceanography, sediment biogeochemistry, marine ecology, molecular microbiology, paleoceanography, geology, as well as climate and biogeochemical modelling. The SFB 754 is organised in 18 interdisciplinary scientific subprojects as well as an outreach project that communicates the research to schools. It is funded by the German Research Foundation (DFG) since 2008 with more than 30 Mio EUR.
Kiel University

Kiel University (CAU) was founded back in 1665. It is Schleswig-Holstein’s oldest and largest university, with over 26,000 students and around 3,000 members of staff. Alumni and researchers have won 12 Nobel Prizes in the past. The CAU has been successfully taking part in the Excellence Initiative since 2006, currently accommodating two Clusters of Excellence (‘The Future Ocean’ and ‘Inflammation at Interfaces’). Kiel University is organised into eight faculties with over 400 professors and offers 190 courses of studies in a variety of disciplines. There are also various affiliated centres such as the world-renowned Kiel Institute for the World Economy.

www.uni-kiel.de

GEOMAR Helmholtz Centre for Ocean Research Kiel

GEOMAR Helmholtz Centre for Ocean Research Kiel is one of the world’s leading institutions in the field of marine sciences. The mission of GEOMAR is to investigate the physical, chemical, biological, and geological processes in the global oceans and their interaction with the seafloor and the atmosphere. Additionally, the centre is bridging the gap between basic and applied science in a number of research areas. GEOMAR currently employs about 1,000 staff and has an annual budget of 75 Mio. EUR. The infrastructure of GEOMAR includes four research vessels, three remotely operated underwater vehicles and an autonomous underwater vehicle with a depth range down to 6,000 meters, the only manned research submersible in Germany (400 m diving capability) as well as a large number of specialized instruments and technologies for ocean and deep-sea research.

www.geomar.de

Cluster of Excellence ‘The Future Ocean’

The Cluster research aims to connect Ocean System Understanding – Ocean Prediction and Scenarios – Sustainable Ocean Management and Governance, while still addressing the three main ocean challenges: Global Change, Hazards and Resources. Researchers study changes in the oceans using a multi-disciplinary approach pooling the expertise of more than 300 marine scientists, economists, mathematicians, computer scientists as well as scholars from politics, social science, philosophy and international law. Early career scientists are supported through the Integrated School of Ocean Sciences (ISOS), and the Integrated Marine Postdoc Network (IMAP). ‘The Future Ocean’ is funded by the German Excellence Initiative of the federal and state governments.

Partners: Kiel University, GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel Institute for the World Economy and Muthesius University of Fine Arts and Design.

www.futureocean.org
Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO)

The Intergovernmental Oceanographic Commission (IOC) of UNESCO promotes international scientific cooperation to ensure that the best knowledge leads to the conservation and sustainable management of our ocean and its resources. UNESCO’s IOC works to coordinate ocean-related activities in its 149 Member States. Since its creation in 1960, the IOC has been providing expertise in all ocean basins toward conserving ocean health, coordinating observing and early warning systems, ensuring ecosystem resilience to climate change and constantly developing knowledge of emerging ocean issues. On behalf of the United Nations, the IOC is leading preparations of the UN’s Decade of Ocean Science for Sustainable Development (2021-2030), mobilizing the scientific community, policy-makers, businesses and civil society around a programme of joint research and technological innovation for the benefit of our planet.

www.ioc-unesco.org

Global Ocean Oxygen Network GO$_2$NE

The Global Ocean Oxygen Network GO$_2$NE, an expert group of international scientists established in 2016, is committed to providing a global and multidisciplinary view of deoxygenation, with a focus on understanding its multiple aspects and impacts. The network offers scientific advice to policy makers to counter this concerning trend and to preserve marine resources in the presence of deoxygenation. The GO$_2$NE’s scientific work, outreach, and capacity building efforts include facilitating communication with other established networks and working groups, improving observations systems, identifying and filling knowledge gaps, as well as developing related capacity development activities. In collaboration with the SFB 754, it recently initiated the news site www.ocean-oxygen.org to provide information on deoxygenation to scientists, stakeholders and the interested public.

German Research Foundation

The German Research Foundation (DFG) is the central research funding organisation in Germany with a budget of 3.2 bn EUR in 2017. The independent and self-governed organisation is financed by the German states and the federal government. Using competitive selection processes it serves all branches of science, engineering, and the humanities through a variety of grant programmes and by funding infrastructure. Various research prizes, including the renowned Gottfried Wilhelm Leibniz Prize, are endowed by the DFG. Encouraging the advancement and training of early career researchers, promoting gender equality in scientific and academic communities, providing scientific policy advice, and fostering relations between the research community, society and the private sector are further mandates of the DFG.

www.dfg.de
Events

Sunday 02.09.2018 | 16:00 - 21:00

Registration and Ice-Breaker

We will start the conference registration during the Ice Breaker event. For this, we have booked the ‘MS Koi’, a swimming first-class event location. During the cruise, finger-food and beverages will be served (included in the conference fee).

While cruising along the Kiel Fjord, hopefully enjoying a wonderful sunset, the trio ‘Hightones’ (Hamburg, Germany) will entertain us with a mixture of Swing, Latin and Rock’n’Roll rhythms. On board you will also meet our DJ Zee Wiese of HOTTA MUSIC SOUND. When the musicians of the ‘Hightones’ need a break for regaining new energy, Zee Wiese will ensure we keep on moving either slowly with nice lounge music in the background, or rather wild & crazy to hot dancing vibes. Zee Wiese will even accompany us during the Early Career Scientists Event and the Conference Dinner.

IMPORTANT: Please be at the pier on time (latest by 16:30), as the MS Koi will sail on schedule (17:00). Return is at 20:00, all participants must have left the vessel by 21:00. You will find the ‘MS Koi’ behind the Satori Speicher, close to the maritime museum.

www.hightones.de

www.hottamusic.de
Early Career Scientists Event:
My Future in Science – Opportunities & Challenges

Participation only upon registration prior to the conference meeting.

On Tuesday evening there will be a special event for early career scientists (students, PhD candidates and postdocs) called “My Future in Science – Opportunities & Challenges”. This event, sponsored by the Joachim Herz Stiftung, will give early career academics the possibility to discuss a variety of topics related to their scientific career in a leisurely and relaxed atmosphere with experienced researchers.

In order to provide an undisturbed and open conversation atmosphere, we will pair up early career and established scientists one-to-one on individual tables. Each conversation will be accompanied by one course (starter, dinner, dessert, each appr. 30 min). The early career scientists will change their table after each course, giving them the chance to have three different, intensive discussions during the evening.

Possible themes to discuss could be inside as well as outside academia:

• Work/Life Balance
• Gender Issues
• Diversity Issues
• Working Abroad
• Funding Opportunities
• Career Opportunities within Academia
• Career Opportunities outside Academia
• Forming the Scientific Profile
• Networking
• Other themes of interest are welcome as well.

In addition we will invite SFB 754 alumni who have pursued a career inside or outside of academia. Before the dinner the alumni will briefly summarize their career after the research work within the SFB 754 and be available after dinner for smaller group discussions during the rest of the evening.

WE THANK THE ‘JOACHIM HERZ FOUNDATION’ FOR FINANCIALLY SUPPORTING THIS EVENING.

Joachim Herz Foundation
The Joachim Herz Stiftung is a nonprofit operating foundation dedicated to promoting education, science and research in the natural sciences, in economics and business administration as well as in the field of personal development. In addition, the foundation also provides grants for small, innovative third-party projects. Since 2017, the foundation also supports research projects in the fields of medicine and law. The Joachim Herz Stiftung was founded in 2008. It is one of the largest foundations in Germany.

Tuesday 04.09.2018 | 13:30 - 14:30 (during lunch break)
Audimax | Hörsaal E

Preparation workshop for the Early Career Scientists Event
For early career scientists only.

John Webb invites the early career scientists to an informal preparation session for their big evening event. The workshop will be during the lunch break. So grab yourself a plate of food and head on over. You can listen, learn and eat: all at the same time. John will be offering tips & tricks on how to prepare for meeting up with the evening expert discussion partners. Maybe you just really want to get the maximum out your evening meet-ups, or maybe you want some advice on balancing career & family, or discussing diversity issues. As a scientist, you might feel like you are on thin ice when it comes to networking and maybe you have never even thought about how to stay present in the thoughts of your conversation partners, even weeks or months after these first meetings. Remember, you only have around 30 min with each expert advisor, so you WILL want to use your time wisely. Curious? Then please come and join – it is never too late to learn something new!
This public event will be in German only as it targets pupils class 9 and higher of schools in Kiel and surrounding, as well as the Kiel community. After 10 years of ocean oxygen research within the SFB 754, we would like to present some highlights of our findings to the local public. After four presentations given by SFB 754 scientists, in a plenary we will discuss the local, regional but also global effects of ocean deoxygenation.

**Vorträge zu SFB 754 Highlights**

- Prof. Dr. Andreas Oschlies, GEOMAR
  Sauerstoff im Meer: Was geht uns das an?
- Dr. Renato Salvatteci, CAU
  Peru: Sauerstoffminimumzone vor der Haustür – was bedeutet das für die Fischerei?
- Dr. Johannes Hahn, GEOMAR
  Jagd auf gigantische Wasserwirbel in der Todeszone
- Dr. Helena Hauss, GEOMAR
  Leben ohne Sauerstoff – ist das möglich?

**Weitere Gäste in der Diskussionsrunde**

- Prof. Dr. Tal Dagan, Institut für Allgemeine Mikrobiologie, CAU
- Prof. Dr. Martin Visbeck, GEOMAR, Sprecher Exzellenzcluster ‘Ozean der Zukunft’, GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel

**Moderation**

Dr. Patricia Grasse & Kristin Burmeister (GEOMAR), Martin Behrens (Gemeinschaftsschule Probstei)

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**Workshop for teachers**

**Only for teachers and with prior registration.**

The programme is divided into two parts. On Friday, lectures from experts on different selected topics on Oxygen Minimum Zones will be held in the Audimax of Kiel University.

The second part, which will be held at the GEOMAR Westshore building on Saturday includes four practical workshops done in parallel on topics ranging from the influence of oxygen on marine nutrient cycles and classroom experiments on oxygen production to consumption and enzyme kinetics. Possible implementation of these activities in the classroom will be discussed in a wrap-up session at the end of the workshops.

**Contact:** Sally Soria-Dengg: sdengg@geomar.de
Thursday 06.09.2018 | 19:00 - 23:00
Norwegenkai | Zur Fähre 1 | 24143 Kiel

Conference Dinner

We look forward to pamper you with a buffet full of a variety of different dishes (also vegetarian and vegan). The buffet as well as the beverages are included in the registration fee.

At the Conference Dinner, Mr. Peter Stoffers, the founder of the Peter and Elke Stoffers Foundation (PES Stiftung), will personally present the winners of the best poster awards together with the SFB 754 speaker, Prof. Andreas Oschlies.

After dinner, the dancing floor will be open. Out of a multifaceted repertoire, the Partyband ‘4FUN’ from Rostock, Germany, will swing your leg with party-evergreens from rock/pop and funk, mixed with current hits. This will for sure be an unforgettable last conference evening!

www.4funband.de

IMPORTANT: Conference participants have one hour to travel individually from the Audimax to the Norwegenkai. From the Audimax to the Central Station you can go by bus, from there it is only a 5 min walk to the Norwegenkai. Note, there is no special dress-code.
During the Conference Dinner

Best Poster Awards

To acknowledge excellent poster presentation skills of early career scientists there will be a Best Poster Award Competition. The prizes are sponsored by the Peter and Elke Stoffers Foundation. There will be six poster prizes in total, four will be awarded by an expert team and two by the audience (all registered participants). The expert team will consist of 10 conveners, representing the 10 different conference topics. The experts will receive evaluation sheets to judge the posters’ scientific content as well as the visual presentation. For the audience prizes we will hand out evaluation sheets to all participants during the registration. Each awardee will receive a honorarium prize of 500 €. The prizes will be presented to the winners along with a certificate by Mr. Peter Stoffers, the founder of the Peter and Elke Stoffers Foundation (PES Stiftung), and the SFB 754 speaker, Prof. Andreas Oschlies, during the Conference Dinner on Thursday.

How to participate?

If you would like your poster to be considered for the Best Poster Award and have not registered yet, please contact the registration desk. Only undergraduate students and PhD candidates are eligible.

WE THANK THE ‘PETER UND ELKE STOFFERS FOUNDATION’ FOR FINANCIALLY SUPPORTING THE BEST POSTER AWARDS.

Peter und Elke Stoffers Foundation

The Peter and Elke Stoffers Foundation (PES) was founded as an initiative of the Kiel merchant Peter Stoffers in 2016. The main goal of the foundation is the education of the younger generation. It therefore supports especially pupils (grades 10 - 13), students and young talents in their urge to explore. PES encourages them in their work to facilitate a better future for humanity. The foundation has three defined target areas: education, research and science. Financial support is especially granted for innovative projects fostering sustainability, grants for funding of stipends or prices within science, and the dissemination of scientific knowledge and communication between science, economy and society. Building the future of tomorrow and assist humanity to have a better life is the main philosophy behind all projects and cooperative relationships. Based in Northern Germany, the foundation reaches out to others of their kind nationwide and does build a network of joined interests. The idea is to team up with other foundations and organisations to accomplish even more and to demonstrate unity in supporting those valuable goals, making the world a better place, each day a little bit, step by step.
The City of Kiel

Kiel is the capital and most populous city in the northern German state of Schleswig-Holstein, with a population of ≈ 250,000. Through its unique location at Kiel Fjord (Kieler Förde), Kiel is on the waterfront like no other baltic metropolis and therefore has become one of the major maritime centres of Germany. For instance, the city is known for a variety of international sailing events, including the annual Kiel Week, which is the biggest sailing event in the world. The Olympic sailing competitions of the 1936 and the 1972 Summer Olympics were held in the Bay of Kiel. Kiel has also been one of the traditional homes of the German Navy’s Baltic fleet, and continues to be a major high-tech shipbuilding centre. Thanks to its location on the Kiel Fjord and the busiest artificial waterway in the world, the Kiel Canal (Nord-Ostsee-Kanal), Kiel is an important sea transport hub. A number of passenger ferries to Sweden, Norway and Lithuania operate from the Kiel Fjord. Moreover, today Kiel Harbour is not only an important port of call for cruise ships touring the Baltic Sea, but of other routes such as crossing the Atlantic or visiting the Norwegian fjords.

Sightseeing

- With the Kiel public transport ticket (www.kvg-kiel.de/en) you can also use the Fjord Ferry from the Kiel railroad bridge via the landing stages Seegarten, Reventlou, Bellevue, Mönkeberg, Möltenort till Friedrichsort. Visit www.sfk-kiel.de/en for ferry routes and timetables.
- Hop On – Hop Off City Sightseeing tours daily from 10:30 - 18:00, www.citysightseeing-kiel.de
- Information about museums in and around Kiel you can find here: www.museen-am-meer.de

For further information on activities in and around Kiel please visit: www.kiel-sailing-city.de
Restaurants / Pubs

Here are “good-weather” selections of Restaurants / Pubs

// At the Kiel Fjord

- **Sandhafen**, a beach bar next to the state parliament at the Kiel Fjord waterfront, [www.facebook.com/sandhafenkiel](http://www.facebook.com/sandhafenkiel)

- **Fischbar**, serving various typical German Fischbrötchen (bread roll with fish) as well as fish & chips, [www.facebook.com/Kiellinie](http://www.facebook.com/Kiellinie) (there is now also a Fischbar Restaurant for bad weather scenarios: [www.facebook.com/fischbardeli1](http://www.facebook.com/fischbardeli1))

In case the weather is not so good

// Close to the venue

- **Jack’s Kitchen** - soulfood for Kiel, next to the Audimax, offers Pizza, Pasta, casseroles/bakes, wraps, salads, cooking with regional products, [www.jackskitchen.de](http://www.jackskitchen.de)

- **Oblomow**, has been a student restaurant / pub since 1968, good food for fair prices, Wednesday Cocktail time from 19:00 to 20:30 (4.50 € each cocktail), [www.oblomow-kiel.de](http://www.oblomow-kiel.de)

- **Johns Burgers**, English speaking staff serving home-made burgers made of fresh regional products, [www.johnsburgers.de](http://www.johnsburgers.de) (Mondays closed)

// Kiel City Centre and a bit to the left & right

- **Mangos**, large selection of various dishes & delicious cocktails are served from 18:00 onwards in Kiel’s oldest subterranean vault, [www.mangos-kiel.de](http://www.mangos-kiel.de)

- **Kieler Brauerei** (Brewery), medieval flair, offering three different types of beer that are brewed at the location, selection of good and solid dishes, large portions served, [www.kieler-brauerei.de](http://www.kieler-brauerei.de)
• **Pizza Originale Italiana POI**, traditional modern and fresh Italian, Pizza are baked on stone, also possible to sit on the roofed terrace, [www.poi-kiel.de](http://www.poi-kiel.de)

• **Soho**, Sushi & modern Thai Restaurant, casual and easy atmosphere, originally designed by a London architect as a noodle bar, [www.soho-kiel.de](http://www.soho-kiel.de)

• **Forstbaumschule**, largest beer garden in Kiel situated in a park / forest area, good wallet-friendly dishes (e.g. Pizza), live music events, [www.forstbaumschule.de](http://www.forstbaumschule.de)

• **Die Villa**, known for their cocktails and street food kitchen, dancing on Fridays and Saturdays, [www.dievillakiel.de](http://www.dievillakiel.de)

• **Traum GmbH**, cinema, disco, salsa & latino evenings, pub and restaurant with many culinary treats and Pizza, [www.traumgmbh.de](http://www.traumgmbh.de)

// **Kieler Förde / Kiel Fjord**

• **Der Alte Mann**, next to the Schifffahrtsmusuem (City and Maritime Museum) at the Kiel Fjord this restaurant serves regional fish specialities, but also dishes without fish, [www.deraltemann-kiel.de](http://www.deraltemann-kiel.de) (Mondays closed)

• **Louf**, Restaurant, Café & Cake, cocktails, you can sit inside or even outside, good spot image of Kiel, great variety of dishes, [www.louf.de](http://www.louf.de)

You can find further information on Restaurants / Bars / Pubs using the following links:

• [www.cafe-kiel.de](http://www.cafe-kiel.de)

• [www.kielerdeometer.de](http://www.kielerdeometer.de)

• [www.kiel-magazin.de](http://www.kiel-magazin.de)
Please note that due to limited space in the conference booklet and on the name tags we reduced, aligned, and abbreviated names and information of universities, research institutions and other organisations you are affiliated with. Despite our efforts to not delete important information, we apologise for mistakes this may have caused.
PROGRAMME
02.09. SUNDAY AFTERNOON

16:00 - 21:00
Registration and Ice-Breaker

Departure 17:00

The Ice-Breaker will take place on the ship ‘MS Koi’. Conference registration will be during the cruise.

You will find the ‘MS Koi’ behind the Satori Speicher, next to the maritime museum.

More information on Page 13
# 03.09. MONDAY MORNING 1

## 08:00 - 08:30 Registration // Foyer Audimax

## 08:30 - 09:00

### WELCOME NOTES

- **Karin Prien**  
  Minister of Education, Science and Cultural Affairs of the Land Schleswig-Holstein

- **Prof. Peter Herzig**  
  Scientific Director | GEOMAR Helmholtz Centre for Ocean Research Kiel

- **Prof. Nele Matz-Lück**  
  Co-Speaker Cluster of Excellence ‘The Future Ocean’ | Kiel University

- **Prof. Andreas Oschlies**  
  Speaker SFB 754 | GEOMAR Helmholtz Centre for Ocean Research Kiel

## 09:00 - 10:45

### 01 Prediction and Monitoring

#### Keynote Talks

- **Audimax | Frederik-Paulsen-Hörsaal**

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>09:00</td>
<td><strong>HENSON, Stephanie</strong></td>
<td>Emergence and detection of climate change – driven trends in oceanic oxygen concentration</td>
</tr>
<tr>
<td>09:35</td>
<td><strong>RESPLANDY, Laure</strong></td>
<td>Constraints on ocean deoxygenation and warming from atmospheric oxygen observations</td>
</tr>
<tr>
<td>10:10</td>
<td><strong>GRUBER, Nicolas</strong></td>
<td>Variability and extremes in ocean (de)oxygenation and water column denitrification in the eastern tropical Pacific</td>
</tr>
</tbody>
</table>

### 10:45 - 11:15 Coffee Break
## 03.09. MONDAY MORNING 2

### 11:15 - 13:00

**02 Ecosystem Impacts**

<table>
<thead>
<tr>
<th>Time</th>
<th>Keynote Talks</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:15</td>
<td>Benthic ecosystem responses to open ocean deoxygenation</td>
</tr>
<tr>
<td></td>
<td><strong>LEVIN, Lisa</strong></td>
</tr>
<tr>
<td>11:50</td>
<td>How the oxygen minimum zone can drive ecosystem functioning from plankton to</td>
</tr>
<tr>
<td></td>
<td>seabirds and fishers</td>
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<tr>
<td></td>
<td><strong>BERTRAND, Arnaud</strong></td>
</tr>
<tr>
<td>12:25</td>
<td>Coastal hypoxia and benthic ecosystem functioning</td>
</tr>
<tr>
<td></td>
<td><strong>NORKKO, Alf</strong></td>
</tr>
<tr>
<td>13:00</td>
<td><strong>13:00 - 14:30 Lunch Break</strong></td>
</tr>
<tr>
<td>Time</td>
<td>Session</td>
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<td>----------------------------------------------</td>
</tr>
<tr>
<td>14:30</td>
<td><strong>Prediction and Monitoring</strong></td>
</tr>
<tr>
<td>14:30</td>
<td>Upper ocean $O_2$ trends: 1958 - 2015</td>
</tr>
<tr>
<td></td>
<td><strong>MINOBE, Shoshiro</strong></td>
</tr>
<tr>
<td>14:45</td>
<td>Autonomous observation of oxygen deficient zone (ODZ) biogeochemistry</td>
</tr>
<tr>
<td></td>
<td><strong>ALTABET, Mark</strong></td>
</tr>
<tr>
<td>15:00</td>
<td>Internal variability as a driver of decadal deoxygenation</td>
</tr>
<tr>
<td></td>
<td><strong>TAKANO, Yohei</strong></td>
</tr>
<tr>
<td>15:15</td>
<td>Quality of the baseline climatologies for oxygen and nutrients for inventory studies</td>
</tr>
<tr>
<td></td>
<td><strong>GARCIA, Hernan</strong></td>
</tr>
<tr>
<td>15:30</td>
<td>Volcanic impacts on air-sea oxygen exchange: insights from the large ensemble experiment</td>
</tr>
<tr>
<td></td>
<td><strong>EDDEBBAR, Yassir</strong></td>
</tr>
<tr>
<td>15:45</td>
<td>The conundrum of marine oxygen: why is the future ocean loosing oxygen despite declining export production?</td>
</tr>
<tr>
<td></td>
<td><strong>KOEVE, Wolfgang</strong></td>
</tr>
<tr>
<td>16:00</td>
<td><strong>Coffee Break</strong></td>
</tr>
<tr>
<td>Time</td>
<td>Session</td>
</tr>
<tr>
<td>-------</td>
<td>----------</td>
</tr>
</tbody>
</table>
| 03.09. | 02       | Block 1 // Audimax | Ecosystem Impacts                                                     | Factors controlling the productivity of plankton communities in the coastal upwelling system of Peru  
**BACH, Lennart**  
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)  
Zooplankton of the low-oxygen waters of Bahia Callao, central Peru - with special reference to the reproductive activity of the copepod *Acartia nsp*  
**AYON, Patricia**  
(Marine Institute of Peru, Peru)  
Intercalated low oxygen maxima, beam attenuation and ADCP amplitude within the suboxic layer off Peru  
**MASKE, Helmut**  
(Center for Scientific Research and Higher Education at Ensenada, Mexico)  
Elemental fluxes mediated by vertically migrating zooplankton and nekton into the mesopelagic oxygen minimum zone off Peru  
**HAUSS, Helena**  
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)  
Potential complexity of zooplankton responses to deoxygenation: very small oxygen differences matter  
**WISHNER, Karen**  
(University of Rhode Island, USA)  
Interactive effects of temperature and low oxygen on the vertical distribution of copepod eggs and nauplii in coastal seas  
**ROMAN, Michael**  
(University of Maryland Center for Environmental Science, USA) |
|       | 03       | Block 1 // Audimax | Ventilation and Oxygen Supply                                         | Ventilation pathways for the North Pacific Oxygen Deficient Zone revealed by secondary oxygen maxima and Lagrangian particle tracking  
**MARGOLSKEE, Andrew**  
(University of Washington, USA)  
Mechanisms of low-frequency oxygen variability in the North Pacific  
**ITO, Taka**  
(Georgia Institute of Technology, USA)  
Variability and drivers of the oxygen minimum zone in the tropical Pacific over the past decades  
**WANG, Xiujun**  
(Beijing Normal University, China)  
Low-oxygen mesoscale eddies in the eastern South Pacific  
**PIZARRO, Oscar**  
(University of Concepción, Chile)  
Interannual variability of the OMZ of the South Eastern Pacific  
**DEWITTE, Boris**  
(LEGOS (IRD/CNRS/CNES/University of Toulouse), France)  
ENSO-driven fluctuations in the vertical extent of oxygen-poor waters in the oxygen minimum zone of the Eastern Tropical South Pacific  
**JOSE, Yonss**  
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:30</td>
<td>08 Coastal Systems: From Understanding to Management</td>
</tr>
</tbody>
</table>
| 16:30  | Chesapeake Bay hypoxia: relative impacts of nitrogen entering from the land, the atmosphere, and the coastal ocean  
        | DA, Fei (VIMS, College of William and Mary, USA)                      |
| 16:45  | Quantifying the relative contributions of riverine versus oceanic nutrient sources to coastal hypoxia  
        | GROßE, Fabian (Dalhousie University, Canada)                          |
| 17:00  | Oscillations of oxygen in the hypoxic transition zone of the Eastern Gotland Basin (Baltic Sea) – causes and consequences on benthic biogeochemical fluxes  
        | SOMMER, Stefan (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
| 17:15  | Upscaling the impact of coastal hypoxia from species to ecosystem function. The case of bioturbation in the Black Sea  
        | GRÉGOIRE, Marilaure (University of Liège, Belgium)                    |
| 17:30  | Co-existence of nitrogen oxidation and reduction in oxygenated estuaries  
<pre><code>    | WAN, Xianhui (Xiamen University, China)                               |
</code></pre>
<p>| 18:00  | Programme ends                                                        |</p>
<table>
<thead>
<tr>
<th>02 Ecosystem Impacts</th>
<th>03 Ventilation and Oxygen Supply</th>
</tr>
</thead>
</table>
| **Block 2 // Audimax | **Time scales of oxygen variability in the eastern tropical North Atlantic**  
| **Hörsaal C**       | **HAHN, Johannes** (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
| Zooplankton-mediated fluxes in the Eastern Tropical North Atlantic  
**KIKO, Rainer** (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |  
**Driven mechanisms for maintaining the equatorial deep jets and the quasi-steady flanking jets and the implications for the equatorial oxygen budget**  
**CLAUS, Martin** (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
| Pelagic key species and mechanisms driving energy flows in the northern Benguela upwelling ecosystem and their feedback into biogeochemical cycles  
**EKAU, Werner** (Leibniz Centre for Tropical Marine Research, Germany) |  
**Ventilation of the eastern tropical North Atlantic oxygen minimum zone by latitudinally alternating zonal jets in a shallow water model**  
**KÖHN, Eike E.** (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
| Size structure, community composition and biomass size spectra of mesopelagic fishes in the tropical Atlantic Ocean and the West-Saharan OMZ in 2015  
**FOCK, Heino** (Thuenen Institute of Sea Fisheries, Germany) |  
**On Nearshore hypoxia and oxygen ventilation in the Eastern tropical North Atlantic**  
**CAPET, Xavier** (LOCEAN-IPSL (UPMC Paris 6/CNRS/IRD/MNHN), France) |
| Demersal fish communities across oxygen gradients: How multiple methodologies can offer unique insights into the ecological impacts of ocean deoxygenation  
**GALLO, Natalya** (Scripps Institution of Oceanography, UCSD, USA) |  
**Simulating fish population responses to coastal hypoxia: movement behavior and the tradeoff between more oxygen and less food**  
**ROSE, Kenneth** (University of Maryland Center for Environmental Science, USA) |
| Comparing fish population responses across oxy gradient  
**GALLO, Natalya** (Scripps Institution of Oceanography, UCSD, USA) |
| Simulating fish population responses to coastal hypoxia: movement behavior and the tradeoff between more oxygen and less food  
**ROSE, Kenneth** (University of Maryland Center for Environmental Science, USA) |  
**Variability of the Atlantic North Equatorial Undercurrent and its impact on oceanic oxygen distribution**  
**BURMEISTER, Kristin** (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
| Early detection of anthropogenic climate change signal in the interior subpolar North Atlantic oxygen  
**TJIPUTRA, Jerry** (Uni Research Climate, Norway) |
### 04.09. TUESDAY MORNING 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>08:30</td>
<td><strong>Ventilation and Oxygen Supply</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Keynote Talks</strong></td>
</tr>
<tr>
<td></td>
<td>**Audimax</td>
</tr>
<tr>
<td>08:30</td>
<td>Ocean deoxygenation in the 21st century: the role of ventilation</td>
</tr>
<tr>
<td></td>
<td><strong>BOPP, Laurent</strong></td>
</tr>
<tr>
<td>09:05</td>
<td>Physical forcings of Eastern Pacific OMZ</td>
</tr>
<tr>
<td></td>
<td><strong>MONTES, Ivonne</strong></td>
</tr>
<tr>
<td>09:40</td>
<td>Drivers and mechanisms of thermocline oxygen changes in the eastern tropical North Atlantic</td>
</tr>
<tr>
<td></td>
<td><strong>BRANDT, Peter</strong></td>
</tr>
<tr>
<td>10:15</td>
<td><strong>Coffee Break</strong></td>
</tr>
</tbody>
</table>

**Note:**
- **Audimax | Frederik-Paulsen-Hörsaal**
- **Ventilation and Oxygen Supply**
- **Keynote Talks**
- **Ocean deoxygenation in the 21st century: the role of ventilation**
- **BOPP, Laurent**
- **Physical forcings of Eastern Pacific OMZ**
- **MONTES, Ivonne**
- **Drivers and mechanisms of thermocline oxygen changes in the eastern tropical North Atlantic**
- **BRANDT, Peter**
- **Coffee Break**
<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:45 - 12:30</td>
<td><strong>Keynote Talks</strong>&lt;br&gt;Audimax</td>
</tr>
<tr>
<td>12:30 - 13:15</td>
<td><strong>Invited Speaker</strong>&lt;br&gt;Audimax</td>
</tr>
<tr>
<td>13:15 - 14:30</td>
<td><strong>Lunch Break</strong></td>
</tr>
</tbody>
</table>
| 13:30 - 14:30 | **Preparation Workshop for Early Career Scientists Event (for early career scientists only) (see Page 15)**<br>Audimax | Hörsaal E<br><br>**John C. Webb**
### 04.09. TUESDAY AFTERNOON 1

<table>
<thead>
<tr>
<th>14:30 - 16:00</th>
<th>06 Physiological Effects of Oxygen &amp; Interactions with Multiple Stressors</th>
<th>Block 1 // Audimax</th>
<th>Hörsaal A</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:30</td>
<td>In situ respiration rates of meso- and bathypelagic animals</td>
<td>REISENBICHLER, Kim</td>
<td>(Monterey Bay Aquarium Research Institute, USA)</td>
</tr>
<tr>
<td>14:45</td>
<td>Oxygen dependence of visual function and ecology in marine larvae</td>
<td>MCCORMICK, Lillian</td>
<td>(Scripps Institution of Oceanography, UCSD, USA)</td>
</tr>
<tr>
<td>15:00</td>
<td>Variation in growth, morphology and reproduction of the bearded goby (Sufflogobius bibarbatus) in varying oxygen environments of northern Benguela</td>
<td>SALVANES, Anne G. V.</td>
<td>(University of Bergen, Norway)</td>
</tr>
<tr>
<td>15:15</td>
<td>Winning ways with hydrogen sulphide on the Namibian shelf</td>
<td>CURRIE, Bronwen</td>
<td>(Ministry of Fisheries and Marine Resources, Namibia)</td>
</tr>
<tr>
<td>15:30</td>
<td>Combined effects of warming and acidification on hypoxia tolerance of northern shrimp, <em>Pandalus borealis</em></td>
<td>CHABOT, Denis</td>
<td>(Maurice-Lamontagne Institute, Canada)</td>
</tr>
<tr>
<td>15:45</td>
<td>Understanding physiological mechanisms of Chilean scallop to the multiple-stressor scenario of upwelling by using an experimental integrative approach</td>
<td>RAMAJO, Laura</td>
<td>(Adolfo Ibañez University, Chile)</td>
</tr>
<tr>
<td>16:00 - 16:30</td>
<td>Coffee Break</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Ventilation and Oxygen Supply

<table>
<thead>
<tr>
<th>Block 3 // Audimax</th>
<th>Hörssaal D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ocean deoxygenation and N₂O emissions projected in multi-millennial global warming simulations</td>
<td>Elevated marine oxygen inventory by enhanced anaerobic respiration in a warmer future ocean</td>
</tr>
<tr>
<td>JOOS, Fortunat (University of Bern, Switzerland)</td>
<td>OSCHLIES, Andreas (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
</tbody>
</table>

### Microbial Communities and their Impact on Biogeochemical Cycles in OMZs

<table>
<thead>
<tr>
<th>Block 1 // Audimax</th>
<th>Hörsaal C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diversity, distribution and abundance of nitrogen fixing microbes in the oxygen minimum zones</td>
<td>Elevated marine oxygen inventory by enhanced anaerobic respiration in a warmer future ocean</td>
</tr>
<tr>
<td>JAYAKUMAR, Amal (Princeton University, USA)</td>
<td>OSCHLIES, Andreas (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td>Regulation of N₂O production by oxygen and organic matter in the ETSP</td>
<td>Elevated marine oxygen inventory by enhanced anaerobic respiration in a warmer future ocean</td>
</tr>
<tr>
<td>FREY, Claudia (University of Basel, Switzerland)</td>
<td>OSCHLIES, Andreas (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td>Microbial degradation activity and organic matter lability in the oxygen minimum zone off Peru</td>
<td>High frequency wind forcing and interior oxygen levels</td>
</tr>
<tr>
<td>MAßMIG, Marie (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
<td>DUTEIL, Olaf (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td>Eukaryotic denitrification pathway of benthic foraminifera thriving in oxygen-depleted environments</td>
<td>High frequency wind forcing and interior oxygen levels</td>
</tr>
<tr>
<td>ROY, Alexandra-Sophie (Kiel University, Germany)</td>
<td>DUTEIL, Olaf (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td>Isotopic fingerprints of benthic nitrogen cycling in the Peruvian oxygen minimum zone</td>
<td>Submesoscales reduce deoxygenation in temperate gyres</td>
</tr>
<tr>
<td>DALE, Andrew W. (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
<td>LÉVY, Marina (LOCEAN-IPSL (UPMC Paris 6/CNRS/IRD/MNHN), France)</td>
</tr>
<tr>
<td>Untangling the key drivers in oxygen minimum zone (OMZ)-influenced waters that shape natural plankton assemblages</td>
<td>Oxygen utilisation rate - a poor measure of ocean respiration</td>
</tr>
<tr>
<td>PAUL, Allanah J. (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
<td>KÄHLER, Paul (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td>Time</td>
<td>Session</td>
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<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>16:30</td>
<td><strong>02 Ecosystem Impacts</strong></td>
</tr>
<tr>
<td></td>
<td>Block 3 // Audimax</td>
</tr>
</tbody>
</table>
| 16:30   | Assessing the effects of recurring seasonal hypoxia on benthic communities and reconstructing baseline community states on the basis of sediment cores (northern Adriatic Sea)  
  TOMASOVYCH, Adam  
  (Slovak Academy of Sciences, Slovakia) |
| 16:45   | Effects of regimes of dissolved oxygen variability on functional diversity of sublittoral macrobenthos off central Peru (12°S) and northern Chile (23°S)  
  GUTIERREZ, Dimitri  
  (Marine Institute of Peru, Peru) |
| 17:00   | Hypoxia in mangroves: occurrence and impact on nursery fish habitats  
  DUBUC, Alexia  
  (James Cook University, Australia) |
| 17:15   | The ocean is losing its breath: declining oxygen in the world’s ocean and coastal waters  
  ISENSEE, Kirsten  
  (Intergovernmental Oceanographic Commission - UNESCO, France) |
| 17:30   |                                                                           |
| 17:45   | Please note: Change of location                                          |

**18:30 - 23:00 Early Career Scientists Event**  
Halle 400 | An der Halle 400 No. 1 | 24143 Kiel  
More information on page 14
<table>
<thead>
<tr>
<th>04 Microbial Communities and their Impact on Biogeochemical Cycles in OMZs</th>
<th>05 Major Upwelling Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Block 2 // Audimax</td>
<td>Hörsaal C**</td>
</tr>
<tr>
<td><strong>A metatranscriptomics/metagenomics approach to obtain insights into the biogeochemistry of the suboxic zone of the Black Sea</strong>&lt;br&gt;JÜRGENS, Klaus&lt;br&gt;(Leibniz Institute for Baltic Sea Research Warnemünde, Germany)</td>
<td><strong>Dispersion of a tracer in the Eastern Tropical South Pacific</strong>&lt;br&gt;FREUND, Madeleine&lt;br&gt;(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td><strong>Ecological strategies of sulfur-oxidizing bacteria in responses to the changing marine environment</strong>&lt;br&gt;DANG, Hongyue&lt;br&gt;(Xiamen University, China)</td>
<td><strong>The role of filaments for ventilating the oxygen minimum zone off Peru</strong>&lt;br&gt;HAUSCHILDT, Jaaaard&lt;br&gt;(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td><strong>Pathways of gravitational particle export in the peruvian oxygen minimum zone</strong>&lt;br&gt;LE MOIGNE, Frederic&lt;br&gt;(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
<td><strong>Impact of non-linear internal waves on the cross slope circulation in the Peruvian upwelling region.</strong>&lt;br&gt;DENGLER, Marcus&lt;br&gt;(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td><strong>The role of marine snow for nitrogen loss from oxygen minimum zones</strong>&lt;br&gt;KARTHÄUSER, Clarissa&lt;br&gt;(Max Planck Institute for Marine Microbiology, Germany)</td>
<td><strong>Linking upwelling, export production and nitrogen cycling processes in the OMZ waters of the ETSP</strong>&lt;br&gt;LAVIK, Gaute&lt;br&gt;(Max Planck Institute for Marine Microbiology, Germany)</td>
</tr>
<tr>
<td><strong>Deep maximum of virus-bacterial ratio in oxygen minimum zone in the South China Sea: preliminary evidence for viral control of bacterial depletion of oxygen</strong>&lt;br&gt;YIN, Kedong&lt;br&gt;(Sun Yat-sen University, China)</td>
<td><strong>Measurements of biogenic volatile organic compounds (BVOCs) in marine boundary layer of Arabian Sea (OMZ): Role of carbon cycle in pre-monsoon season</strong>&lt;br&gt;SAHU, Lokesh Kumar&lt;br&gt;(Physical Research Laboratory, India)</td>
</tr>
</tbody>
</table>

**18:30 - 23:00 Early Career Scientists Event**
Halle 400 | An der Halle 400 No. 1 | 24143 Kiel
More information on page 14
### 05.09. WEDNESDAY MORNING 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>09:00</td>
<td><strong>Keynote Talks</strong>&lt;br&gt;Major Upwelling Systems&lt;br&gt;05 Audimax</td>
</tr>
<tr>
<td>09:00</td>
<td>Factors affecting the variability of the Arabian Sea OMZ over seasonal, interannual and climate-change time scales&lt;br&gt;LÉVY, Marina</td>
</tr>
<tr>
<td>09:35</td>
<td>The “bad” breath of the ocean: Greenhouse gas emissions from Eastern Boundary Upwelling Ecosystems&lt;br&gt;ARÉVALO-MARTÍNEZ, Damian L.</td>
</tr>
<tr>
<td>10:10</td>
<td>Does the Ocean lose its breath?&lt;br&gt;LÖSCHER, Carolin</td>
</tr>
<tr>
<td>10:45</td>
<td><strong>Coffee Break</strong></td>
</tr>
</tbody>
</table>

**Schedule:**

- **09:00 - 10:45**
  - **Keynote Talks**
    - Factors affecting the variability of the Arabian Sea OMZ over seasonal, interannual and climate-change time scales<br>LÉVY, Marina
    - The “bad” breath of the ocean: Greenhouse gas emissions from Eastern Boundary Upwelling Ecosystems<br>ARÉVALO-MARTÍNEZ, Damian L.
    - Does the Ocean lose its breath?<br>LÖSCHER, Carolin
### 05.09. Wednesday Morning 2

#### 11:15 - 13:00

<table>
<thead>
<tr>
<th>Time</th>
<th>Title</th>
<th>Presenter</th>
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</thead>
<tbody>
<tr>
<td>11:15</td>
<td>Microbial biota in anaerobic and microaerobic habitats</td>
<td>Fenchel, Tom</td>
</tr>
<tr>
<td>11:50</td>
<td>Critical oxygen levels of marine animals and the consequences of ocean deoxygenation and warming</td>
<td>Seibel, Brad</td>
</tr>
<tr>
<td>12:25</td>
<td>It’s not just oxygen: Understanding and managing a multiple stressor world</td>
<td>Breitburg, Denise</td>
</tr>
</tbody>
</table>

**Keynote Talks**

Audimax | Frederik-Paulsen-Hörsaal

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**13:00 - 14:30 Lunch Break**
### 05.09. WEDNESDAY AFTERNOON 1

#### 14:30 - 16:00

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:30</td>
<td>Is oxygen limitation the cause for summer heat wave mortality in a coastal keystone predator?</td>
<td><strong>MELZNER, Frank</strong>&lt;br&gt;(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td>14:45</td>
<td>Intraspecific diversity and the selection of correlated sensitivities to multiple global change factors</td>
<td><strong>WAHL, Martin</strong>&lt;br&gt;(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td>15:00</td>
<td>The effects of hypoxia and ocean acidification on grazing interactions within giant kelp forests</td>
<td><strong>NG, Crystal</strong>&lt;br&gt;(Stanford University, USA)</td>
</tr>
<tr>
<td>15:15</td>
<td>Variable yet predominantly additive effects of concurrent hypoxia and elevated pCO₂ on marine biota</td>
<td><strong>KLEIN, Shannon</strong>&lt;br&gt;(King Abdullah University of Science and Technology, Saudi Arabia)</td>
</tr>
<tr>
<td>15:30</td>
<td>Ocean deoxygenation overrules ocean warming and acidification impacts in marine biota</td>
<td><strong>ROSA, Rui</strong>&lt;br&gt;(University of Lisbon, Portugal)</td>
</tr>
<tr>
<td>15:45</td>
<td>Marine invertebrate responses to temperature-related stressors and their interactions</td>
<td><strong>REDDIN, Carl</strong>&lt;br&gt;(University of Erlangen–Nürnberg, Germany)</td>
</tr>
</tbody>
</table>

#### 16:00 - 16:30 Coffee Break
### 05.09. Wednesday Afternoon 1

#### 10 Biogeochemical Cycles: Feedbacks and Interactions
Block 1 // Audimax | Hörsaal C

- **Particle flux of sinking organic matter in the peruvian oxygen minimum zone**
  - **CISTERNAS-NOVOA, Carolina**
    (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

- **Sinking organic matter fluxes and remineralization attenuation in the Peruvian oxygen minimum zone**
  - **XIE, Ruifang**
    (GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Germany)

- **As good as it gets: fitting a global biogeochemical model to oxygen minimum zones**
  - **KRIEST, Iris**
    (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

- **Ocean phosphorus inventory and oceanic deoxygenation: large uncertainties in future projections on millennial timescales**
  - **KEMENA, Tronje Peer**
    (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

- **Benthic trace metal fluxes in the oxygen minimum zone off Peru**
  - **PLAß, Anna**
    (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

#### 05 Major Upwelling Systems
Block 2 // Audimax | Hörsaal D

- **Variability and trends of the oxygen minimum zone at the coastal upwelling system off Peru**
  - **GRACO, Michelle Ivette**
    (Marine Institute of Peru, Peru)

- **Intra-seasonal variability of the eastern boundary circulation off Peru and biogeochemical consequence**
  - **LÜDKE, Jan**
    (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

- **Spatial heterogeneity of dissolved oxygen and hypoxia events in shallow waters of central Chile: diurnal and seasonal patterns in an upwelling ecosystem**
  - **STORCH, Daniela**
    (Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Germany)

- **Recent biogeochemical trends in the Peru upwelling system**
  - **ECHEVIN, Vincent**
    (LOCEAN-IPSL (UPMC Paris 6/CNRS/IRD/MNHN), France)

- **Drivers of anoxia in a large embayment of an eastern boundary upwelling system: St Helena Bay**
  - **PITCHER, Grant**
    (Fisheries Research and Development, DAFF, South Africa)

- **El Niño influence on Peruvian shelf trace metal supply to the ocean**
  - **RAPP, Insa**
    (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)
05.09. WEDNESDAY AFTERNOON 2

16:30 - 18:00

06 Audimax | Hörsaal A

16:30
How ocean deoxygenation affects fish: Implications of Gill-Oxygen Limitation Theory (GOLT)

PAULY, Daniel
(University of British Columbia, Canada)

16:45

17:00

17:15

17:30

17:45

18:00 - 20:30
Poster Session with fingerfood and drinks

Tent in front of the Audimax

Public Lecture

Audimax | Frederik-Paulsen-Hörsaal

All presentations and the discussion will be in German.

Geht dem Ozean die Luft aus?

Vorträge zu SFB 754 Highlights

Sauerstoff im Meer: Was geht uns das an?
OSCHLIES, Andreas
GEOMAR

Peru: Sauerstoffminimumzone vor der Haustür – was bedeutet das für die Fischerei?
SALVATTECI, Renato
CAU

Jagd auf gigantische Wasserwirbel in der Todeszone
HAHN, Johannes
GEOMAR

Leben ohne Sauerstoff – ist das möglich?
HAUSS, Helena
GEOMAR

Weitere Gäste in der Diskussionsrunde

DAGAN, Tal
CAU

VISBECK, Martin
GEOMAR, Sprecher Exzellenzcluster »Ozean der Zukunft«

Moderation

BURMEISTER, Kristin
GEOMAR
GRASSE, Patricia
GEOMAR
BEHRENS, Martin
Gemeinschaftsschule Probstei

Ende ca. 18:30
<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
<th>Room</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00 - 11:30</td>
<td>Biogeochemical Cycles: Feedbacks and Interactions</td>
<td>Block 2 // Audimax</td>
</tr>
<tr>
<td></td>
<td><strong>Radium isotopes as tracers of shelf-derived trace element inputs along the Benguela upwelling zone</strong></td>
<td><strong>VIEIRA, Lucia Helena</strong> (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>Sources and composition of water-soluble trace elements in aerosols over the Benguela and Peruvian oxygen minimum zone</strong></td>
<td><strong>YONG, Jaw Chuen</strong> (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>The influence of iron on extended elemental stoichiometries in diazotrophs</strong></td>
<td><strong>MARKI, Alexandra</strong> (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>Nutrient controls on productivity overlying and offshore of oxygen minimum zones</strong></td>
<td><strong>BROWNING, Thomas</strong> (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>H$_2$S events in the Peruvian oxygen minimum zone enhances dissolved Fe concentrations</strong></td>
<td><strong>SCHLOSSER, Christian</strong> (GEOMAR Helmholtz Centre Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>How the oxygen concentration can impact the redox processes of trace elements and reactive oxygen species</strong></td>
<td><strong>WUTTIG, Kathrin</strong> (Antarctic and Climate Systems CRC, University of Tasmania)</td>
</tr>
<tr>
<td>11:45 - 13:00</td>
<td>Ventilation and Oxygen Supply</td>
<td>Block 4 // Audimax</td>
</tr>
<tr>
<td></td>
<td><strong>Oxygenation and deoxygenation of Atlantic and Pacific Ocean Oxygen Minimum Zones by the wind interacting with mesoscale eddies</strong></td>
<td><strong>KARSTENSEN, Johannes</strong> (GEOMAR, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>Near-inertial wave interaction with coherent anticyclonic eddies – a ventilation source for oxygen minimum zones?</strong></td>
<td><strong>SCHÜTTE, Florian</strong> (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>Understanding the dynamics of oxygen minimum zones by deliberate tracer release experiments (TREs)</strong></td>
<td><strong>TANHUA, Toste</strong> (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>Understanding the Dynamics of the Oxic-Anoxic Interface in the Black Sea</strong></td>
<td><strong>STANEV, Emil Vassilev</strong> (Helmholtz Centre for Materials and Coastal Research, Germany)</td>
</tr>
<tr>
<td></td>
<td><strong>Shift in the Black Sea ventilation regime and decline of its oxygen inventory</strong></td>
<td><strong>CAPET, Arthur</strong> (University of Liège, Belgium)</td>
</tr>
<tr>
<td></td>
<td><strong>Strong intensification of the Arabian Sea oxygen minimum zone in response to Arabian Gulf warming</strong></td>
<td><strong>LACHKAR, Zouhair</strong> (New York University Abu Dhabi, United Arab Emirates)</td>
</tr>
<tr>
<td>13:15 - 14:45</td>
<td>Poster Session with fingerfood and drinks</td>
<td>Tent in front of the Audimax</td>
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### 06.09. THURSDAY MORNING 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<tbody>
<tr>
<td>09:00</td>
<td><strong>07 Impacts on Fisheries / Socioeconomics</strong></td>
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<tr>
<td></td>
<td><strong>Keynote Talks</strong></td>
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<tr>
<td></td>
<td>Audimax</td>
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<tr>
<td>09:00</td>
<td>Deoxygenation effects on fisheries: a mosaic of effects and responses</td>
</tr>
<tr>
<td></td>
<td>ROSE, Kenneth</td>
</tr>
<tr>
<td>09:35</td>
<td>Effect of deoxygenation on fish biology and fisheries in an enclosed</td>
</tr>
<tr>
<td></td>
<td>CASINI, Michele</td>
</tr>
<tr>
<td>10:10</td>
<td>Fish, ocean oxygen depletion and the food security of current and</td>
</tr>
<tr>
<td></td>
<td>SUMAILA, Rashid</td>
</tr>
<tr>
<td>10:45</td>
<td><strong>Coffee Break</strong></td>
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</tbody>
</table>

**09:00 - 10:45**
### 06.09. THURSDAY MORNING 2

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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</thead>
<tbody>
<tr>
<td>11:15</td>
<td><strong>08 Coastal Systems: From Understanding to Management</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Keynote Talks</strong></td>
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<tr>
<td></td>
<td>Audimax</td>
</tr>
<tr>
<td>11:15</td>
<td>Greening of the land and the coastal ocean</td>
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<tr>
<td></td>
<td>RABALAIAS, Nancy</td>
</tr>
<tr>
<td>11:50</td>
<td>Coupled physical-biogeochemical study of eutrophication/hypoxia in the Pearl River estuary off Hong Kong</td>
</tr>
<tr>
<td></td>
<td>GAN, Jianping</td>
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<tr>
<td>12:25</td>
<td>The Baltic Sea: from understanding to management</td>
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<td>CONLEY, Daniel</td>
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<tr>
<td>13:00 - 14:30</td>
<td>Lunch Break</td>
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### 06.09. THURSDAY AFTERNOON 1

**14:30 - 16:15**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
<th>Speaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:30</td>
<td>Economic repercussions of tipping points in the Humboldt upwelling system</td>
<td><strong>BRONNMANN, Julia</strong> (Kiel University, Germany)</td>
</tr>
<tr>
<td>14:45</td>
<td>Valuing ecosystem services at risk from deoxygenation of oceans, estuaries, and coastal seas</td>
<td><strong>LIMBURG, Karin E.</strong> (SUNY College of Environmental Science and Forestry, USA)</td>
</tr>
<tr>
<td>15:00</td>
<td>Ecological-economic sustainability of the Baltic cod fisheries under global change</td>
<td><strong>STIASNY, Martina</strong> (Kiel University, Germany)</td>
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</tbody>
</table>

**16:00 - 16:30 Coffee Break**

16:00
<table>
<thead>
<tr>
<th>08</th>
<th>Coastal Systems: From Understanding to Management</th>
<th>09</th>
<th>Ocean Deoxygenation - How the Past can Inform the Future</th>
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<tbody>
<tr>
<td></td>
<td>Block 2 // Audimax</td>
<td>Hörsaal C</td>
<td>Block 1 // Audimax</td>
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<tr>
<td><strong>06.09. THURSDAY AFTERNOON 1</strong></td>
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<tr>
<td>Controls on coastal hypoxia: a global synthesis</td>
<td>Variability of dissolved oxygen over the last millennium and the 21st century in an earth system model.</td>
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<tr>
<td>FENNEL, Katja</td>
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<tr>
<td>(Dalhousie University, Canada)</td>
<td>HAMEAU, Angélique</td>
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<td>(University of Bern, Switzerland)</td>
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<tr>
<td>Oxygen concentrations from water column to seabed – integrating observations and modelling to support assessments of status and predict change</td>
<td>Reconstruction of paleo-redox conditions in particle rain vs. diffusion dominated settings in Pacific oxygen minimum zones</td>
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<td>GREENWOOD, Naomi</td>
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<tr>
<td>(Cefas, UK)</td>
<td>EROGLU, Suemeyya</td>
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<td></td>
<td>(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
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<tr>
<td>On the eutrophication, hypoxia and ocean acidification in the coastal ocean</td>
<td>I/Ca ratios of carbonates as proxy for changes of deoxygenation in the past: a Nano-SIMS study on benthic foraminifera for better mechanistic understanding, evaluation and application</td>
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<td>DAI, Minhan</td>
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<tr>
<td>(Xiamen University, China)</td>
<td>LIEBETRAU, Volker</td>
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<td>(GEOMAR, Germany)</td>
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<tr>
<td>The future of coastal hypoxia under scenarios of river management</td>
<td>Decadal to millennial-scale changes in oxygen minimum zone intensity, export production and fish fluctuations in the Humboldt Current System</td>
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<td>JUSTIC, Dubravko</td>
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<tr>
<td>(Louisiana State University, USA)</td>
<td>SALVATTECI, Renato</td>
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<td>(Kiel University, Germany)</td>
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<tr>
<td>Climate change is projected to exacerbate impacts of coastal eutrophication in the northern Gulf of Mexico</td>
<td>Decadal to multidecadal changes in marine subsurface oxygenation off central Peru since the XIX century</td>
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<td>LAURENT, Arnaud</td>
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<tr>
<td>(Dalhousie University, Canada)</td>
<td>CARDICH, Jorge</td>
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<td>(Cayetano Heredia University, Peru)</td>
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<tr>
<td>Future climate change exacerbates hypoxia in Chesapeake Bay due to warming temperatures</td>
<td>Multidecadal changes of OMZ intensity over the Peruvian upper-slope inferred by pore density in benthic foraminifer <em>Bolivina seminuda</em> since XIXth century</td>
<td></td>
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<td>HINSON, Kyle</td>
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<tr>
<td>(VIMS, College of William and Mary, USA)</td>
<td>ROMERO CHUQUIVAL, Dennis</td>
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<td>(Marine Institute of Peru, Peru)</td>
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<td></td>
<td>Benthic foraminiferal Mn/Ca evidence for bottom water deoxygenation in the Baltic Sea over the past 7,500 years</td>
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<td>NI, Sha</td>
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<tr>
<td></td>
<td>(Lund University, Sweden)</td>
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</table>
### 06.09. THURSDAY AFTERNOON 2

**16:30 - 18:00**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
</tr>
</thead>
<tbody>
<tr>
<td>16:30</td>
<td><strong>05 Major Upwelling Systems</strong> Block 3 // Audimax</td>
</tr>
</tbody>
</table>
| 16:30 | Dissolved organic matter cycling in the coastal upwelling system off central Peru during an “El Niño” year | **IGARZA, Maricarmen**  
(ICBM, University of Oldenburg, Germany) |
| 16:45 | Distributions and emissions of dissolved methane in coastal upwelling region off Peru | **SUN, Mingshuang**  
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
| 17:00 | Pathways and variability of $N_2O$ emissions in the Pacific Ocean | **BIANCHI, Daniele**  
(University of California, Los Angeles, USA) |
| 17:15 | Insights of the dynamics in the East Pacific Upwelling System from a nested 1/20° ocean circulation model | **GETZLAFF, Klaus**  
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany) |
| 17:30 | Dissolved oxygen dynamics in coastal upwelling systems: insights from idealized submesoscale physical-biogeochemical modelling | **GARÇON, Véronique**  
(LEGOS, France) |
| 17:45 | Demonstrating the value of enhanced multidisciplinary sustained observations for understanding variability in the oxycline and its impacts on the EBUS ecosystems | **TELSZEWSKI, Maciej**  
(International Ocean Carbon Coordination Project, Poland) |

**Please note: Change of location**

### 19:00 - 23:00 Conference Dinner with Best Poster Awards

Norwegenkai | Zur Fähre 1 | 24143 Kiel  
More information on page 17
<table>
<thead>
<tr>
<th>09</th>
<th>Ocean Deoxygenation – How the Past can Inform the Future</th>
<th>Block 2 // Audimax</th>
<th>Hörsaal D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spread of ocean anoxia and sluggish overturning circulation in a warmer-than-today world: does the geological record support this scenario?</td>
<td>KUHNT, Wolfgang (Kiel University, Germany)</td>
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<td>Climate-carbon cycle dynamics on a warmer-than-modern Miocene Earth</td>
<td>HOLBOURN, Ann (Kiel University, Germany)</td>
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<td>Nitrogen fixation in the coastal Peruvian upwelling zone following a simulated upwelling event</td>
<td>KITTU, Leila (GEOMAR Helmholtz-Centre for Ocean Research Kiel, Germany)</td>
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<td>Biologically-associated nitrous oxide accumulation in the euphotic zone</td>
<td>KAO, Shuhji (Xiamen University, China)</td>
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<td>Silicon and nitrogen cycling in the upwelling area off Peru: a dual isotope approach</td>
<td>GRASSE, Patricia (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
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<td>Long term variability in the denitrification rate in the eastern tropical North Pacific</td>
<td>DEVOL, Allan (University of Washington, USA)</td>
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<td>Benthic N-cycling in the Peruvian Oxygen Minimum Zone in relation to variable bottom water redox conditions</td>
<td>CLEMENS, David (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
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<td>An experimental and modeling investigation of sediment nutrient cycling during further deoxygenation on the peruvian margin</td>
<td>STOLPOVSKY, Konstantin (GEOMAR Helmholtz Zentrum für Ozeanforschung Kiel, Germany)</td>
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<td>Oscillations in Cretaceous ocean productivity and deoxygenation induced by redox-dependent nutrient cycling</td>
<td>WALLMANN, Klaus (GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)</td>
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<td>Impact of Cenomanian-Turonian Anoxic Events on ocean oxygenation: High-resolution records from the Atlantic Tarfaya-Laayoune Basin, SW Morocco</td>
<td>BEIL, Sebastian (Kiel University, Germany)</td>
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<td>Constraining global (de)oxygination during Phanerozoic climate events</td>
<td>OWENS, Jeremy D. (Florida State University, USA)</td>
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19:00 - 23:00 Conference Dinner with Best Poster Awards

Norwegenkai | Zur Fähre 1 | 24143 Kiel
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<td>Frederik-Paulsen-Hörsaal**</td>
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<td>09:00</td>
<td>Past variability and recent trends of subsurface ocean oxygenation</td>
<td>GUTIÉRREZ, Dimitri</td>
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<td>in the Eastern Tropical South Pacific: insights from proxy records</td>
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<td>09:35</td>
<td>Large changes in ocean oxygenation during the last ice age: observations</td>
<td>GALBRAITH, Eric</td>
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<td>mechanisms and ecosystem responses to change</td>
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<td>Looking back into the future with a geochemical oxygenation proxy (I/Ca)</td>
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<td>11:15</td>
<td>The regulation of oxygen to low concentrations in the bay of bengal</td>
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<td>11:50</td>
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<td>A comparative study of coastal ocean hypoxia and acidification in two large river dominated systems (northern Gulf of Mexico and East China Sea)</td>
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<td>12:25</td>
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<td>Impacts of a changing global phosphorus cycle on coastal ocean deoxygenation</td>
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### 07.09. FRIDAY AFTERNOON 1

| 14:30 - 16:15 | **09 Ocean Deoxygenation - How the Past can Inform the Future**  
Block 3 // Audimax | Hörsaal A |
|---------------|-------------------------------------------------------------------|
| **14:30**     | Exploring the links between flood cyclicity and the OMZ development on the Nile deep-sea fan during the African Humid Period  
**BLANCHET, Cecile**  
(Helmholtz-Centre Potsdam German Research Centre for Geosciences, Germany) |
| **14:45**     | Nitrogen Removal Across Glacial Terminations in the Eastern Tropical South Pacific  
**SEPÚLVEDA, Julio**  
(University of Colorado Boulder, USA) |
| **15:00**     | A quantitative nitrate reconstruction over the last 22,000 years in the intermediate Pacific based on the pore density of the denitrifying foraminifera *Bolivina spissa*  
**GLOCK, Nicolaas**  
(GEOMAR, Germany) |
| **15:15**     | The Natural Variability of Marine de-oxygenation in the Eastern-Tropical Pacific since the last Glacial Maximum  
**PICHEVIN, Laetitia**  
(University of Edinburgh, UK) |
| **15:30**     | Benthic pelagic coupling in the Peruvian upwelling system over the last 25 thousand years  
**ERDEM, Zeynep**  
(NIOZ Royal Netherlands Institute for Sea Research / Utrecht University, Netherlands) |
| **15:45**     | Multidecadal to millennial-scale changes in Oxygen Minimum Zone intensity off Peru during the last 20 kyr: proxy-model comparison  
**SCHNEIDER, Ralph**  
(Kiel University, Germany) |

**16:00 - 16:30 Coffee Break**

**16:00**

**16:30 Conference ends**
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**Efficient removal of nitrogen and phosphorus in a eutrophic coastal system recovering from hypoxia**

**VAN HELMOND, Niels**
(Utrecht University, Netherlands / Lund University, Sweden)

**Upwelling induced anoxia in a eutrophic estuary, southwest coast of India: influence of lateral inputs**

**GOPURATHINGAL DEVASSYKUTTY, Martin**
(Kerala University of Fisheries and Ocean Studies, India)

**Regeneration of phosphorus in the ocean during past greenhouse climates: role of redox conditions and impact on primary productivity**

**PAPADOMANOLAKI, Nina M.**
(Utrecht University, Netherlands)

**Time-series of the secondary nitrite maximum in the ETSP reveal tight coupling of ENSO and nitrogen processes in the OMZ**

**BANGE, Hermann W.**
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

**Nitrogen-carbon connections in a deoxygenating ocean**

**LANDOLFI, Angela**
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

**Symmetric marine biogeochemical responses in warming and cooling worlds**

**KVALE, Karin**
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

**Improving the “bio” part of biogeochemical models**

**PAHLOW, Markus**
(GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany)

**Benthic community resilience in a harsh place: hypoxia and tsunami perturbations in the coast of the southern Humboldt Current System**

**QUIÑONES, Renato A.**
(University of Concepción, Chile)

**Seasonal and annual variability of coastal sulphur plumes and forcing processes in the Benguela upwelling system**

**DADOU, Isabelle**
(LEGOS (IRD/CNRS/CNES/University of Toulouse), France)

**Linking shelf/break processes to coastal hypoxia in the upwelling core of the central California Current System**

**HEWETT, Kate**
(University of California, Davis, USA)

**Influence of hypoxic upwelled waters on the distribution of trace metals in the surficial sediments of the Cochin estuary.**

**PARENKAT MONY, Deepulal**
(CSIR-National Institute of Oceanography, India)

**Human regulation of fresh-salt water budget and hypoxia in semi enclosed seas**

**ZACHARIAS, Ierotheos**
(University of Patras, Greece)
Gendered innovations in science, climate change, machine learning, and robotics

Londa Schiebinger // schieb@stanford.edu

How can we harness the creative power of gender analysis for discovery and innovation? In this talk I identify three strategic approaches to gender in research, policy, and practice:
1) “Fix the Numbers of Women” focuses on increasing women’s participation;
2) “Fix the Institutions” promotes gender equality in careers through structural change in research organizations; and
3) “Fix the Knowledge” or “Gendered Innovations” stimulates excellence in science and technology by integrating sex and gender analysis into research.

This talk focuses on the third approach. I will discuss several case studies, including sex and gender analysis in basic science, climate change, machine learning, and robotics. To match the global reach of science and technology, Gendered Innovations was developed through a collaboration of over a hundred experts from across the United States, Europe, Canada, and Asia. Major funders for Gendered Innovations include the European Commission, the U.S. National Science Foundation, and Stanford University.

Londa Schiebinger | Londa Schiebinger is the John L. Hinds Professor of History of Science at Stanford University. She currently directs the EU/US Gendered Innovations in Science, Health & Medicine, Engineering, and Environment project. She is a leading international expert on gender in science and technology and has addressed the United Nations on the topic of “Gender, Science, and Technology.” She is an elected member of the American Academy of Arts and Sciences and the recipient of numerous prizes and awards, including the prestigious Alexander von Humboldt Research Prize and Guggenheim Fellowship. Her work on Gendered Innovations (genderedinnovations.stanford.edu) harnesses the creative power of sex and gender analysis to enhance excellence and reproducibility in science and technology.
01
Prediction and Monitoring

Topic abstract

The content of dissolved oxygen in the ocean is sensitive to climate variability and climate change. Due to the strong temperature dependence of its solubility, oceanic oxygen is expected to decline in a future warming ocean, which was already demonstrated by earth system models. Observations of oceanic oxygen trends over several decades indicate that also oxygen minimum zones in the subsurface ocean are affected, showing an intensification (further oxygen decrease) and/or expansion of their spatial extent. In this session we invite studies on the detection and quantification of oceanic oxygen change on timescales up to multidecadal. We welcome contributions on a range of spatial scales, from focused studies on certain oceanic regions to the global ocean oxygen budget, using observational data, model results, and ideally a combination of both.

Conveners:
Birgit Schneider // Kiel University, Germany
Mojib Latif // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
Arne Körtzinger // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
Osvaldo Ullao // University of Concepción, Chile

KEYNOTE SPEAKERS

03.09. MONDAY | 09:00
Emergence and detection of climate change-driven trends in oceanic oxygen concentration

Stephanie Henson // S.Henson@noc.ac.uk

Climate change is expected to modify ecological responses in the ocean, with the potential for important effects on the ecosystem services provided to humankind. As part of the effort towards detection of long-term trends, a network of ocean observatories and time series stations provide high quality data for a number of key parameters, such as oxygen concentration. The temporal and spatial scales over which observations of thermocline oxygen concentration must be made to robustly detect a long-term trend are assessed. As a global average, continuous time series are required for ~ 26 years to distinguish a climate change trend in oxygen concentration from natural variability. Regional differences are extensive, with temperate latitudes generally requiring shorter time series (<~30 years) to detect trends than other areas. In addition, the ‘footprint’ of existing and planned time series stations, that is the area over which a station is representative of a broader region, is quantified. The existing network of observatories is representative of oxygen concentrations over only 9% of the global ocean. Climate-driven changes in oxygen concentration are unlikely to occur in isolation and multiple factors may act additively or synergistically to increase the impact of deoxygenation. How rapidly multiple drivers of marine ecosystem
change, including oxygen concentration, develop in the future ocean is assessed. By analysing an ensemble of models we find that, within the next 15 years, the climate change-driven trends in multiple ecosystem drivers emerge from the background of natural variability in 55% of the ocean and propagate rapidly to encompass 86% of the ocean by 2050 under a ‘business-as-usual’ scenario. However, the exposure of marine ecosystems to climate change-induced stress can be drastically reduced via climate mitigation measures; with mitigation, the proportion of ocean susceptible to multiple drivers within the next 15 years is reduced to 34%. Mitigation slows the pace at which multiple drivers emerge, allowing an additional 20 years for adaptation in marine ecological and socio-economic systems alike.

Stephanie Henson | Stephanie Henson is a Senior Scientist at the National Oceanography Centre and Honorary Associate Professor at the University of Southampton. She leads an active research group in global biogeochemical oceanography, currently made up of 2 post-docs and 5 PhD students. Her particular research interests aim at understanding the variability and climate change effects on phytoplankton populations and subsequent impacts on the biological carbon pump. Her research exploits autonomous vehicles, satellite and in situ data, as well as output from biogeochemical models. In 2012, she received the EGU Award for Outstanding Young Scientist for her ‘fundamental contribution to the study of marine ecosystems’ and in 2016 she was awarded a highly competitive European Research Council Consolidator Grant.

03.09. MONDAY | 09:35
Constraints on ocean de-oxygenation and warming from atmospheric oxygen observations
Laure Resplandy // laurer@princeton.edu

O₂ inventories in the ocean and the atmosphere are linked. As the ocean warms, it loses O₂ to the atmosphere. The amount of O₂ lost by the ocean could be quantified with the complementary change observed in the atmosphere, using precise atmospheric O₂ measurements spanning nearly three decades. This method is not limited by data sparseness, as fast mixing in the atmosphere efficiently integrates the global ocean signal, and could provide an independent constraint on the global ocean O₂ loss obtained from hydrographic data. Here, we use atmospheric O₂ and CO₂ measurements combined into the tracer “atmospheric potential oxygen” (APO) to remove land biosphere influences in atmospheric O₂. The signature of ocean changes (solubility, ocean circulation and biological photosynthesis and respiration) in APO is further isolated from the impacts of industrial processes, anthropogenic aerosol deposition etc. We show that a clear positive signal in APO emerges, i.e. the global ocean response to climate change has unambiguously led to a net ocean outgassing of O₂ and CO₂. We use this observed ocean-driven change in APO to evaluate ocean de-oxygenation and discuss the uncertainties related to this method that implicitly assumes a carbon-to-heat ratio in the ocean. Hydrographic observations and Earth
system models indicate, however, that this ocean-driven APO signal is largely dominated by solubility changes, and is therefore a good proxy of the global change in ocean heat content. Using this tight link between APO and heat, we provide a much-needed independent constraint on the ocean heat uptake, at the high end of previous in-situ temperature based estimates ($1.41 \pm 0.36 \times 10^{22}$ J/y since 1991).

**Laure Resplandy** | Laure Resplandy is Assistant Professor at Princeton University in the Geosciences Department and the Princeton Environmental Institute. Her research interests are on the influence of climate and ocean circulation on marine biogeochemistry and ecosystems, in particular the changes in ocean oxygenation and the interactions between the carbon cycle and climate. In her work she uses data from observations and ocean and climate models.

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**03.09. MONDAY | 10:10**

**Variability and extremes in ocean (de)oxygenation and water column denitrification in the eastern tropical Pacific**

**Nicolas Gruber** // nicolas.gruber@env.ethz.ch
Simon Yang // University of California, Los Angeles, USA
Ana C. Franco // ETH Zürich, Switzerland
Matthias Münnich // ETH Zürich, Switzerland
Meike Vogt // ETH Zürich, Switzerland

The Eastern Tropical Pacific (ETP) hosts two of the world’s three Oxygen Deficient Zones (ODZs), large bodies of suboxic water that are subject to high rates of water column denitrification (WCD). In the mean, these two ODZs are responsible for 15 to 40% of all fixed N loss in the ocean, but knowledge is limited on how this loss varies in time. Here, we use hindcast simulations with both a global and a regional model to assess the variability and the extremes in the (de)oxygenation of the ETP and its impact on WCD. Using the global model, i.e., the ocean component of the NCAR Community Earth System Model, we showed already that the El Niño–Southern Oscillation (ENSO) is a major driver for extreme conditions in the ODZ. Namely, we found that ENSO causes large variations in WCD, with mature La Niña (El Niño) conditions having peak denitrification rates that are up to 70% higher (lower) than the mean rates (Yang et al., 2017). This large variability is the result of wind-driven changes in circulation and isopycnal structure concurrently modifying the thermocline distribution of $O_2$ and organic matter export in such a way that the response of WCD is strongly amplified. Of particular importance is the shoaling (deepening) of the upper boundary of the ODZs, as this results in a much larger fraction of the exported organic matter being subject to anaerobic remineralization, i.e., WCD. While the global model is well positioned to diagnose and analyze such large-scale events, its usefulness is limited to assess the role of smaller, shorter, but often more intense extreme events. To this end, we will be using hindcast simulations with a high-resolution regional model of the ETP region.
based on the Regional Oceanic Modeling System (ROMS). Initial analyses suggested that some of these events are associated with mesoscale eddies that create very strong low oxygen environments, while other events are the result of regional-scale oceanic or atmospheric “weather” conditions. Of particular relevance are those events when ENSO and local processes push the system toward very extreme conditions. Given the highly non-linear nature of the marine oxygen and nitrogen cycle, such extreme events can leave a disproportional impact on the overall (de)oxygenation of the ETP and its WCD, with strong implications on the global-scale balance of the marine N cycle and the emission of the greenhouse gas N\textsubscript{2}O.

**Nicolas Gruber** | Nicholas Gruber is full Professor for Environmental Physics at the Department of Environmental Systems Science at ETH Zurich since July 2006. His research interests are the study of biogeochemical cycles on regional to global scales and on timescales from months to millennia, with a particular focus on the interaction of these cycles with Earth’s climate system. His goal is to better understand the physical, chemical and biological processes that control these cycles and to be able to make predictions for the future, especially with regard to the potential feedbacks between the global carbon cycle and a changing climate. His primary research tools are the interpretation and analysis of observational data coupled with the use of models ranging in complexity from simple box models to general circulation models.
Historic observations of dissolved oxygen $O_2$ in the ocean are analyzed to quantify multidecadal trends and variability from 1958 to 2015. The global gridded oxygen anomaly dataset for the upper 1000 m on $1 \times 1$ degree grid is produced in Hokkaido University based on ocean observations collected in the World Ocean Database 2013 with additional quality control. The resultant oxygen anomaly field is used to quantify upper ocean $O_2$ trends at global and hemispheric scales. A widespread negative $O_2$ trend is beginning to emerge from the envelope of interannual variability.

Ocean reanalysis data are used to evaluate relationships with changes in ocean heat content (OHC) and oxygen solubility ($O_{2,\text{sat}}$). Global $O_2$ decline is evident after the 1980s, accompanied by an increase in global OHC. The global upper ocean $O_2$ inventory (0–1000 m) changed at the rate of $-243 \pm 124$ T mol $O_2$ per decade. Further, the $O_2$ inventory is negatively correlated with the OHC ($r = -0.86$; 0–1000 m) and the regression coefficient of $O_2$ to OHC is approximately $-8.2 \pm 0.66$ nmol $O_2$ J$^{-1}$, on the same order of magnitude as the simulated $O_2$-heat relationship typically found in ocean climate models. Variability and trends in the observed upper ocean $O_2$ concentration are dominated by the apparent oxygen utilization component with relatively small contributions from $O_{2,\text{sat}}$. This indicates that changing ocean circulation, mixing, and/or biochemical processes, rather than the direct thermally induced solubility effects, are the primary drivers for the observed $O_2$ changes. The spatial patterns of the multidecadal trend include regions of enhanced ocean deoxygenation including the subpolar North Pacific, eastern boundary upwelling systems, and tropical oxygen minimum zones. Further studies are warranted to understand and attribute the global $O_2$ trends and their regional expressions.

**Autonomous observation of oxygen deficient zone (ODZ) biogeochemistry**

Mark Altabet // University of Massachusetts Dartmouth, USA // maltabet@umassd.edu
Craig McNeil // University of Washington, USA
Eric D’Asaro // University of Washington, USA
Andrew Reed // University of Washington, USA
Annie Bourbonnais // University of Massachusetts Dartmouth, USA

Open ocean oxygen deficient zones (ODZ’s) host unique subsurface biogeochemical processes that have global impacts including fixed nitrogen loss and the cycling of $N_2O$. They have been predicted to expand geographically in response to global warming though contrary perspectives are available. In addition, biogeochemical activity is highly variable in time and space as associated with coastal upwelling plumes and certain types of mesoscale eddies. Correspondingly, ship based observations are insufficient to both capture relevant scales of variability and provide the sustained time series records required to detect long term ($\geq$ decadal) changes. While many of the observational requirements of ODZ’s overlap with those of the global ocean, the
unique subsurface biogeochemistry of ODZ’s requires additional sensor capabilities. In the cores of ODZ’s, O₂ is often undetectable even with nM sensitivity and key ODZ microbial nitrogen cycle processes now appear to have O₂ sensitivities in the 0 to 3 μM range. Hence, relatively small changes in O₂ control the buildup of nitrite and the loss of fixed nitrogen to N₂ gas. Up to now, there has been no commercially available, autonomously-deployable O₂ sensor. Here we show field data from float deployments in the Mexican ODZ that the Clark-type SBE43 O₂ sensor is capable of reliable nM measurements. To do so, sufficient exposure to ODZ waters was needed for O₂ to diffuse out of elastomeric parts and for data processing to be geared to the nM range. Working with SeaBird, a prototype NanoSBE43 sensor has been produced and satisfactorily tested. Measurements of biogenic N₂ production is definitive for N-loss in ODZ’s but analytically challenging particularly for autonomous deployment. We have used a gas tension device (GTD) to do so, with which total dissolved gas pressure is measured. In ODZ’s, ~99% of the total pressure is from N₂ and its concentration is derived from Henry’s law. The biogenic contribution is determined by subtracting atmospheric and physical supersaturation terms. Short term float deployments showed vertical profiles consistent with lab-based measurements made by mass spectrometer determination of N₂/Ar ratio. A GTD-Argo float deployed since Nov. 2016 has continued to operate reliably with an apparent precision of 0.15 μmol kg⁻¹.

**Internal variability as a driver of decadal deoxygenation**

**Yohei Takano // Max Planck Institute for Meteorology, Germany //**

**yohei.takano@mpimet.mpg.de**

**Tatiana Ilyina // Max Planck Institute for Meteorology, Germany**

Ocean deoxygenation in the past decades is commonly considered as a consequence of global warming. Because of large internal variability in the climate system, it is generally hard to robustly conclude the cause of deoxygenation from limited observations. Here, we explore the potential role of the internal variability in shaping the decadal deoxygenation using the MPI-ESM’s Large Ensemble Simulations and the observations from World Ocean Database 2013. We find that the internal variability could induce basin-scale deoxygenation on multi-decadal timescales comparable to what has been observed in the past decades. This indicates that the internal variability could potentially dominate the multi-decadal trend of oceanic oxygen. We further analyzed the model outputs taking into account past observational coverage. This approach will highlight the consequence of limited observational coverage on interpreting the multi-decadal oxygen trends. The limited number of observations could add spurious uncertainty on top of the uncertainty rising from the internal variability. These uncertainties are likely to persist in the near future projections under the stabilized climate scenario (RCP4.5), which could remain as a major obstacle on monitoring deoxygenation. The global and regional analyses also indicate the possible impact of multi-basin climatic processes, which could induce multi-decadal deoxygenation among multi-basins. This indicates that the role of decadal climate and ocean biogeochemical variability also need to be explored for the mechanistic understanding on multi-basin deoxygenation as well as improving the model.
Quality of the baseline climatologies for oxygen and nutrients for inventory studies

Hernan Garcia // NOAA National Centers for Environmental Information, USA // hernan.garcia@noaa.gov
Tim Boyer // NOAA National Centers for Environmental Information, USA
James Reagan // NOAA National Centers for Environmental Information / CICS, University of Maryland, USA

Quantifying ocean variability requires baseline observations of known quality on relevant spatial and temporal scales. The World Ocean Database (WOD) is the largest digital collection of freely accessible, uniformly formatted, and quality controlled historical and modern in situ ocean profile data. These data are the basis for developing the World Ocean Atlas (WOA) series. We compared the data quality of WOA 2013 version 2 (WOA13v2) and the Global Ocean Data Analysis Project version-2 (GLODAPv2). WOA13v2 objectively analyzed fields are based on quality-controlled data for the period 1955-2012 using ~15 million profiles from multiple observing systems. GLODAPv2 was derived from measurements collected during 700+ research cruises from 1972-2013. While the observations used in these climatologies underwent different levels of quality control and objective mapping, average differences (WOA-GLODAP) are small when compared to the uncertainty of measurements on the global scale below ~500 m depth for temperature (0.003±0.160 °C), salinity (0.000±0.015), oxygen (0.4±4.7 μmol/kg), silicate (-0.3±3.8 μmol/kg), nitrate+nitrite (-0.22±0.95 μmol/kg), and phosphate (-0.02±0.07 μmol/kg). Above about 500 m depth, there are significant differences likely related to summer dominated seasonal bias in the GLODAPv2. WOA 2018 is planned for September 2018 and will contain much additional data. We plan to develop an additional experimental O2 (μmol/kg) hybrid climatology using both in situ and sensor-based data from bio Argo, CTD, and gliders corrected for calibration depth offsets. Using sensor-based O2 data from floats, gliders, and CTD could potentially add an additional ~0.5 million profiles to the ~0.9 in situ O2 profiles in the WOA18 O2 climatology. What remains is a concerted community effort to help add available O2 and nutrient data not found in WOD that would enable a common high-quality WOD O2 dataset for the international research community to use.

Volcanic impacts on air-sea oxygen exchange: insights from the large ensemble experiment

Yassir Eddebar // Scripps Institution of Oceanography, UCSD, USA // yeddeba@ucsd.edu
Keith Rodgers // Princeton University, USA
Matt Long // National Center for Atmospheric Research, USA
Ralph Keeling // Scripps Institution of Oceanography, UCSD, USA

Volcanic eruptions are expected to have a major influence on ocean physics and biogeochemistry. The magnitude, spatial patterns, and mechanisms of volcanic impacts on the oceans, however, remain poorly understood due to the confounding effects of internal variability and limited observations. Here, the oceanic response to recent major tropical eruptions is evaluated in the Large Ensemble experiments of the fully coupled Earth system models of CESM and GFDL, focusing on air-sea heat, oxygen and carbon exchanges. Substantial and spatially complex ocean heat loss and oxygen and carbon uptake immediately follow the Agung, El Chichon and Pinatubo eruptions. These volcanic signals are relatively consistent across eruptions.
and models, and are in general agreement with available observations. The oceanic response to tropical eruptions is characterized by intense surface cooling over the subtropics and northern high latitudes, but is also accompanied by El Niño-like surface warming in the eastern and central tropical Pacific initiated by climatological upwelling of warm subsurface anomalies in the east. These El Niño-like changes in the source and intensity of equatorial upwelling lead to anomalous outgassing of O₂, but are largely counteracted by intensified ventilation at higher latitudes that drive the global oceanic uptake of O₂. Volcanic eruptions thus induce a complex biogeochemical ocean response that is highly relevant to the attribution of recently observed O₂ trends in the ocean and their prediction, and may serve as a powerful analog for the unintended consequences of geoengineering in the ocean.

The conundrum of marine oxygen: why is the future ocean loosing oxygen despite declining export production?

Wolfgang Koeve // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany // wkoeve@geomar.de
Paul Kähler // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
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The current generation of climate models leaves us with a conundrum. On the one hand, the models project a decline of the export of organic matter from the surface ocean and a decline in biological oxygen consumption in the ocean interior, which should be consistent with an increase of the ocean’s oxygen content. On the other hand, they project an increase in apparent oxygen utilization (AOU), an explanation of a large share of the overall loss of marine oxygen in the same models. A decrease of the export of organic matter and an increase of its degradation product (the oxygen debt, i.e. AOU) appears contradictory. Using a global ocean biogeochemical model we quantify how aerobic respiration (oxygen utilization per time) is translated into its respective storage product (AOU) and find large regional variations and different depth dependencies of the respective storage-to-respiration ratio. We designed idealised model tracers accumulating AOU from the degradation of organic matter stemming from predefined ocean regions. By combining a large number of regional/depth specific AOU tracers, we can resolve the regional and depth specific variations of the storage-to-respiration ratio. Dividing the ocean into 20 latitudinal zones, we find that the storage-to-export ratio in the Southern Ocean is 10 times larger than in the subtropics. Using one AOU tracer per 2.8x2.8 degree area (the horizontal resolution of our model) increases the spread of regional storage-to-export ratio again by a factor of 10. We finally quantify how oxygen consumption in different depth layers contributes to global AOU. 90% of the integrated respiration takes place in the upper 1000m, but only 37% of global AOU originates from there. About 44% of the global AOU is associated with about 4% of global respiration, which takes place in the deep ocean below 2000m. The horizontally averaged storage-to-respiration ratio increases with depth; it is 16 times larger in the deepest model layers than the global mean. The observed regional decoupling between the driving force of the biological carbon pump (export) and its imprint (storage of degradation products) is key to understand why future ocean projections often find an increase in global AOU (ocean deoxygenation) with a concomitant decrease in export production.
Expanding marine hypoxia will likely have significant long-term impacts on ocean chemistry and ecology, and on coastal communities around the world. As the site of the world’s most expansive natural oxygen minimum zone, the Pacific Ocean is particularly sensitive to ongoing and future deoxygenation. Time-series observations from across the Pacific Basin, from British Columbia, to Hawaii, Japan, Chile and other regions, have revealed a complex pattern of decadal-scale oxygen changes across this ocean. The OxyNet project is a Canadian-based, international effort that aims to examine current spatial and temporal trends, future trajectories and potential impacts of deoxygenation across the Pacific Ocean, and in Canadian waters of the Arctic and Atlantic Oceans. In this presentation we will outline the overall strategies to tackle the objectives above, which include: 1) the compilation of existing time-series observations of oxygen and related variables across the Pacific Ocean, and Canadian waters of the Arctic and Atlantic Oceans; 2) calibration of autonomous oxygen measurements from moorings, profiling floats, and gliders for integration into other existing data archives; 3) assessment of current ocean deoxygenation drivers and future trajectories based on output from numerical simulations. We will couple our data analysis and modelling with resource economic analysis aimed at quantifying impacts of oxygen loss potential the value of British Columbia wild fisheries and aquaculture due to changes in the suitability of marine habitat for key fish species.

OxyNet is an interdisciplinary project that involves collaborations with Chile, USA, Japan and across Canada, bringing together an international group of observational oceanographers, numerical modellers and economists, with key stakeholders from Fisheries and Oceans Canada and the British Columbia Salmon Farmers Association. We have also formed a partnership with the Vancouver Aquarium to develop high impact public outreach and educational materials, including new visual gallery displays.

(02) Spatial and temporal variability of oxygen minimum layer and its monitoring by biogeochemical Argo floats in the North Pacific

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Oxygen minimum layer (OML) in the North Pacific, which is clearly appeared as oxygen minimum below main thermocline, has larger area among the global OMLs. Concentration of dissolved oxygen in the North Pacific OML is significantly decreasing and its area and thickness is also expanding based on a small number of ship and station observations. In previous observational studies, the mechanism of decreasing
trend might be caused by strengthened surface stratification and surface warming, which makes decreasing oxygen solubility and inflow of high-oxygen sea water from outside. Recently, some repeat ship observations with high accuracy data for physical and biogeochemical parameters were quantitatively detected those variations and trends, suggesting of which depend on area and depth (e.g., along 137 E and 165 E line-observations which are conducted every year by Japan Meteorological Agency; Takatani et al., 2012; Sasano et al., 2015). It might be one evidence of relationship between variability of OML and physical process such as ocean circulation and mixing. Actually in this study we carried out analyses of OML variability in the North Pacific different amplitude and tendency are detected using limited Argo float data with dissolved oxygen. Although the number and density of data are still not enough to clarify detailed variability, recent decreasing trend of oxygen concentration and expansion of OML are represented from spatial discrete data in the western North Pacific region, the result of which is similar to the previous studies. However, it is far from totally understanding OML distribution and its variability at this time, especially in the central North Pacific region. Therefore, further deployment of oxygen float for OML monitoring and also improvement of data quality control method for dissolved oxygen are required. Based on the communique in G7 Ise-shima summit, JAMSTEC plans to deploy some biogeochemical Argo floats (nutrient, pH, O2 and/or Chl-a, including deep Argo float) mainly in the North Pacific region (around biogeochemical observation point of S1 at 30N,145E and K2 at 47N,160E). The deployment is directed to contribute the international BGC Argo project (BGC Argo Task Team, 2016), and also this will make us enable to capture detailed distribution and mechanism of OML in the North Pacific.

(03) Novel optical oxygen sensor for profiling observation platforms: fast response time enables higher spatial and temporal data resolution

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Ocean warming has a severe impact on oxygen distribution because it reduces oxygen solubility and increases stratification in the upper ocean. Models predict a decline of the global oxygen inventory of about 1-7% over the next century and data show a decrease of more than 2% since 1960 (Schmidtko et al., Nature, 2017). Quantifying global as well as regional changes of oxygen will improve the understanding of chemical, biological and physical processes, especially in oxygen minimum zones (OMZ) where consistent trends of intensification and spatial expansion exit (e.g., Stramma et al., Science, 2008). Although optical sensors, so-called optodes, are available to accurately measure changes in ocean oxygen levels, users still wish to obtain better spatial and temporal resolution on profiling observation platforms than can be currently achieved. Here we demonstrate the utility of a novel and fast, commercially-available optode for in-situ and autonomous oxygen measurements, potentially closing this gap. This novel oxygen optode shows a temperature-dependent response time (t63%) of about 4 seconds and is thereby at least 50% faster compared to other optical oxygen sensors. We aim to fully characterize this optode with
regard to accuracy, precision, pressure dependence, long-term stability and drift, response time as well as air-calibration compatibility. Results build on data from extensive laboratory experiments and field deployments in the Tropical North, South and Southern Atlantic (underway, mooring, float and CTD-cast applications). This promises high quality observations for detecting oxygen level changes on small and fast-changing scales in this ocean region. This novel optode could be used on a wide range of autonomous observation platforms such as ships for Repeat Hydrography, time-series stations and wave gliders, yet is especially promising on floats, gliders and fast-moving ships. In a changing ocean those applications eventually will contribute valuable information to the global oxygen budget.

(04) Recent deoxygenation in the Japan Sea Proper Water in the northeastern Japan Basin

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The Japan Sea is a semi-closed deep sea located in the northwestern margin of the North Pacific. Its deep layers below about 300 m is filled with a quite homogeneous water called Japan Sea Proper Water (JSPW). Here, a gradual decrease of dissolved oxygen (O₂) and an increase of potential temperature (θ) have been observed by hydrographic measurements since 1950s. The O₂ decrease and the warming have been considered to be associated with the weakened cooling and ventilation in winter due to climate change in the northwestern region of the Japan Sea where the JSPW is formed. In this work, we investigated the temporal variability in the properties of the JSPW in the northeastern Japan Basin of the Japan Sea where the water depth exceeds 3500 m, using high-quality data of ship-based measurements being conducted each year since 2010 by the Japan Meteorological Agency. From the vertical profiles of and O₂ and their temporal variabilities, the JSPW is classified into three distinctive layers such as the Upper JSPW, the Deep Water and the Bottom Water. The largest O₂ decreases (11 to 18 mol/kg for 2010-2017) was observed in the Upper JSPW between 500 m and 1000 m where the vertical gradients of and O₂ are both much larger than in the Deep Water below. Consequently, an O₂ minimum layer emerged at around 1000 m in 2013 and is being developed to date. The decrease of O₂ in the Upper JSPW accompanied the increase of nitrate, thereby they are attributed to the increased remineralization in this water. The decrease of O₂ and warming (4 mol/kg and 0.01°C, respectively, for the same period) were also observed on ≈27.349 kg/m³ in the deeper Bottom Water below 2500 m where the water is vertically uniform. The results of this study are helpful in understanding the difference of circulation structure in the Japan Basin, the formation of JSPW, and mixing and biological process. Further examination is also necessary to reveal the variability and its mechanism of warming and deoxygenation in the JSPW by analysis of a comparable high-quality hydrographic observation data in the Japan Sea.
(05) Understanding controls on oxygen deficits in UK waters using a community ecosystem model and isotope tools

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Oxygen (O$_2$) is essential for complex marine life, including commercially important species of fish and shellfish. Ongoing assessments have identified significant downward trends in O$_2$ concentrations in the Northern and Southern North Sea and English Channel. However, the same assessments also identified significant gaps in the data and monitoring practices, as well as lack of understanding of how the interactions between physical, biological and climatological processes control O$_2$ concentrations. During a new project, we aim to narrow these gaps in understanding using a combination of i) new and existing observational datasets; ii) model data generated by the European Regional Seas Ecosystem Model (ERSEM) and iii) a novel combination of oxygen isotope data and model simulations. The work will be split into two phases: Phase 1): Identification of the mechanisms affecting O$_2$ deficiency using the model and observational data; and Phase 2): Investigating the use of oxygen isotopes to help better understand oxygen cycling and the relative contribution of different biological populations to O$_2$ production and consumption. Here, we will present an overview of the project and planned future work.

(06) Decline and bidecadal oscillations of dissolved oxygen in the Oyashio region and their propagation to the western North Pacific

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The western North Pacific is one of the oceans where oxygen (O$_2$) concentration has been declining significantly over the past several decades. Among the studies in the western North Pacific, we have identified trends of declining O$_2$ along the meridional sections at 137E (P09) (Takatani et al., 2012) and at 165E (P13) (Sasano et al., 2015), respectively, where Japan Meteorological Agency (JMA) has been making high-frequency measurements of physical and biogeochemical Essential Ocean Variables including O$_2$. In this study, we extended the analyses of long-term O$_2$ changes in the Oyashio region, i.e., the southwestern region of the western boundary current in the western subarctic, by Ono et al (2001) back to the year 1954 over the past 61 years using quality-controlled data acquired by the JMA. Concentrations of O$_2$ in the Oyashio region have been declining significantly and oscillating over bidecadal timescales on the isopycnal layers spanning = 26.6-27.5 kg m$^{-3}$. The mean rate of the long-term O$_2$ decrease is the highest (-0.70 ± 0.06 mol kg$^{-1}$ yr$^{-1}$) on = 26.7 kg m$^{-3}$ in the
temperature minimum layer. The O$_2$ decline here is predominantly attributed to the reduction of ventilation in winter due to warming and freshening. At $= 27.4$ kg m$^{-3}$ in the Oxygen Minimum Layer (OML) at around the depth of 950 m, O$_2$ concentration is 43 mol kg$^{-1}$ on average and has been declining at a mean rate of -0.14 $\pm$ 0.03 mol kg$^{-1}$ yr$^{-1}$ for the past six decades. The trends in the OML are attributable to a reduction in ventilation in the Sea of Okhotsk associated with a reduction in sea ice formation and the propagation of its impact to the Oyashio through diapycnal mixing adjacent to the Bussol’ Strait in the Kuril Islands. These trends of O$_2$ decline is accompanying bidecadal oscillations and have also been found in the downstream to the east in the 165E section at latitudes 30N-42.5N on $= 26.8$ kg m$^{-3}$ with attenuated amplitudes at latitudes of 40N-45N in the OML on $= 27.4$ kg m$^{-3}$. These results indicate that the signal of secular declines of O$_2$, together with bidecadal oscillations, is being propagated broadly from the Oyashio source region into the interior of the North Pacific Ocean.

**(07) Global ocean oxygen decline as estimated from observations and current climate models**

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A global compilation of oxygen measurements over the past decades indicates that the global oceans were loosing oxygen in a rate of nearly 1 Pmol per decade for the time period 1960-2015. The loss is non-uniform, as some areas show little to no significant loss in oxygen, while oxygen is dropping at rates of 4% per decade in other regions. A detailed analysis of oxygen changes shows a distinct impact of solubility changes due to ocean warming in the upper 1000m, as well as deep ocean changes most likely explainable by ventilation changes. The full set of CMIP5 climate models with oxygen is compared to the observations. While having the same order of magnitude for solubility changes, these are distributed differently to the observations. The overall oxygen decline is generally only half the size of the observed one, indicating substantial model deficiencies. An inter model comparison reveals significant spread and variability of the changes in the horizontal as well as in the vertical for the time period analyzed. We conclude that the CMIP5 climate model set analyzed here still has shortcomings in representing oxygen variations correctly. Nevertheless the correct magnitude of modeled solubility changes indicates that, overall, total oceanic heat uptake is simulated relatively well, while changes in oceanic circulation and/or biogeochemistry may be systematically underrepresented in the current set of climate models.
Topic abstract

Declining oxygen in the open ocean and coastal waters (systems strongly influenced by their watershed) has the potential to greatly alter marine ecosystems. Whether due to global warming, high nutrient loads, or a combination of the two, low oxygen affects distributions, interactions, and physiology of both pelagic and benthic species, resulting in profound changes in biodiversity, food webs and ecosystem structure and functioning. Effects may be direct (such as respiratory stress) or indirect (such as changes in nutrient inventories and stoichiometry), and variation among species in their tolerance and response to low oxygen can play an important role in determining consequences. Even seemingly subtle changes in oxycline depth can have large impacts due to interactions with other habitat structuring factors such as light levels, nutrient availability, and biomass distributions. This theme session will explore effects and implications of declining and low oxygen in both coastal and oceanic systems. We welcome presentations that consider organismal, community, food web and ecosystem-level effects of oxygen declines, and that focus on any component of marine systems from microbes to apex predators.

Conveners
Denise Breitburg // Smithsonian Environmental Research Center, USA
Helena Hauss // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
Patricia Ayon // Marine Institute of Peru, Peru

KEYNOTE SPEAKERS

03.09. MONDAY | 11:15

Benthic ecosystem responses to open ocean deoxygenation

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Knowledge of benthic ecosystem response to ocean deoxygenation can be derived from the paleo-record, natural gradients, laboratory and mesocosm experiments and by using environmental proxies. Here I will focus on how natural oxygen gradients on upwelling margins associated with oxygen minimum zones offer tremendous insight into the consequences of ocean deoxygenation for benthic ecosystems. Changes in ecosystem structure include declines in biodiversity manifested as altered taxonomic composition, number and distribution of species, declines in body size, biomass and architectural complexity of taxa, as well as changes in vertical and geographic distribution. These structural changes are translated into altered ecosystem functions involving production, habitat provision, bioturbation, colonization potential and resilience, and trophic functions reflected in feeding modes, symbioses and carbon fixation pathways as well as visual behaviors, species interactions and benthopelagic coupling. Functional shifts are then manifested as altered ecosystem services. Fisheries may diminish under dysoxic conditions but flourish where individuals
aggregate at hypoxic zone margins. Enhanced local C sequestration may emerge from limited remineralization and high deposition within OMZs or from carbonate precipitation under anaerobic methane oxidation, whereas stratification-induced nutrient limitation may ultimately limit atmospheric C drawdown. Genetic novelty in OMZs could fuel new industrial applications. Changes in greenhouse gases, habitat availability and species distributions create climate and hydrographic feedbacks that could further modify ecosystems. Exceedingly small increases or declines in oxygen (of 5 mMol kg\(^{-1}\) or less) can lead to state changes in benthic ecosystems when they are initiated at low oxygen concentrations. Thus, even small changes in oxygenation projected to occur in the next century may have large consequences on margins with oxygen minima. Our challenge is to identify where and when these will matter most and manage accordingly. In the majority of open ocean settings, oxygen rarely changes without concurrent shifts in temperature, CO\(_2\) and food supply. Understanding the interplay of these factors in shaping ecosystem structure, function and services is of increasing importance in a rapidly changing ocean.

**Lisa Levin** | Dr. Lisa Levin is a sea-going biological oceanographer and Distinguished Professor at the Scripps Institution of Oceanography, University of California San Diego. She has a PhD from Scripps Institution of Oceanography, served on the faculty of North Carolina State University for 9 years and has been back at Scripps since 1992. Her research addresses the ecology of animal communities at the sea floor, including deep continental margins and coastal wetlands. She currently studies the environmental drivers shaping oxygen minimum zone and methane seep ecosystems, and the larger consequences of climate change and human industrialization for the deep sea. This work has taken her to deep waters of the Pacific, Indian and Atlantic Oceans on over 40 research cruises, many employing submersibles, ROVs, and AUVs. Dr. Levin is founder and co-lead of the Deep-Ocean Stewardship Initiative, an international, multidisciplinary network of experts providing guidance on environmental management and sustainability of the deep ocean. She is also co-lead of the Deep-Ocean Observing Strategy, a GOOS program linking scientific observation to societal needs. From 2011-2017 Dr. Levin served as Director for the Center for Marine Biodiversity and Conservation at Scripps. Dr. Levin has edited for the journals Limnology and Oceanography, MEPS, Annu. Rev. Marine Science, Marine Ecology and Science Advances, has served on numerous steering and advisory committees (e.g., Census of Marine Life, BOEM, OCB, SCOR) and is currently a member of the Global Ocean Oxygen Network (IOC-UNESCO). She is a fellow of the American Geophysical Union, a fellow of the AAAS, recipient of the 2011 IOC Anton Bruun Medal, and 2018 recipient of the ASLO A.C. Redfield Lifetime Achievement Award.
How the OMZ can drive ecosystem functioning from plankton to seabirds and fishers

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Eastern boundary current systems (EBUS) present contrasted levels of anoxia. A shallow oxycline reduces the habitat for most species, concentrating pelagic life within a thin surface layer. This is particularly significant at night when diel migrant organisms occupy the surface oxygenated layer to ‘pay their oxygen debt’. Such organisms’ concentration can enhance trophic interactions among species. Some winners indeed benefit from the lower energetic cost to forage. On the other hand, certain species cannot survive within a too narrow oxygenated habitat and are expelled from the system. In addition, habitat compression does not occur in the vertical plane only. Indeed the oxycline/pycnocline is not a flat boundary but is shaped by internal wave, submeso- and meso-scale processes. This lead to local downward deformation of the clines, generating small-scale oases for life. In this context, the objective of this work is to review the impact of the oxygen minimum zone, in particular the spatiotemporal dynamics of its upper boundary, on planktonic and nektonic (fish and squids) species in EBUS. In addition, we will discuss on the consequences for population dynamics and foraging efficiency of air-breathing predators, in particular seabirds and fishers.

Arnaud Bertrand | Dr. Arnaud Bertrand is a marine ecologist working at the Institut de Recherche pour le Développement (France). His research is focused on the development of integrated approaches from physics to fisheries, including biogeochemical parameters. For 20 years, he considered oxygen as a key factor driving ecological processes in a variety of tropical ecosystems. He worked 15 years in the Humboldt Current system off Peru and Chile and is currently located in Northeast Brazil where he develops a research program grounded on multidisciplinary surveys. He particularly investigated the role of dissolved oxygen on the horizontal and vertical structuration of pelagic ecosystems and further ecological interactions. For that purpose, he developed original methods to estimate the oxycline depth from acoustic data. This allows finely defining the volume habitat of pelagic species and extracting physical structures along-scale (from internal-waves to mesoscale). He also worked on the impact of dissolved oxygen concentration and oxycline depth on the spatiotemporal patterns of distribution of a variety of pelagic species but also on top predators foraging success. He holds a PhD in fisheries ecology from Ecole Nationale Supérieure Agronomique of Rennes (France). He is currently Visitant Professor at the Universidade Federal de Pernambuco and the Universidade Federal Rural de Pernambuco (Recife, Brazil).
Coastal hypoxia and benthic ecosystem functioning

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Soft-sediment habitats are important in the global cycles of elements and energy. The benthic fauna play pivotal roles in affecting benthic-pelagic coupling and sediment biogeochemistry, but rapidly changing oxygen conditions are profoundly changing benthic–pelagic processes. In coastal seas, excessive organic enrichment and rising temperatures are resulting in spreading hypoxia, comprising not only the integrity of faunal communities, but also their contribution to key processes and ecosystem functions in coastal ecosystems, including nutrient transformation and retention. Over the past 40 years, since the publication of the Pearson & Rosenberg model on benthic succession, our understanding of structural and functional change associated with increasing organic enrichment has grown tremendously. Nevertheless, our knowledge of how feedbacks between the biodiversity of macrofaunal communities and key ecosystem processes such as organic matter mineralization, burial, and nutrient transformation pathways change across gradients of hypoxic stress are still limited. Hence our ability to generalize how changing biodiversity modifies ecosystem functions in real world settings is limited due to the complexity of natural ecosystems. In this talk I will provide examples from a combination of in situ field experiments, large-scale field surveys and modelling efforts across the Baltic Sea, which aim to resolve how macrofaunal communities process organic matter and mediate nutrient fluxes across the sediment-water interface, while exploring how gradients in eutrophication and hypoxia modify these relationships. These studies suggest that the relationship between benthic community structure and nutrient fluxes is highly context dependent and dictated by local communities and environmental conditions. Changes in the abundance and distribution of functionally important species due to progressing eutrophication and climate change thus has important feedbacks on the functioning of seafloor ecosystems. Embedding experimental work along environmental gradients may thus be particularly powerful for resolving such context dependency in benthic-pelagic coupling and ecosystem functioning, to meet the demands of management and conservation.

Alf Norkko | Dr. Alf Norkko is a marine ecologist with a focus on benthic habitats. After his PhD at Åbo Akademi University in 1997, he spent five years in New Zealand at NIWA, and a couple of years at Kristineberg Marine Research Station in Sweden, before returning to Finland. Since 2012 he is Professor at Tvärminne Zoological Station (University of Helsinki), and he currently also serves as a Guest Professor at the Baltic Sea Centre at Stockholm University. He is broadly interested in community ecology, exploring the value of biodiversity, its role for ecosystem functioning and the mechanisms important for its maintenance and marine conservation. Coastal hypoxia as a stressor to benthic fauna has been a major topic throughout his research career. He has worked on the disturbance and resilience of benthic communities as well as impacts on benthic-pelagic coupling and biogeochemical cycles.
Factors controlling the productivity of plankton communities in the coastal upwelling system of Peru

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Eastern boundary upwelling systems (EBUS) are among the most productive ecosystems on Earth. Chemical and biological processes in EBUS are strongly influenced by the subto anoxic conditions that are typically found in water masses below the productive surface layer. During February to April 2017 we conducted an in situ mesocosm experiment near Callao (Peru) to study the factors that control primary, secondary, and export production in a region which harbours one of the most extreme oxygen minimum zones (OMZ) worldwide. First results suggest that upwelling of OMZ influenced seawater from different locations have a small effect on productivity as long as macronutrient concentrations in the upwelled OMZ water masses are similar. Conversely, the structure of the plankton community had a strikingly large influence on the productivity and the transfer of biomass between the different particulate matter pools. For instance, communities dominated by smaller phytoplankton functional groups generated considerably less biomass suspended in the water column but similarly high export production than communities dominated by larger species. The temporal development of productivity as observed over the course of the experiment suggests that the coastal upwelling system functions similar to a „batch culture“. Primary production is fueled by upwelled nutrients that are frequently injected into the euphotic zone but phytoplankton growth rates are limited by very low light penetration (due to the high turbidity of seawater). The build-up of phytoplankton biomass is kept in check by grazers which rapidly transfer primary production to higher trophic levels and/or detrital matter. The relatively constant levels of phytoplankton biomass is reflected in the downward flux of sinking detritus which is also remarkably constant at least over the 7 week timescale of the mesocosm study. Our dataset revealed key factors that control the productivity in the coastal upwelling system of Peru and provides mechanistic understanding to implement these processes in models.

Zooplankton of the low-oxygen waters of Bahia Callao, central Peru - with special reference to the reproductive activity of the copepod Acartia nsp

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The near-coastal zone boardering the Humboldt Current System is highly productive and has a high economic value for artesanal fisheries. However, it is under constant thread from low oxygen due to local decomposition processes, high plankton
productivity and the already low oxygen content of the upwelling water mass. Zooplankton distribution in the Bahia Callao, a low oxygen bay in Central Peru, was studied during two cruises. Environmental conditions had changed dramatically between cruises: in March oxygen concentrations were lower, especially near the sea floor, while in September oxygen concentrations were higher in the whole water column. Zooplankton abundance and community composition changed drastically. We assume that the Bahia Callao is typical for many bays along the Peruvian coast and represents a novel type of so-called dead zones, with changes of favourable and non-favourable living conditions at high frequency depending on the advection of low oxygen waters. The reproductive activity of *Acartia* nsp, the dominant copepod in the nearshore zone, was studied from November 2005 to December 2006 at a fixed station with 2 or 3 samplings per month. Oceanographic data (temperature, salinity, oxygen) were collected simultaneously. The effect of environmental conditions on egg production and egg viability is discussed.

**Intercalated low oxygen maxima, beam attenuation and ADCP amplitude within the suboxic layer off Peru**

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The functioning of oxygen minimum zones in the Pacific remains debated. In particular, the fate of the OM is unclear owing to competing processes (preservation versus microbial activity). Recent high-vertical resolution in situ observations off Peru reveal an unexpected biogeochemical structuring in the oxygen minimum zone, potentially associated with a specific vertical particles distribution and ecosystem niches, impacting the vertical transfer of both energy and essential elements. Within the Suboxic Layer (<20 µmol kg⁻¹, SL), we found Intercalated Oxygen Maxima (IOM) less than 10 µmol kg⁻¹ above background and less than 50 m in vertical extent. Typically, IOMs are found in the SL with lower vertical density gradient, regionally or within the SL of one station. CTD attached ADCP of 300 kHz (LADCP) showed: echo maxima persisted throughout the day within the SL associated with these IOMs and sometimes without IOM, echo maxima persisted at the upper and below the lower oxycline throughout the day. LADCP also showed echo maxima that migrated diurnally, and were located within the stratified, no-IOM depth of the SL during the day. These daytime echo maxima did not overlap the strong echo maxima associated with the lower oxycline. Beam attenuation (Cp) showed a maximum close to the upper oxycline. In the depth range of the stratified no-IOM part of the SL, the Cp decreased approximately exponentially. Cp displayed no profile pattern associated with the IOMs. Cp profiles showed no apparent relation with LADCP echo profiles as might be expected if Cp is a proxy of particulate organic matter and LADCP echo a proxy of zooplankton.
Elemental fluxes mediated by vertically migrating zooplankton and nekton into the mesopelagic oxygen minimum zone off Peru

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In the Peruvian Upwelling system, the mesopelagic oxygen minimum zone (OMZ) is the main vertically structuring feature of the pelagic habitat. Several zooplankton and nekton organisms undertake diurnal vertical migrations (DVMs) into anoxic depths. It has been argued that these migrations contribute substantially to the oxygen consumption as well as excretion of dissolved compounds (in particular ammonium) in subsurface waters. However, metabolic suppression as a response to low ambient pO2 was not considered in these estimates. Here, we present estimates of zooplankton and nekton-mediated ammonium release, oxygen consumption, and carbon export flux based on vertically stratified net hauls (day/night, upper 1000m). Samples were scanned, followed by image analysis and size-/taxon-specific estimation of metabolic rates of all identified organisms as a function of their biomass as well as ambient temperature and pO2. The main crustacean migrants were euphausiids (mainly E. mucronata) on offshore stations and the commercially exploited squat lobster Pleuroncodes monodon on the upper shelf, where it undertakes migration to the seafloor during the day (which leads to biomass underestimation during pelagic surveys). Correction for metabolic suppression results in a substantial reduction of e.g. ammonium release within the OMZ core. We argue that nighttime aggregations of euphausiids near the upper oxycline likely play a more important role (both in terms of oxygen consumption and providing NH4 for anammox) and explore the ecological niche boundary conditions of euphausiids using high-resolution profiles obtained with an Underwater Vision Profiler (UVP5).

Potential complexity of zooplankton responses to deoxygenation: very small oxygen differences matter

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Significant variability in zooplankton abundances and distributions, associated with very small differences in oxygen concentration and temperature, were documented at midwater depths within the strong oxygen minimum zone of the Eastern Tropical North Pacific in Jan – Feb 2017. First, a towed hydrographic profiler, the Wire Flyer, was deployed on ~50 km long transects between 325–650m or 525-850m depths. Locations of midwater features showing oxygen gradients were identified for targeted zooplankton sampling. Horizontally-sequenced zooplankton samples along with hydrographic data were then collected with a MOCNESS net system towed through
the feature at a constant depth (either ~430m or ~800m). Day and night vertically-stratified tows were also done for several depth intervals and locations. Species abundances and distributions (copepods, euphausiids, fish), and total zooplankton biomass, were analyzed relative to depth and oxygen Horizontally sequenced tows showed strong differences in abundances of particular species associated with very small changes in oxygen concentration even though the sampling depth remained relatively constant. Vertically-stratified tows provided broader context for the full range of a species habitat including diel vertical migration. Respiration measurements of key species collected live in Tucker trawls at these same locations determined their physiological tolerances (critical partial pressure of oxygen (Pcrit) at selected temperatures) that were related to their distributions. Plots of the Metabolic Index for selected species illuminated physiologically suitable habitat along these transects. These results suggest substantial unexpected complexity in responses of oceanic organisms and ecosystems to predicted future deoxygenation.

**Interactive effects of temperature and low oxygen on the vertical distribution of copepod eggs and nauplii in coastal seas**

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As a result of cultural eutrophication, bottom water hypoxia has been increasing globally in estuarine and shelf waters. Coastal hypoxia has the potential to adversely impact pelagic zooplankton communities by increasing the mortality of copepod eggs which can sink into low oxygen bottom waters. Using depth-specific sampling we examined the vertical distribution of copepod eggs and nauplii over different seasons in a coastal plain estuary of the eastern United States, the Chesapeake Bay. We compare the vertical distribution of copepod eggs and nauplii to the results of a mechanistic model which takes into account the sinking rate of copepod eggs; the temperature-driven hatching rate of copepod eggs in the water column; and the effects of low oxygen on egg hatching.

**Zooplankton-mediated fluxes in the Eastern Tropical North Atlantic**

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Zooplankton occupies an important role in pelagic ecosystems as it provides the link between primary producers and higher trophic levels and to a large extent shapes elemental cycles. Zooplankton organisms feed on all kinds of small particulate matter (e.g. phytoplankton, detritus, smaller zooplankton organisms) and egested fecal pellets
contribute substantially to the passive sinking flux out of the surface layer. Some zooplankton species also conduct diel vertical migrations (DVMs) between the surface layer where they feed at nighttime and midwater depth below the sunlit euphotic zone where they hide at daytime from predation. These DVMs result in the active export of organic and inorganic matter from the surface layer as zooplankton organisms excrete, defecate, respire and get eaten at depth. In the Eastern Tropical North Atlantic (ETNA), the daytime depth (300-600 m) coincides with an oxygen minimum zone (OMZ) that was observed to expand and intensify in the past decades. We here constrain zooplankton impacts on the nitrogen and oxygen budget in the upper 1000 m of the ETNA using a comprehensive set of day and night catches with a Hydrobios Multinet, analysed using the Zooscan method. We estimate that about 13 to 28 % of the external nitrogen supply (diapycnal diffusion, atmospheric deposition, nitrogen fixation) to the upper 100 m of the water column is lost via DVM activity of zooplankton. Likewise, zooplankton contributes about 20 % to oxygen consumption in the 300 to 600 m depth layer. Changes in zooplankton abundance and migration behavior due to decreasing oxygen levels at midwater depth could therefore considerably alter the elemental cycling of oxygen and carbon in the ETNA OMZ, but might also impact the removal of nitrogen from the surface layer.

Pelagic key species and mechanisms driving energy flows in the northern Benguela upwelling ecosystem and their feedback into biogeochemical cycles

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The northern Benguela Upwelling System (nBUS) has been facing increasing temperatures and decreasing dissolved oxygen (DO) levels over the last decades. This has implications for key processes and trophic interactions within the ecosystem including shifts in community composition, distribution ranges, and trophic levels, changes in energy flows and migration patterns with feedbacks to biogeochemical processes. Here we summarise the results gained from the GENUS project (Geochemistry and Ecology of the Namibian Upwelling System) focussing on the geochemical and ecological structures and processes dominating the pelagic component of the nBUS. Spatial and temporal distribution patterns of key species of zooplankton and fish larvae allowed biomass estimates (5 to 81 g Wet Mass m⁻² (10 to 90% quantile) with a median of 19.5 g Wet Mass m⁻² for the upper 200 m) and potential impacts on the vertical carbon flux. Vertical distribution ranges of key taxa were determined reflecting their specific abilities to tolerate hypoxia and, hence, their different adaptive mechanisms to cope with the OMZ. The shoaling of the 2.5 mL-oxycline (0.24 m y⁻¹) constrains sensitive species and hampers daily and seasonal vertical migrations. It may also affect the ability of organisms to maintain themselves within nearshore habitats by hindering vertical migration into deeper onshore currents. Respiration rates of key species were determined with one standard method (optode respirometry) showing an average respiration rate of 54.6 mL O₂ d⁻¹ (g Dry Mass)⁻¹ for the bulk fraction of mesozooplankton allowing
also the estimate of DO consumption by mesozooplankton at different depth layers. Stable isotopic ratios (N, C) revealed trophic interactions and positions of zooplankton and fish. Our results show many players within a small range of trophic levels and a dominance of zooplankton taxa (copepods, euphausiids) in terms of biomass over small pelagic fish (sardine, anchovy), essential for future higher-resolution ecosystem modelling.

**Size structure, community composition and biomass size spectra of mesopelagic fishes in the tropical Atlantic Ocean and the West-Saharan OMZ in 2015**

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In 2015, 5 stations each were sampled in the tropical Atlantic and the West-Sahara OMZ for mesopelagic fauna. Community analysis revealed a close relationship between OMZ and tropical region, although some species increased in abundance in the OMZ (e.g. *Nannobrachium isaacsi*, Myctophidae; *Malacosteus niger*, Malacosteidae). Length composition and size ranges revealed a smaller maximum size for OMZ specimens (except for *Myctophum affine*, Myctophidae) and a significant difference in size structure for 11 out tested species. A tenfold higher abundance of specimens in the size range 30-60 mm standard length appeared in the OMZ. It is concluded that observed differences in length structure are due to environmental changes and local productivity.

**Demersal fish communities across oxygen gradients: How multiple methodologies can offer unique insights into the ecological impacts of ocean deoxygenation**

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Predicting the ecological impacts of deoxygenation for deep-sea communities on continental margins is challenging due to the difficulty of conducting community-level manipulative experiments in the deep sea. However, there is a pressing need to understand these impacts since oxygen is declining at midwater depths and continental margins are important habitats for demersal fish communities, including many fisheries species. Existing variability in the oxygen dynamics of continental margin ecosystems over spatial, vertical, and temporal scales, can be leveraged as natural experiments. In the Southern California Bight (SCB), strong vertical gradients in oxygen exist, due to the presence of an oxygen minimum zone between depths of ~450-1200 m. In this study, we utilize trawls, remotely operated vehicles (ROVs), and autonomous landers to study the effects of hypoxia on demersal fish community ecology in the SCB. Across temporal scales, oxygen exhibits diurnal, event-based, and seasonal variability off San Diego. We have developed a novel autonomous lander, DOV BEEBE, which is outfitted with environmental sensors, a camera system, and an
acoustic release system. BEEBE has been deployed on the upper continental margin (100-400 m) off San Diego for 3-week periods, to characterize the natural variability of oxygen within the oxygen limiting zone and observe demersal fish community responses to existing oxygen variability. Utilizing ROVs and trawl samples, we have studied how fish community composition, density, and diversity change across oxygen gradients (100-1200 m), and have conducted stable isotope analysis to examine how trophic ecology differs in low oxygen environments. We find that changes in demersal fish community structure under low oxygen conditions are accompanied by trophic changes which include: enriched $\delta^{15}$N signatures, suggesting higher trophic position, a reduced trophic niche breadth for the fish community, and a shift from more specialist to more generalist diets. Based on gut content and stable isotope data for the fish community, we find that reliance on pelagic food sources decreases in low oxygen environments, suggesting that benthic-pelagic coupling may be disrupted in areas with oxygen minimum zones. Utilizing multiple methodologies in systems with strong natural gradients in oxygen provides insight into how deoxygenation may impact demersal fish communities in the future. We predict deoxygenation will reduce demersal fish diversity, lead to habitat loss for certain fisheries species, and alter density, composition, and trophic relationships. Autonomous landers can complement rarer ship-based sampling and can be a powerful tool for monitoring seafloor community responses to short and long-term oxygen changes.

**Simulating fish population responses to coastal hypoxia: movement behavior and the tradeoff between more oxygen and less food**

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The Gulf of Mexico experiences a large hypoxic area in the summer from nutrient loadings that originate from activities in the watershed. We are developing individual-based population models of croaker, menhaden, and shrimp to analyze how hypoxia effects on reproduction, growth, mortality, and movement of individuals leads to population-level responses. These population models are the last step in a series of coupled models: DLEM (nutrient delivery from watershed to coast) to Delft3D (diversions for restoration) to FVCOM (3-D physics) to WASP (water quality) to fish population model. The population models follow the hourly growth, mortality, reproduction, and movement of individuals within the 3-D FVCOM spatial grid. Currents, temperature, salinity, dissolved oxygen, and chlorophyll-a concentrations generated by the FVCOM-WASP models are used as inputs to the population models. Hypoxia effects were imposed using laboratory-based relationships that convert
exposure to dissolved oxygen concentrations to reductions in growth, fecundity, and survival. We used 50-year simulations under present-day and reduced nutrient loadings (e.g., implementation of best management practices in watershed) to quantify the tradeoff of reduced nutrients resulting in higher oxygen but also potentially less food. Because of the uncertainties of the linkage of nutrient loadings to fish food, several alternative assumptions were simulated ranging from no effects on food to a direct reduction proportion to the lowered chlorophyll concentrations. We also simulated fish population responses under several assumptions of individual fish avoidance behavior, which affects their exposure to low dissolved oxygen concentrations and subsequent effects of hypoxia on mortality, growth, and reproduction. We illustrate the tradeoff between more oxygen and less food and the effects of avoidance behavior using the coupled modeling approach configured for croaker.

Assessing the effects of recurring seasonal hypoxia on benthic communities and reconstructing baseline community states on the basis of sediment cores (northern Adriatic Sea)

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Estimating the effects of recurring seasonal hypoxia on the long-term composition, diversity, and functioning of macrobenthic communities on continental shelves is challenging because early 20th century monitoring surveys are rare and the sedimentary sequences in cores are mixed by bioturbation. Here, we evaluate the effects of eutrophication and frequent hypoxic events on macrobenthic communities in the northern Adriatic Sea, where bottom-water dissolved oxygen concentrations were measured since the early 20th century. Previous studies showed that seasonal hypoxia, and occasionally anoxia, leads to mass mortality of macrobenthic fauna in the northern Adriatic Sea and to delayed recoveries occurring for several years. However, long-term consequences of repeated oxygen-depletion events on benthic communities remain unknown. We account for bioturbation mixing in sediment cores by amino-acid racemization calibrated by radiocarbon dating of the bivalve Corbula gibba at Po Delta and in the Gulf of Trieste. We show that, first, strongly bioturbated sediments typical of natural highstand conditions, deposited in the early 20th century, were replaced by the late 20th century sediments with preserved flood layers and high proportion of total organic carbon (TOC). Second, geochronological dating of bivalve shells shows that the shift from the early to the late 20th century is associated with a decrease in time averaging of death assemblages (from ~25-50 years to ~10-20 years). We suggest that this shift reflects a decline in the depth of the fully-mixed layer from more than 20 cm just to few centimeters. Third, the increase in abundance of the opportunistic bivalve and the strong decline in abundance of hypoxia-sensitive species temporally coincided with the decrease in the depth and frequency of bioturbational mixing, with higher preservation of organic matter, and with higher frequency of seasonal hypoxia in the late 20th century. This depositional and ecosystem regime shift occurred approximately in ~1950 AD. Therefore, the effects of enhanced food supply on the long-term composition of macrobenthic communities were overwhelmed by oxygen depletion even when hypoxic conditions are limited to few weeks per year in the northern Adriatic Sea.
Effects of regimes of dissolved oxygen variability on functional diversity of sublittoral macrobenthos off central Peru (12°S) and northern Chile (23°S)

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In the Humboldt Current System water deoxygenation occurs naturally producing oxygen minimum zones where the fauna usually present different levels of adaptations or tolerance to low oxygen conditions. The high variability of the system causes variability of hypoxia at different spatial and temporal scales throughout the HCS, and the responses of the seabed biota may be different between localities along the latitudinal gradient. Herein, we evaluated the effect of oxygen variability on the community structure and functional diversity of the sublittoral macrobenthos off Callao (12°S, central Peru) and Mejillones (23°S, northern Chile) studying time series data taken between February and October 2016. 15-years historical dissolved oxygen data (2000-2016), were analyzed for characterizing the frequency of oxygenation and hypoxic events and the seasonal variability and were identified three oxygen regimes at equivalent depths in both locations. At 30m depth a seasonal hypoxic regime was present at a semiannual (Callao) or annual (Mejillones) cycle. At 50m there was a predominant hypoxic regime, with three seasons of the year under hypoxic conditions in Callao, with winter oxygenation. Additionally, in Callao at 90m depth the regime was persistent severe hypoxia throughout the year, with rare and very short episodic oxygenation. When we assessed the effect of oxygen and its variability in these regimens we identified a functional diversity loss gradient, consistent with the increased severity and persistence of hypoxia. The “seasonal hypoxic” habitat showed higher expression of feeding-strategies and life forms, which indicates more energy pathways and higher horizontal and vertical exportation of mater and energy. At the “predominant hypoxia” habitat some of these strategies remains but the diversity of live forms decreased. The regime of persistent hypoxia presented the lowest values of functional diversity, which is characteristic of a community limited to the recycling of nutrients that indicates an early stage of ecological succession. This is evidence of the profound effect that oxygen depletion causes in the ecosystem function and energy flows.

Hypoxia in mangroves: occurrence and impact on nursery fish habitats

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Mangroves naturally experience short-term dissolved oxygen (DO) fluctuations, making them susceptible to diel hypoxia. Hypoxia has adverse effects on aerobic organisms such as fish as it leads to physiological and behavioural altering community dynamics of marine animals. DO is a fundamental parameter of water quality, but few studies have examined short-term changes of DO and the associated impacts on
mangrove fish assemblages. This study examined diel DO fluctuations associated with tidal variations in mangroves in Australia and New Caledonia using high-frequency loggers. Meantime, underwater video cameras (UVCs) were deployed to link variations in fish assemblages to DO. Results highly suggested that DO could be one of the main factors influencing fish assemblages. However, as DO concurrently fluctuates with numerous factors (temperature, pH, depth, salinity), it was hazardous to confidently identify DO as a driver of fish assemblages without more investigations. Therefore, field results were used to conduct physiological experiments using respirometry to determine hypoxia thresholds of species exhibiting different mangrove utilisation patterns potentially influenced by DO. This understanding was then used to investigate how low DO influences fish assemblages and their mangrove utilisation. Hypoxia ($\leq 50\%$ saturation) was commonly reported in mangroves of New Caledonia and Australia, especially during ebbing night tide, neap tide, and low tide. Severely hypoxic events ($<10\%$ saturation) were occasionally observed in these relatively undisturbed systems. Continuous monitoring of fish assemblages using UVCs provided invaluable information on how fish use mangroves, and allowed us to determine how DO influences fish present in mangrove forests. Indeed, some species would be systematically observed once DO reached unharmful levels (between 70 and 80\% saturation), while other species were constantly observed even if DO was low. Physiological experiments corroborated these results, supporting our hypothesis that DO plays a crucial role in determining the value of mangroves for fish. These results demonstrated that in some mangrove systems, DO naturally reaches levels that can lead to physiological stress for fish, potentially making these habitats temporally unsuitable. Mangroves are often used to dump nutrient-rich effluents from anthropogenic activities. These effluents contribute to eutrophication which alters the natural DO cycle and exacerbate the occurrence and severity of potentially natural diel hypoxic events. In a rapidly changing world, these nursery habitats are threatened as aquatic organisms utilising them are already coping with extreme environmental conditions that if further degraded may disadvantage species or even exclude some, leading to potential loss of high value nursery grounds.

The Ocean is losing its breath: declining oxygen in the world’s ocean and coastal waters

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Although it is known that oxygen is critical to the biology, ecology and biogeochemical cycling of the oceans, and to the influence of the oceans on the earth’s climate, major uncertainties remain - especially in our ability to scale up from small spatial scales and short time periods to fish stocks, global oxygen patterns and future times. Continued research, observation analysis and community engagement are required to not only detect the spatial and temporal extent of ocean deoxygenation, but also to advance the understanding of underlying processes to develop adaption and mitigation strategies. The ingredients needed to make those advances - data, modelling and experiments - are in hand or are being developed. Through the participation of concerned scientists
from across the world, the IOC expert group, the Global Ocean Oxygen Network GO2NE, established in 2016, is committed to providing a global and multidisciplinary view on deoxygenation, with a focus on understanding its various aspects and impacts. The network offers scientific advice to policy makers and stakeholders to counter alarming deoxygenation, and to preserve marine resources in the presence of declining oxygen levels. Besides its scientific work and outreach activities, the network aims to facilitate communication with other established networks and working groups (e.g. IOCCP, GOOS, IGMETS, GOA-ON, GlobalHAB, WESTPAC-O2NE), improving observations systems, identifying and filling knowledge gaps, as well as developing deoxygenation-related capacity development activities in order to fill these gaps. And though specific steps to slow and reverse deoxygenation vary among locations depending on the cause of the problem, co-occurring stressors and locally specific capacities and demands, there are action which will help to restore the ocean's oxygen and minimize the impacts of deoxygenation: -Reduction of greenhouse gas emissions that cause atmospheric and ocean warming; -Reduction of nutrient inputs that exacerbate oxygen loss in coastal waters and semi-enclosed seas; -Inclusion of climate change effects in development of nutrient reduction strategies; -Alleviation of anthropogenic stressors that threaten resilience and increase vulnerability of marine ecosystems to deoxygenation; -Adoption of marine spatial planning and fisheries management strategies addressing deoxygenation vulnerabilities and the protection of affected species and habitats; -Recognition of ocean deoxygenation as one of multiple climate stressors; and -Working to to unify research, management and policy actions in the coastal and open ocean across biology, geochemistry and physics, across problems of warming, acidification and deoxygenation, and across academic, industry, government and regulatory sectors.

**POSTER PRESENTATIONS**

(08) Distribution of gelatinous macrozooplankton in relation to oxygen minimum zones in the eastern tropical Atlantic

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Expansion and shoaling of mesopelagic oxygen minimum zones are impacting pelagic communities worldwide, but faunal responses are poorly known due to a lack of observations. In the eastern tropical Atlantic deoxygenation of the water column happens at one of the fastest rates worldwide. Gelatinous macrozooplankton (e.g. hydrozoans, ctenophores, pelagic tunicates) are predicted to cope well with reduced oxygen levels; they have relatively low metabolic rates and some species can store oxygen in their mesoglea. These characteristics have led to the hypothesis that gelatinous fauna may be winners in future hypoxic oceans. We studied the distribution and abundance of macrozooplankton species in relation to oxygen in the water column of the Republic of Cape Verde to 1) establish baseline observations
of the diversity, distribution and abundance of mesopelagic gelatinous fauna and 2) to predict how vertical expansion of the OMZ will impact these fauna. Using the pelagic in situ observation system (PELAGIOS) we performed pelagic video transects down to 1000 m in ocean regions with typical OMZ conditions (oxygen minimum at 300-400 m), as well in a mesoscale cyclonic eddy. Identification and quantification of the observed dominant gelatinous taxa and correlation with the physical and chemical water column data resulted in detailed vertical distribution plots of medusae, ctenophores and siphonophores. The observed vertical distributions can be grouped into 7 general patterns in relation to the OMZ; (i) Above the OMZ (Cestidae); (ii) Above and within the OMZ (Praya spp.); (iii) Within the OMZ (Colobonema spp., Halitrephes maasi, Lilyopsis medusa, Thalassocalyce inconstans); (iv) Within and below the OMZ (Halicreas minimum); (v) Below the OMZ (Atolla spp.); (vi) Above and Below the OMZ (Beroe spp.); (vii) Above and within and below the OMZ (Solmissus spp.). We discuss these distribution patterns in the context of future ocean conditions in the eastern tropical Atlantic.

(09) Food web functioning in oxygen minimum zones: insights from worldwide isotopic data

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Oxygen minimum zones (OMZs) are defined as water masses where O$_2$ concentrations are <0.5 mL L$^{-1}$ (<22μM). Permanent OMZs cover over 1 million Km$^2$ of seafloor and intersect the continental margins of the Pacific, Indian and Atlantic Oceans. OMZs are predicted to expand in response to global warming. OMZ expansion has implications for food webs and ecosystem function through reorganization and compression of faunal communities. Understanding faunal responses and ecosystem processes in permanent OMZs is becoming increasingly important given the undetermined and potentially adverse consequences of OMZ expansion and increasing ocean deoxygenation. Naturally occurring OMZs provide an excellent in situ laboratory to test hypotheses, which can be related to increasing ocean deoxygenation and OMZ expansion. Stable isotopes provide a powerful framework for studying metabolic and nutritional pathways in food webs. This is because both carbon and nitrogen isotopes have distinct isotopic values associated with different metabolic pathways. OMZs are microbial biogeochemical reactors with complex and diverse microbial communities utilising a variety of metabolic pathways. In this study we used stable isotopes to investigate the trophic structure of infaunal benthic food webs across OMZs in the: Indian, Pacific and South East Atlantic Oceans. We compare these results with food webs at continental margins, which are not impacted by OMZs. Our data reveal a broad range in mean consumer δ$^{15}$N values ranging from: 4‰ to 14‰ for OMZ margins and 7.9‰ to 11.6‰ for other margins. Ranges in consumer δ$^{13}$C values were smaller, ranging: -15.6‰ to -19.9‰ for OMZ margins and -19.5‰ to -22.7‰ for other margins. We calculated sample size corrected Bayesian food web metrics to analyse trophic niche width. OMZ food webs had larger trophic niche widths compared to other margins. This suggests the presence of a diverse range of food sources and metabolic pathways in benthic OMZ food webs.
(10) Plankton community structure from Annaba Bay (SW Mediterranean) under contrasting hydrologic influences

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The aim of this study was to analyze the seasonal distribution and composition of the plankton community and to assess changes in the environmental conditions that may affect the population’s structure and abundance. The plankton was monthly sampled during February 2010-January 2011 at two contrasting sites of Annaba Bay, Algeria. The phytoplankton and zooplankton biomasses and the hydrologic parameters (temperature, salinity, dissolved oxygen, macronutrients) were jointly measured. The inner bay (site 1, southern part) which is directly impacted by estuarine, industrial and household inputs had very low levels of dissolved oxygen, but high levels of nutrient and strong plankton biomasses occurred throughout the year. During the warm period (April-October), this eutrophicated and hypoxic area experienced several bloom events mainly from dinophyceae species. Blooms and mass development episodes of the heterotrophic dinoflagellate Noctulica scintillans extended here for many months (February-May), being frequent over the whole southern bay. This eutrophicated area also supports the dominance of numerous opportunistic copepod and cladoceran species, which tolerate the fluctuation, hypoxic waters and the weak resilience characterizing the area. The outer bay (site 2, northern part) directly influenced by the intrusions of the modified Atlantic water current, was well-oxygenated, but showed very low levels of nutrients and plankton biomasses. Site 2 was also characterized by high diversity and low densities of both the phytoplankton and zooplankton communities. The number of copepod species of this area was 3-fold higher than that of the area close to the continental inputs, but their abundance was 3-fold lower. Moreover, the oligotrophic northern part of the bay was mainly cohabited by the neritic, oceanic and deep species, which are supplied during the cold and mixing period (November-March). Compared to the previous studies of 1992, the plankton from Annaba Bay has significantly changed, with the dominance of the dinoflagellates over diatom taxa and the prevalence of the copepods Paracalanus indicus and Oithona similis over Acartia species and Oithona nana. The contrasting hydrologic conditions prevailing the bay result in a particular structure of the planktonic system and the functioning of the coastal ecosystem.

(11) Determining the Cape Verde island mass effect across trophic levels

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The pelagic ecosystem off Cape Verde is influenced by a mesopelagic oxygen minimum zone (OMZ). Since the term “island-mass effect” (IME) for the increase in plankton biomass around oceanic islands was proposed, the study of productive processes in these ecosystems has gained importance. The physical and biogeochemical mechanisms involved in this phenomenon are varied and related to upwelling, vertical mixing, internal waves, eddies and filaments, benthic nutrient regeneration,
and river run-off. These processes are known to affect the distribution of nutrients, chlorophyll, primary and secondary production and may also shape the depth and intensity of the OMZ, in turn affecting the distribution of pelagic organisms. The main objective of this study is to determine the Cape Verde island mass effect across trophic levels to obtain a mathematical description of the distance effect. I hypothesize that atmospheric dust input (nutrients, iron) might dampen the effect compared to e.g. central Pacific islands where the IME occurs in a marine desert without substantial atmospheric nutrient input. To identify the proximate drivers of the IME, zooplankton samples and echosounder data were collected around the Cape Verde Islands during the CCLME Ecosystem Survey onboard of R/V Fridtjof Nansen from June 04 to 20 in 2011. Furthermore, zooplankton samples collected on the open ocean Cape Verde time series station CVOO and off the west coast of Africa aboard the R/V Thalassa, where zooplankton biomass was higher inshore compared to the offshore stations, as well as satellite and glider data were used to compare the local patterns.

(12) Diel vertical migration of mesozooplankton associated with presence of an oxygen minimum zone off northern Chile

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The oxygen minimum zone (OMZ) in the eastern South Pacific Ocean is an intrinsic characteristic of the water column and a permanent feature that covers the coastal zone of Ecuador, Peru and Chile. During the last two decades studies in this region have shown that waters with low oxygen content become a physiological constraint for pelagic and benthic organisms, and so impacting biomass, productivity and species diversity, as well as limiting the diel vertical migration of zooplankton organisms. The diel vertical migration of zooplankton in relation to the OMZ was investigated across a zonal section off Iquique (20ºS), in the coastal zone off northern region of Chile which is subjected to important coastal upwelling throughout the year. The oceanographic information and zooplankton samples were collected during the LowPhox cruise performed in October 2015 onboard the R/V Cabo de Hornos. The Zooplankton hauls were done in five depth strata from 800 m depth to the surface, during day and night condition using a Hydro-Bios Multinet, with a 0.25 m² opening area and equipped with 200 um mesh-size nets. The samples were digitized with a ZooScan digital imaging system and then identified and automatically classified in taxonomic categories. Results are presented for the major taxonomic groups of mesozooplankton. The dominant taxa were Appendicularia, Copepoda, Eggs, Euphausiacea, Nauplius, Ostracoda, Salpidae and Siphonophora. A high percentage of these taxa performed nictimeral displacements. The vertical distribution of zooplankton was modal and it was characterized by: 1) non-migrant groups, such as Salpidae and Siphonophora which showed limited nictemeral movements, probably because of the chemical barrier imposed by the OMZ; and 2) migrant groups with a greater range of vertical distribution such as the case of the copepod Rhincalanus spp, Annelids, Briozos, other copepods, Euphausids, Gastropods and Foraminifera, which even showed intrusions into the OMZ during the night. The differential vertical displacement of taxa indicates that a significant fraction of the zooplankton can interact with the OMZ with biogeochemical consequences associated with the active transport of Carbon and nitrogen into this hypoxic water, although the migration seems to be attenuated by the ecological barrier imposed by the OMZ.
Ventilation and Oxygen Supply

Topic abstract

Ocean oxygen observations for five decades since 1960 indicate a decrease of about 2% of the global ocean oxygen inventory and climate models predict continuous deoxygenation of the global ocean in the future. In the open ocean changes in ventilation and oxygen supply are considered to be major drivers of trends in the oxygen inventory. Global warming and wind changes seem to be the major causes. Changes in temperature, winds and currents will alter physical processes. In addition biological processes can influence the oxygen and nutrient distribution. Superimposed on the oxygen trends are climate modes, like the Pacific Decadal Oscillation in the Pacific, the North Atlantic Oscillation in the Atlantic, the Indian Ocean Dipole in the Indian Ocean or the Southern Annual Mode. So far it is mostly unknown what the contribution of the climate modes on the oxygen inventory and multi-decadal trends is. In this session we are seeking oral and poster contributions on large-scale distribution and variations of oxygen and nutrient distribution, on the pathways of ventilation either related to a regional context (in particular OMZs) or the implied mechanisms (e.g. zonal jets in the tropics, mid/high latitude subduction). We welcome also investigations on how existing pathways and processes are being perturbed by climate variability in the ocean from observations and modelling, and presentations which relate the oxygen changes to observed and modelled biogeochemical variations.

Conveners
Véronique Garçon // LEGOS (IRD/CNRS/CNES/University of Toulouse), France
Lothar Stramma // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
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KEYNOTE SPEAKERS

04.09. TUESDAY | 08:30

Ocean deoxygenation in the 21st century: the role of ventilation

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All Earth System models project a consistent decrease in the oxygen content of the ocean for the coming decades. The processes at play in each of the models are ocean warming, reduced ventilation and increased stratification. At the regional scale and for the subsurface ocean however, these model projections are much less robust, which reflect a complex interplay of processes responsible for the changes in ocean oxygen levels. In this presentation, I make use of simulations performed in the context of the Coupled Model Intercomparison project 5 (CMIP5). I will show that the sub-surface deoxygenation trend is partly balanced by a reduction in sub-surface respiration. I will also show that in many of these models, the tropical ocean undergoes partial re-ventilation, and hence a rejuvenation of the sub-surface water.
masses, even in case of increased vertical stratification. This may lead to a partial tropical sub-surface re-oxygenation with global warming. To get more insights into the role of ventilation in oxygen trends, changes in oxygen fluxes are analysed at the base of the mixed layer in one of the CMIP5 models. I also turn to past climates, such as the Last Glacial Maximum, or even deep time anoxic events, to decipher the role of ventilation in driving past changes in oxygen.

Laurent Bopp | Dr. Laurent Bopp is a Senior Research Scientist at the Centre National de la Recherche Scientifique (CNRS) and Adjunct Professor at the Ecole Normale Supérieure (ENS) in Paris. His main research interests concern the links between climate change, marine biogeochemistry and ocean ecosystems. He is an expert in ocean biogeochemistry modeling and has been among the first to introduce marine biogeochemistry in climate models to study carbon-climate feedbacks, ocean acidification and ocean de-oxygenation, as well as the impact of climate change on ocean marine ecosystems. He is the author of more than 150 publications and was involved in the last IPCC report as a lead author; he is a member of the Scientific Steering Committee of IMBeR (Integrated Marine Biosphere Research) since 2014; he is also involved in the EU H-2020 CRESCENDO project (WP leader) on the next generation of Earth System models.

04.09. TUESDAY | 09:05

Physical forcings of Eastern Pacific OMZ

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The Eastern Pacific (EP) hosts one of the most productive eastern boundary upwelling systems (EBUS) of the world oceans, encompassing an extended oxygen minimum zone (OMZ). EBUS is characterized by complex dynamical processes spanning a wide range of spatio-temporal variability due to the strong coupling between the ocean and atmosphere. In particular, the EP OMZ is strongly modulated by the remote variability exerted by the equatorial dynamic (i.e., circulation, El Niño), local variability exerted by coastal upwelling driven by the divergence in Ekman transport and by high-frequency variability exerted by mesoscale activity. We provide here a brief synthesis of current research related to dynamical processes, both physical and biogeochemical, involved in the EP OMZ.
Ivonne Montes | During her PhD, Ivonne Montes applied a Regional Ocean Model System and Lagrangian approaches to fill gaps in in-situ observations of current systems in the Southeastern Tropical Pacific. During her Postdoc under the EUROceans Consortium ‘Ocean deoxygenation’ Flagship program funded by EUR-OCEANS which took place in France, Germany and Peru, she carried pioneered studies on coupled physical-biogeochemical regional modeling applied to the Eastern boundary current system (Mexico and Peru/Chile) to investigate the processes maintaining the oxygen minimum zone off Peru. Since 2014, she is a Research Scientist at Instituto Geofísico del Perú (IGP) where, as a first task, she led a project to implement a High-performance Computing System that actually is part of the Geophysical Fluid Dynamics Laboratory of IGP, and is available for all the scientific community. Currently, she focuses on the study of the role of the oceans in climate, the impact of remote and local air-sea interactions over the upwelling systems, and climate change associated processes. As part of the scientific community, she serves as a member of the Global Ocean Oxygen Network (GO2NE, initiative from IOC-UNESCO, an interdisciplinary network with particular concerns about the low oxygen concentrations in both the open ocean and coastal waters) and she is acting as co-chair of the recently approved SCOR Working Group 155 ‘Eastern boundary upwelling systems (EBUS): diversity, coupled dynamics and sensitivity to climate change’.

04.09. TUESDAY | 09:40

Drivers and mechanisms of thermocline oxygen changes in the eastern tropical North Atlantic

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The tropical thermocline that covers the strongly stratified region below the oceanic mixed layer accommodates extended oxygen minimum zones (OMZs). The subtropical-tropical circulation of the Pacific and Atlantic oceans characterized by the wind-driven equatorward and westward flow of newly subducted water masses sets the poleward boundaries of the OMZs in both oceans. Energetic circulation along the equator results in enhanced oxygen supply to the eastern basins from the well-ventilated western boundary thereby separating the OMZs of both hemispheres by an equatorial oxygen maximum. Observations indicate a significant and broad-scale decrease of oxygen levels and associated increase in the volume of oxygen deficient waters of the eastern tropical North Atlantic (ETNA) during the past 50 years, which is part of the widespread deoxygenation of the global ocean’s thermocline. During the recent decade covered by enhanced observations in the framework of the German collaborative research centre SFB754 a more distinct pattern emerges consisting of regions with decreasing and increasing oxygen along the 23°W repeat section cutting through the ETNA OMZ. The observed spatial variations in the obtained ten-year trend may help to understand the underlying drivers and mechanisms of long-term oxygen changes. Current models do not reproduce observed patterns of oxygen changes in the ocean’s thermocline. Nevertheless, they reveal a close correlation between
declining oxygen levels and increases in water age on isopycnal surfaces in the thermocline suggesting decreasing ventilation as the dominant driver of thermocline deoxygenation whereas changes in respiration seem to play only a minor role. Here we investigate and review possible drivers and mechanisms of the observed oxygen changes in the tropical thermocline including changes in the wind-driven and eddy-driven circulation, alterations of ventilation pathways, and changes in stratification by taking into account a large data base of hydrographic, oxygen and current data as well as idealized process and realistic models.

**Peter Brandt** | Since 2007, Peter Brandt has been Professor for Experimental Oceanography in the Research Division Ocean Circulation and Climate Dynamics at the GEOMAR Helmholtz Centre for Ocean Research Kiel. He started his research in the remote sensing group of the Institute of Oceanography, University of Hamburg, where he completed his PhD in 1996 by studying internal wave dynamics of sea straits. In 1999, he joined the physical oceanography group at GEOMAR (also former Leibniz Institute of Marine Sciences). Here he focused on physical mechanisms of ocean variability in key regions of the thermohaline and wind-driven circulation. He was chief scientist of and participated on a large number of research cruises in the Indian and subpolar and tropical Atlantic oceans. As principle investigator he takes part in several national and international projects including the EU FP7 project “Enhancing prediction of tropical Atlantic climate and its impacts (PREFACE)” or the German Collaborative Research Center 754 “Climate-Biogeochemistry Interactions in the Tropical Ocean”. His main research interests are different physical processes relevant for the general ocean circulation and climate variability including equatorial and planetary ocean waves, mesoscale eddies, small-scale internal waves and mixing processes. His work encompasses strong interdisciplinary cooperation with biogeochemical scientists/groups to study oxygen distribution, ventilation and consumption in the tropical oceans as well as the interaction of physical and biogeochemical processes in the oceanic nutrient or carbon cycles.
ORAL PRESENTATIONS

Ventilation pathways for the North Pacific Oxygen Deficient Zone revealed by secondary oxygen maxima and Lagrangian particle tracking

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The oxygen deficient zones (ODZs) are confined to small volumes of the ocean but exert large influence on biogeochemical cycles, by altering the redox chemistry and microbial transformation of nutrients in these regions. The factors that regulate the size and sensitivity of ODZs to oceanic change are numerous, complex, and remain poorly understood. We synthesize recent autonomous and historical shipboard hydrographic observations with a high-resolution circulation model to show that the Northern Subsurface Countercurrent produces pronounced Secondary Oxygen Maxima (SOMs) in the Eastern Tropical North Pacific ODZ. We demonstrate that these SOMs are the result of an important eddy ventilation mechanism for the ODZ using a combination of Lagrangian particle tracking and an eddy-permitting numerical model simulation with an embedded ecosystem. The primary ventilation mechanisms for the North Pacific ODZ are the eddies produced by the Northern Subsurface Countercurrent, the water supplied by the North Equatorial Undercurrent Jets and seasonal detrainment of oxygen along the continent. These results suggest that predicting changes in the ODZ will require a better understanding of the narrow zonal jets that supply its oxygen.

Mechanisms of low-frequency oxygen variability in the North Pacific

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This study investigates the mechanisms of interannual and decadal variability of dissolved oxygen (O2) in the North Pacific using historical bottle O2 data and a physical-biogeochemical hindcast simulation. An ocean-ice configuration of the Community Earth System Model (CESM) is used to for the hindcast. The simulated variability of upper ocean (200m) O2 is broadly consistent with observations in the western and eastern Pacific where sampling density is relatively higher. The dominant mode of O2 variability in this depth range explains 24.8% of the variance and is significantly correlated with the Pacific Decadal Oscillation (PDO) index (r = 0.68). Two major mechanisms are proposed as null hypotheses by which the PDO controls O2 variability. Vertical movement of isopycnals (“heave”) may drive O2 variability in deep tropics. Isopycnal surfaces are depressed in the eastern tropics under the positive (El Nino-like) phase of PDO, leading to O2 increases in the upper water column. In contrast to the tropics, changes in subduction associated with the PDO are the primary control on extra-tropical O2 variability. These hypotheses are tested by contrasting the anomalies
of O$_2$ and heave-induced O$_2$ where the latter is calculated from potential density anomalies. At 200m depth, isopycnal heave is the leading control on O$_2$ variability except for the central subtropics, downstream of the subduction region. Further examination of the amplitude of O$_2$ anomalies reveals that the null hypothesis cannot fully explain the tropical O$_2$ variability, likely indicating the reinforcing changes in the biological O$_2$ consumption. These mechanisms, synchronized with the PDO, develops a basin-scale pattern of O$_2$ variability that are comparable in magnitude to the projected rates of ocean deoxygenation in this century.

Variability and drivers of the oxygen minimum zone in the tropical Pacific over the past decades

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Deoxygenation has been a big concern because oxygen is an essential element for all levels of marine life. Data has shown an expansion of Oxygen-Minimum-Zone (OMZ) with a declining trend in dissolved oxygen (DO) over the past decades in the tropical Pacific. However, there is a lack of quantitative analyses of sources and sinks to elucidate the underlying mechanisms. Here, we employ a validated ocean physical-biogeochemical model to test the previously proposed hypotheses for the decline of mid-depth DO, and to evaluate the variability and drivers of the tropical Pacific PMZ. Our analyses demonstrate that changes in the size of OMZ and DO inventory in the tropical Pacific reflect a delicate balance between oxygen supply and consumption. Our analyses demonstrate that during the warming period of 1981-1997, both oxygen supply and consumption were low in the mid-waters, but oxygen consumption exceeded supply, which led to a decreasing trend in the middepth DO. On the other hand, oxygen supply exceeded consumption during the warming pause (post ~2000) in some parts of the basin; the strengthening of wind-driven ocean transport since around 2000 has ceased the expansion of the OMZ and led to a pause in the decline of mid-depth DO in the tropical Pacific. Our model sensitivity studies show that the decline of mid-depth DO in the northeastern tropical Pacific OMZ (the largest OMZ) has no direct linkage to the increase of production in the upper water column. The mid-depth DO is largely influenced by the level of dissolved organic matter accumulated in the mid-waters, and partly related to thermocline depth. This study highlights the significance of physical forcing on the tropical OMZs, indicating that future climate change will have implications for ocean deoxygenation.

Low-oxygen mesoscale eddies in the eastern South Pacific

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The highly productive eastern boundary upwelling system of the South Pacific is characterized by the presence of an intense and shallow oxygen minimum zone (OMZ). Near the coast of South America these oxygen depleted waters are advected
poleward by the Peru-Chile Undercurrent extending the southern limit of the OMZ along the coast as far south as ~40°S. Off central Chile (30°S-40°S) mesoscale eddies play an important role in the flux of heat and dissolved substances in the coastal transition zone, impacting directly the dynamics the OMZ. In this work we analyze the impact of a special class of eddies: namely subsurface (intratermocline) anticyclonic mesoscale eddies (SAMEs), on the OMZ dynamics. These eddies have a well defined core characterized by very low-oxygen waters and high salinity, and can be clearly identified from a Temperature-Salinity-Oxygen diagram. Based on underwater glider observations, along with satellite data we describe the oceanographic characteristics of SAMEs along with some of their cinematic and dynamic properties. Based on a high-resolution numerical model simulations we analyze the generation mechanisms of SAMEs and their relationship to the poleward undercurrent variability.

**Interannual variability of the OMZ of the South Eastern Pacific**

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While observations suggest a long-term expansion of the OMZ in the South Eastern Pacific (SEP) which has been suggested to be due to global warming, the SEP OMZ also apparently exhibits a notable decadal variability in its upper and lower limits. Large uncertainties of the fate of the SEP OMZ in a warmer climate as simulated by Earth system models also questions to which extent natural variability in the OMZ can obscure the detection of externally forced trends. Here we analyze a long-term regional simulation of the OMZ of Peru and Chile and show that a large share of the variability is not linearly related to the equatorial forcing (ENSO), suggesting that it originates from internal dynamics associated to both local non-linear physical and biogeochemical processes. The natural variability in the model is further diagnosed from sensitivity experiments to the ocean boundary forcing of the regional model. The simulations of the Community Earth System Model (CESM) Large Ensemble are also analyzed suggesting that low-resolution coupled models may underestimate natural variability. Implications of our results are discussed in terms of the concept of emergent constraints and of the challenge for observing systems.

**ENSO-driven fluctuations in the vertical extent of oxygen-poor waters in the oxygen minimum zone of the Eastern Tropical South Pacific**

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The El Niño Southern Oscillation (ENSO) with its warm (El Niño) and cold (La Niña) phase has strong impacts on marine ecosystems off Peru. This influence extends from changes in nutrient availability to productivity and oxygen levels. While several
studies have demonstrated the influence of ENSO events on biological productivity, less is known about their impact on oxygen concentrations. In situ observations along the Peruvian and Chilean coast have shown a strong water column oxygenation during the 1997/1998 strong El Niño event. These observations suggest a deepening of the oxygen minimum zone (OMZ) along the continental shelf. However, due to reduced spatial coverage of the existing in situ observations, no studies have yet demonstrated the OMZ response to El Niño events in the whole Eastern Tropical South Pacific (ETSP). Herein, we provide a comprehensive analysis of the ENSO influence on OMZ dynamics. Interannual variability of the OMZ during the period 1990-2010 is derived from a coupled physical-biogeochemical model. Our results show a reduction of the vertical extent of the OMZ during the El Niño phase. During La Niña phase, there is a vertical expansion of oxygen-poor waters. These fluctuations in OMZ extent are due to changes in oxygen supply into its core depth from both lateral and vertical margins of the OMZ.

**Time scales of oxygen variability in the eastern tropical North Atlantic**

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In the framework of the German collaborative research centre SFB754 and associated programs, a large data set consisting of shipboard and moored observations has been collected in the eastern tropical North Atlantic (ETNA) during the past 10 years. This data provides an unprecedented comprehensive insight into the variability of oxygen, hydrography and velocity of the oxygen minimum zone (OMZ) of the ETNA, centered at 11°N, and the well-ventilated equatorial regime south of it. Here, we discuss the variability observed from intraseasonal up to even decadal time scales throughout the SFB754 period. The ETNA is subject to a coherent decadal oxygen change pattern with a strong oxygen decrease at the depth of the upper OMZ boundary (200-400m), whereas a moderate oxygen increase is found below the core depth of the OMZ (500-800m). Hydrography and zonal velocity also changed which suggest that the decadal oxygen change pattern we observe is likely due to circulation changes: a weakening of the shallow wind-driven circulation at depth of the upper OMZ boundary and an intensification of the latitudinally alternating zonal jets below the OMZ core depth. Seasonal and interannual oxygen variability in the upper 500m is at least partly connected to variations of zonal currents, which are either due to meridional shifts of the current core or transport variability associated with the current. Below about 500 m close to OMZ core, a well-defined seasonal cycle is observed, most likely associated with horizontal shifts of the lateral OMZ boundaries due to propagation of seasonal Rossby waves. Intrasseasonal variability is driven by mesoscale eddies and baroclinic Rossby waves. At the depth of the OMZ core, they contribute to a net lateral oxygen flux into the OMZ. At depths above 300m, anomalous low oxygen concentrations episodically appear, which are induced by mesoscale eddies with
enhanced biological activity on top of the isolated eddy core. This phenomenon is well described for latitudes at around 16-20°N, but the dynamics and origin of these eddies are so far unknown for lower latitudes (8-12°N). The decade-long intense shipboard and moored observations enabled identifying key regions for oxygen variability in the OMZ. Future observing efforts in the ETNA after the SFB754 are most likely less intense. In an effort to establish sustained oxygen observations for the ETNA we have added oxygen sensors to selected moorings of the PIRATA buoy network, recently even allowing real-time oxygen data access.

**Driving mechanisms for maintaining the equatorial deep jets and the quasi-steady flanking jets and the implications for the equatorial oxygen budget**

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The equatorial deep jets and the quasi-steady flanking jets are part of the zonal jet system in the equatorial ocean and play a role in setting the equatorial maximum in oxygen that has been known since the Meteor cruises from the 1920’s. Nevertheless, these zonal jets are missing from the models we use for ocean/climate studies, even ocean models with high horizontal resolution. Here we present a new perspective on the dynamics of the equatorial ocean and show, using mooring data and idealized model simulations, that the equatorial deep jets are maintained by the convergence of meridional flux of zonal momentum on the equator associated with intraseasonal waves, analogous to the maintenance of the atmospheric jet stream by mid-latitude storm systems. The main driving mechanism for the quasi-steady flanking jets might be related to the existence of equatorial deep jets producing a zonal flux of zonal momentum thus maintaining a nearly depth independent westward flow at the equator embedded in eastward flow at 2° latitude on both sides of the equator. The implications for modelling the oxygen distribution in the equatorial ocean will be discussed.

**Ventilation of the eastern tropical North Atlantic oxygen minimum zone by latitudinally alternating zonal jets in a shallow water model**

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Increased observational efforts have revealed a multi-decadal decrease of oxygen concentrations with superimposed interannual to decadal variability in the oxygen minimum zone (OMZ) of the eastern tropical North Atlantic (ETNA). Recent studies have linked this variability to long-term changes in the ventilation by the latitudinally alternating zonal jets (LAZJs). In this study a 1.5 layer non-linear shallow water model coupled to an advection-diffusion model is employed in basins with either rectangular
or Atlantic geometry to obtain a conceptual understanding of the influence of the LAZJs on the ventilation of the ETNA OMZ. Using an equatorial annual period forcing, westward propagating off-equatorial Rossby waves are generated that subsequently break up into non-linear eddies. The responsible non-linear triad instability mechanism thereby sets the amplitude and size of the generated eddies, which rectify to LAZJs when temporally averaged. An oxygen-mimicking tracer is transported by the resulting velocity field, forming a region with minimum tracer concentration whose location is in general agreement with the observed ETNA OMZ. The thickness-weighted tracer budget reveals that the Eulerian mean advective flux convergence outweighs the eddy advective flux convergence in balancing the strongly simplified tracer consumption. Thickness-weighted averaging the advective flux convergence also yields an eddy mixing term which is shown to play an important role in the budget and is analysed in more detail. Despite the purely annual period forcing, interannual to decadal and longer tracer variability is excited in the basin, including the region of the ETNA OMZ. A comparison between modelled and observed oxygen trends in the lower OMZ does not lead to a rejection of the null hypothesis that the observed decadal oxygen trends are part of the system’s intrinsic variability. However, the observed pronounced decadal oxygen decrease in the upper OMZ during 2006-2013 is not reproduced by the model. On a multi-decadal time scale, the picture is reversed. In contrast to the upper OMZ, the multi-decadal oxygen decrease in the lower OMZ is not reproduced by the idealised model. While this would support the idea of an anthropogenically driven long term deoxygenation of the lower OMZ, it is important to bear the simplicity and shortcomings of the model in mind. Further, the sparsity in measured oxygen data before the recently increased observational efforts complicates the reliable estimation of multi-decadal trends.

**On Nearshore hypoxia and oxygen ventilation in the Eastern tropical North Atlantic**

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Among the eastern boundary systems, the Eastern tropical North Atlantic (ETNA) has the least extreme deoxygenation condition, both in terms of OMZ geographical extent and also of oxygen depletion level. On the other hand, the vertical structure of the oxygen distribution is such that low hypoxic values are found at ~ 100 m depth offshore of Senegal and Mauritania. This depth is approximately where the source waters for coastal upwelling are drawn from. In this presentation, the importance of these low oxygen concentrations values for the West African shelf ecosystems will be discussed briefly. Subsequently, elements of the offshore and continental slope circulation will be presented to clarify the ventilation context associated with the ETNA shallow hypoxic conditions. Owing to scarcity of in situ data in part of the ETNA, we will mainly rely on a model simulation to do so (albeit after careful evaluation
Variability of the Atlantic North Equatorial Undercurrent and its impact on oceanic oxygen distribution

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In the Oxygen Minimum Zone (OMZ) of the Eastern Tropical North Atlantic (ETNA) oxygen values vary on daily to multidecadal time scales. The OMZ is ventilated by weak eastward flowing zonal currents, among them the North Equatorial Undercurrent (NEUC). It is located between 4°N and 6°N in a depth range of 50 m to 400 m and its core velocity varies between 0.1 ms⁻¹ and 0.3 ms⁻¹. It has been suggested that the NEUC is an important oxygen supply pathway to the ETNA OMZ. Here we investigate the variability of the NEUC on interannual time scales and its impact on oxygen levels in the ETNA OMZ. The variability and driving mechanisms of the NEUC are not well understood. Obtaining reliable transport estimates of the NEUC from observations and models is difficult, mainly because the cores of the NEUC and the North Equatorial Countercurrent (NECC) above cannot be clearly distinguished over most of the year. For our analysis we are using observational data from 20 ship sections along 23°W from 2002 to 2016 and the output of a high-resolution ocean model in which a 1/10° nest of the tropical Atlantic is embedded into a global 1/2° model. The model captures the zonal current field of the tropical Atlantic reasonably well although the NEUC tends to be too strong compared to observations. Utilizing a new, path-following algorithm to investigate its location and intensity, we find that about 20% of the NEUC variability on interannual time scales can be explained by wind variability in the tropical Atlantic. These large-scale wind changes are related to the Atlantic Meridional Mode (AMM), a climate mode that represents an interhemispheric SST gradient in the tropical Atlantic. Interannual variations in both the position and the intensity of the NEUC are significantly correlated with the AMM index. Composites further show a weakening and a southward shift of the NEUC during positive AMM phases and vice versa. Positive AMM phases are thus associated with reduced oxygen concentrations in the NEUC and decreasing oxygen levels in the ETNA OMZ region.

Early detection of anthropogenic climate change signal in the interior subpolar North Atlantic oxygen

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The response of oxygen concentrations in the subpolar North Atlantic (SPNA) to future climate change is poorly understood. Here, we investigate the multi-decadal variability in the interior oxygen at 1500 m depth and its association with the North
Atlantic subpolar gyre index (a proxy for the subpolar gyre strength) for both models and data. During its positive phase, persistent anomalously strong mixing in the Labrador Sea entrains oxygen-rich water into the interior southern SPNA, while the opposite is true during a negative phase. We evaluate a suite of IPCC-class Earth System Models (ESMs) according to their fitness in representing the observed variability. Under a high CO₂ future scenario, the best performing ESMs project a steady decline in the SPNA oxygen, driven partly by lower oxygen solubility in warmer climate and partly by increases in apparent oxygen utilization largely due to the long-term weakening of the LSW ventilation. The projected deoxygenation is shown to depend on the sensitivity of the simulated Labrador Sea mixed layer depth to temperature increase. This anthropogenic signal on the interior Labrador Sea oxygen is projected to emerge in the early 21st century, decades before the temperature and salinity signals, suggesting that the interior oxygen in the study region is more sensitive to circulation changes than temperature and salinity.

**Ocean deoxygenation and N₂O emissions projected in mulit-millenial global warming simulations**

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We investigate century and multi-millennial scale changes in marine oxygen (O₂), marine emissions of nitrous oxide (N₂O), warming, and compound hazard in terms of metabolic conditions for a range of temperature targets, including those mentioned in the Paris Agreement. Scenarios, where radiative forcing is stabilized by 2300, are used in ensemble simulations with the Bern3D Earth System Model of Intermediate Complexity. We attribute the contributions of O₂ changes from changes in solubility, and the interplay of ocean biology and ventilation by carrying four explicit O₂ tracers and an ideal age tracer. Transiently, the global mean ocean oxygen concentration decreases by a few percent under low and by 40% under high forcing. Deoxygenation peaks about thousand years after stabilization of radiative forcing and new steady state conditions establish after AD 8000 in our model. Hypoxic waters expand over the next millennium and recovery is slow and remains incomplete under high forcing. The equilibration timescale of oceanic oxygen is therefore longer than the thermal equilibration timescale of both the atmosphere (~1000 years) and the ocean (~4000 years). The changes in O₂ strongly correlate with water mass age, linked to changes in Indo-Pacific and Atlantic overturning, and are also impacted by gradual oxygen loss due to warming. Distinct and close to linear relationships between the equilibrium temperature response and marine O₂ loss emerge. For example in the upper ocean, the decline of a metabolic index, quantified by the ratio of O₂ supply to an organism’s O₂ demand, is reduced by 6.2% per degree of avoided equilibrium warming. Measures of peak hypoxia exhibit a strong sensitivity to additional warming. Volumes of water with less than 50 microM O₂, for instance, increase between 36% to 76% per degree warming. Turning to N₂O, surface and deep ocean N₂O observations constrain N₂O production from nitrification and denitrification to 4.5 (3 – 6.1) TgN per year in our model. The modelled changes in physical transport, oxygen concentrations and organic matter remineralization affect N₂O production, consumption and emissions. Under high forcing, N₂O production decreases by about 8% over this century due to decreasing organic matter export and remineralization. Thereafter,
production increases slowly by about 20% due to widespread deoxygenation and high remineralization, and enhanced emission lead to a small positive N$_2$O-climate feedback. Our simulations reveal a tight coupling between marine physical changes, the carbon cycle, O$_2$, N$_2$O and climate change and long time scales of key ocean processes.

**Elevated marine oxygen inventory by enhanced anaerobic respiration in a warmer future ocean**

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A multi-millennial global-warming simulation with an Earth system model of intermediate complexity with fixed phosphorus inventory and driven by business-as-usual CO$_2$ emissions until year 2100 and a linear decline to zero emissions in year 2300 and thereafter, yields a marine oxygen inventory that exceeds the preindustrial oxygen inventory in the simulated warmer future climate, with surface air temperatures about 7°C and mean ocean temperatures about 3°C warmer than pre-industrial. An initial, multi-centennial decline in the oxygen inventory and its subsequent recovery roughly correspond to the rearrangement of the ocean overturning circulation as the ocean warms from the top. The oxygen deficient volume expands threefold on a millennial time scale and shows only a partial recovery to more than twice the pre-industrial volume after a few thousand years. An interior-ocean oxygen source unaccounted for in previous studies stems from enhanced anaerobic remineralisation in expanding oxygen deficient zones: With denitrification replacing some of the current ocean’s aerobic remineralization, the resulting net loss of fixed nitrogen is equivalent to a net oxygen gain by the ocean. In our simulation, the ocean’s inventory of fixed nitrogen declines by about 17% by the year 8000. The concomitantly avoided aerobic remineralization alone increases oceanic oxygen by 3% over the same time period. Adding physical and biogeochemical effects, the global ocean oxygen inventory simulated by our model in year 8000 is 5% higher than the preindustrial one, despite a more than two-fold expansion of the oxygen deficient volume.

**Robust millennial-scale recovery of deep ocean ventilation and oxygenation with global warming?**

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Coupled climate model simulations consistently project for the 21st century reduced ventilation of the deep ocean and a loss of oxygen in response to global warming, yet the warming at the end of the last ice age – similar in amplitude to the warming projected for the end of the century – resulted in a better ventilated deep ocean. Here, we use multi-millennial global warming simulations with the comprehensive Earth system model GFDL ESM2M under a 1% yr$^{-1}$ atmospheric CO$_2$ increase to 2xCO$_2$ and
constant forcing thereafter scenario to show that this counterintuitive result may be a consequence of different rates of ocean warming. After full equilibration of the model with the doubling of atmospheric CO$_2$, achieved after ~4000 years, the deep ocean is actually better ventilated and oxygenated, consistent with paleo-proxy records and intermediate complexity model simulations. We suggest that this millennial-scale ventilation recovery is initiated by the Atlantic Meridional Overturning Circulation, which rejuvenates after atmospheric CO$_2$ has stabilized thereby enhancing the transport of salty waters originating from the subtropical Atlantic Ocean to the Southern Ocean. The upwelling of these anomalous salty waters in the Southern Ocean gradually erodes the freshwater cap (halocline) that usually prevents convection. After approximately 700 years, the onset of deep water formation in the Ross Sea mainly drives the acceleration of Antarctic Bottom water formation and the oxygenation of the deep ocean. The exact timing of the deep water formation onset in the Ross Sea is driven by stochastic processes. Atmosphere-ocean interactions, such as changes in Southern Hemisphere westerly winds and surface density fluxes can be excluded as potential main drivers of the deep ocean ventilation recovery. Such millennial-scale increase in Southern Ocean deep-water formation under global warming may increase the ocean inventory of preformed nutrients and ultimately decreases the carbon uptake capacity of the ocean. To test the robustness of our results, we also use multiple coupled Earth system model simulations that are integrated for more than thousand years and are part of the new model intercomparison project LongRunMIP.

**High frequency wind forcings and interior oxygen levels**

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The near-surface atmosphere layer, and in particular the wind intensity, controls the ocean properties. The Ekman circulation depends on the wind stress, which strength also determines the amount of diffusion in the upper layer. The intensity of the latent and sensible fluxes at surface depend linearly of the wind speed. The wind also directly impacts the biogeochemical cycles as it modulates the kinetic of gases equilibrium such as oxygen. Using an ocean general circulation model we assess here the importance of the high frequency forcing in setting the ocean properties. We remove specifically the “weather frequencies” (<10 days) of the wind component in the forcing of the 1-momentum equation, 2-mixing length scale and 3-surface fluxes. These experiments are based on the normal year of the CORE forcing dataset (COREv2-NYF). We emphasize the importance of the “weather frequencies” in the modulation of the biogeochemical cycles and the oxygen concentration at centennial time scale.

**Submesoscales reduce deoxygenation in temperate gyres**

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Climate projections with Earth System Models (ESM) suggest that strong deoxygenation is projected to occur by the end of the 21st century in the temperate gyres of the North Pacific and North Atlantic. This deoxygenation trend is the consequence of a balance between 1) reduced oxygen solubility associated with warmer temperatures
2) reduced ventilation, and 3) is partly counter-balanced by reduced oxygen consumption at subsurface associated with reduced photosynthesis at the surface. These three processes, solubility, ventilation and productivity/respiration are known to be affected by physical processes occurring at meso and submesoscale which are not properly accounted for in ESM. In order to examine how our current projections of deoxygenation may be biased by the lack of horizontal resolution of current ESM, we carry a model study in which an idealized configuration of the temperate North Atlantic/Pacific gyres is run for several decades at three different horizontal resolutions: 100km, 12km and 4km. Two scenarios are examined: a preindustrial scenario, with a seasonally repeating atmospheric forcing, and a climate change scenario where a constant temperature trend is added to the previous forcing. The physical component of the model is NEMO, and the biogeochemical component is LOBSTER. Our idealized model is able to reproduce the deoxygenation trend projected by ESM with a similar amplitude. We find lower levels of deoxygenation with increasing model resolution despite lower productivity/respiration. We interpret the results by examining the trends in the oxygen equation.

Oxygen utilisation rate - a poor measure of ocean respiration

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We use a simple 1D model and 3D global ocean biogeochemical models to evaluate the concept of computing the subsurface oceanic oxygen utilization rate (OUR) from the changes of apparent oxygen utilization (AOU) and water age along trajectories on isopycnal surfaces. We find that OUR underestimates globally averaged total oceanic oxygen consumption (respiration) substantially. Most of this difference is observed in the upper 1000m of the ocean, with the discrepancies increasing towards the surface where OUR underestimates oxygen consumption by as much as factor of four. Hitherto the major problem in the OUR determination has been considered to be the determination of water age, that is the time passed since the last contact of a body of water with the atmosphere, when its oxygen concentration is assumed to have reached equilibrium with air (“saturation”). We find, however, more fundamental and large errors in the concept of OUR itself. AOU from which OUR is calculated is not only the imprint of respiration in the ocean’s interior, but the net result of respiration and oxygen supply, i.e. AOU generation and destruction. Similarly, water age is the net result of ageing and age destruction at the surface. Now AOU and water age are subject to advection and diffusive mixing, and only when they are affected by both in the same way does the OUR calculated represent the correct rate of oxygen consumption. This is the case only with uniform respiration rates, when the proportions of AOU and age are not changed by transport. Inhomogenous distributions of respiration yield underestimates (when maximum rates occur near the outcrops of isopycnals) or overestimates (when maxima occur far from the outcrops). Given the distribution of respiration on isopycnal surfaces in the ocean (and in the models employed), that is high rates near their northern and southern outcrops and low rates below the oligotrophic gyres as well as rates decreasing with water depth everywhere, underestimates are the rule. Integrating these effects globally in an ocean biogeochemical model we find that AOU-over-age based estimates underestimate true
model respiration by a factor of three.

**Oxygenation and deoxygenation of Atlantic and Pacific Ocean oxygen minimum zones by the wind interacting with mesoscale eddies**

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Recent modelling studies revealed the importance of mesoscale eddies for a lateral transport of water mass anomalies from the eastern boundary upwelling systems into oxygen minimum zones (OMZ). Observational studies on individual eddies show that mesoscale dynamic change the biogeochemical eddy characteristics “en-route”. Vertical nutrient flux into the euphotic layer controls local productivity and e.g. particle sinking and respiration/remineralization. In anoxic extreme environments (Pacific OMZ) short term, episodic flux of oxygen can have long lasting effect on sustaining aerobic communities and thus microbial diversity. Different concepts of vertical fluxes in eddies have been discussed. “Eddy/wind interaction” based on the concept of a momentum flux difference across an eddy and applying an Ekman balance upwelling (anticyclonic eddies) or downwelling (cyclonic eddies) over the eddy is proposed. However, continues changes in wind stress direction occur over eddies and hence a time derivative on the wind stress/flow must be considered in the balance and hence Ekman is not applicable. Time varying flow, wind stress and Coriolis force is solved in the framework of inertial currents/waves (NIWs). For the eddies wind stress variability can be created by the eddy rotation and mesoscale wind fluctuations are not always required. Near inertial internal wave (NIIW) energy propagation is modified by the vorticity structure of eddies: anticyclones are “superinertial” and NIIW energy propagates downward, cyclones are “subinertial” and energy is trapped and may dissipate at shallow depth. At the transition zone from the eddy core to the surrounding water a relative vorticity anomaly of reversed sign is created hence all eddies are associated with both, superinertial and subinertial regions and a dynamical boundary between the two regions is the maximum swirl velocity of the eddy. Using opportunistic high-resolution eddy surveys in the Atlantic and Pacific OMZ regions we estimate NIIW shear induced vertical flux through eddies. We observe that NIIW induced shear supports layering of properties in superinertial regions and reaching several hundreds of meters depth. The combination of lateral intrusion and vertical shear can drive deep-reaching vertical property exchange. Analysing the areal extend of all eddy core and eddy transition regions in Atlantic and Pacific OMZs we assess the subinertial and superinertial areas and estimate the associated vertical flux of properties. We use a new eddy tracking data set (Laxenaire et al.) based on absolute dynamic topography and which include the signature of “standing” eddies not detectable in sea-level anomaly based algorithms.
Near-inertial wave interaction with coherent anticyclonic eddies – a ventilation source for oxygen minimum zones?

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More than thirty years ago the interaction between near-inertial wave (NIW) propagation and geostrophic flow was already investigated. It was theoretically shown that anticyclonic eddies can trap and enhance downward propagation of NIW energy. A critical-layer can be formed below these eddies where the associated vorticity anomaly vanishes. Today, several recent model studies point out the importance of the interaction between eddies and NIWs for the downward transport of NIW energy into the deeper ocean, where it could provide an energy source for turbulent mixing. However, observations of critical layer trapping in combination with measurements of turbulent dissipation rates are rare. Here, we present results from several multiple platform observational studies based on gliders, moorings and shipboard measurements carried out in the oxygen minimum zones (OMZ) of the Pacific and Atlantic Oceans. The investigation of several coherent anticyclonic eddies allows a detailed view on their impacts on the near-inertial energy distribution. Shipboard and moored velocity measurements in coherent anticyclonic eddies show pronounced alternating current bands with amplitudes up to 15 cm/s below the eddies, which are associated with NIWs. The strongest NIW amplitudes are found around the mixed-layer depth and at the eddy base. Much weaker amplitudes are found within the interior of the eddy, whereas at around 700 m – 1000 m depth (depends on the individual eddy) they vanish completely. Additionally, microstructure measurements show enhanced dissipation rates associated to the high amplitudes of the NIWs. This suggests that a critical-layer is formed at the eddy base where near-inertial energy accumulates and is dissipated leading to enhanced mixing. This elevated mixing can potentially be associated to an oxygen flux from the deeper more oxygenated water into the OMZ core. As around 15% of the OMZ areas are covered with anticyclonic eddies, this mechanism could contribute to the ventilation of the OMZ from below, which has so far not been considered.

Understanding the dynamics of OMZs by deliberate Tracer Release Experiments (TREs)

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The dynamics of oxygen minimum zones (OMZs) are influenced by supply and consumption of oxygen through a range of processes. These include the supply of
oxygen through diffusive processes across (diapycnal diffusivity, Kz), and along (isopycnal diffusivity, Kx and Ky, for zonal and meridional diffusivity) isopycnals, but also the flow of nutrients from the deeper layers to the photic zone that can fuel biological productivity, and by remineralization of sinking particles that consume oxygen. In order to quantify some of these, hard to measure, processes we have conducted three deliberate Tracer Release Experiments during the SFB754 project. The first experiment, Guinnea Upwelling TRE (GUTRE) focused on the diapycnal flow of oxygen through the upper oxycline of the Eastern Tropical North Atlantic (ETNA). A follow up experiment, the Oxygen Supply TRE (OSTRE) focused on the lateral (isopycnal) supply of oxygen to the core of the OMZ in the ETNA. A third experiment was carried out in the Eastern Tropical South Pacific (ETSP) OMZ off Peru (POSTRE) where the focus was on quantifying the pathway of nutrients released from anoxic sediments through the benthic boundary layer. During the GUTRE experiment we were able to quantify Kz with high accuracy and noted the importance of bottom topography and density stratification for the diapycnal mixing coefficient and the significance of relating to pressure or density in these calculations. These estimates were refined by the OSTRE experiment and reveal only a small difference in Kz for the two different depth (density) levels of the two experiments. For OSTRE we introduced sampling in a regular grid in a 4×4° control area in order to quantify the amount tracer left in a defined area over time. Initial results suggest a significantly higher Kx compared to Ky, and a significant contribution of mean advection to the model. The POSTRE experiment was designed differently in that the tracer was released just above the bottom at a fixed position, so that the injection density had a larger variance than a “standard” TRE. The results from a survey 17 months after release clearly indicate a rapid pathway of tracer (i.e. nutrients) from the sediment to reach the top of the OMZ and the photic layer close to the coast. Profiles of tracer advected from the coast indicate a Kz value comparable to the Kz measured in the ETNA.

Understanding the Dynamics of the Oxic-Anoxic Interface in the Black Sea

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The Black Sea, the largest semiclosed anoxic basin on Earth, can be considered as an excellent natural laboratory for oxic and anoxic biogeochemical processes. The suboxic zone, a thin interface between oxic and anoxic waters, still remains poorly understood because it has been undersampled. This has led to alternative concepts regarding the underlying processes that create it. Existing hypotheses suggest that the interface originates either by isopycnal intrusions that introduce oxygen or the dynamics of manganese redox cycling that are associated with the sinking of particles or chemosynthetic bacteria. Here we reexamine these concepts using high-resolution oxygen, sulfide, nitrate, and particle concentration profiles obtained with sensors deployed on profiling floats. Our results show an extremely stable structure in density space over the entire basin with the exception of areas near the Bosporus plume and in the southern areas dominated by coastal anticyclones. The absence of large-scale horizontal intrusive signatures in the open-sea supports a hypothesis prioritizing the role of biogeochemical processes.
Shift in the Black Sea ventilation regime and decline of its oxygen inventory

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Life in the Black Sea is confined in a thin surface oxygenated layer, bounded by a strong and permanent salinity gradient (halocline) that maintains the remaining 90% of the water column in euxinic conditions. We showed that from 1955 to 2016, the oxygen inventory in the Black Sea has decreased by 44% and that the basin-averaged oxygen penetration depth has decreased from 140 m in 1955 to 80 m in 2016, which is the shallowest annual value recorded during that period [1]. Here, we discuss the physical/biogeochemical drivers of this deoxygenation trends. In the 1970s-1980s, the Black Sea faced severe eutrophication. Enhanced respiration rates then reduced the thickness of the oxygenated layer. Following increase in the oxygen inventory (1985–1995) supported arguments in favor of the stability of the oxic layer. Concomitant with a reduction of nutrient loads, it also depicted a Black Sea recovering from eutrophication. However, this view neglected the variability in ventilation mechanisms. Oxygenated conditions at intermediate depth (50-100m) are maintained by the annual formation of dense cold waters that brings oxygenated waters on top of the halocline, in the Cold Intermediate Layer (CIL). Recently, the lowest oxygen inventories were observed in concurrence with the lowest CIL cold content, suggesting a weakening of this ventilation mechanism. To explore the long-term variability of Black Sea ventilation, we produced a composite time series for the CIL cold content using observations (ship casts, Argo), empirical (atmospheric predictors) and mechanistic (3D hydrodynamic) models. The agreement between independent data sources confirms the reliability of this description of the Black Sea CIL evolution during the last 60 years. A robust regime shift analysis highlights a strong ventilation period concomitant with the “recovery” period of the early 1990s. However, an anomalous restricted ventilation regime prevails from 2008 to present day, that can be attributed to warmer air temperature. This new regime is characterized by the sporadic absence of the annual cold water formation which lead to significant ageing of the intermediate waters, and thereby opens the way for a further upward migration of the oxycline depth.

References: [1] Capet et al. (2016) Biogeosciences

Strong intensification of the Arabian Sea oxygen minimum zone in response to Arabian Gulf warming

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Semi-enclosed seas are prone to amplified warming under future climate change due to their landlocked nature and strong sensitivity to continental climate. This is particularly true for the Arabian Gulf (AG) due to its shallow depth and proximity to the fast warming Arabian Peninsula. While the predicted rapid warming of the AG is expected to challenge its local ecosystem already subject to extreme temperatures, the potential consequences for such a warming on the biogeochemistry of the Indian
Ocean at large have not yet been investigated. In particular, the effects of such changes on the oxygen minimum zone (OMZ) of the Arabian Sea remain unclear. Here, we investigate the impacts of the AG warming on the intensity of the Arabian Sea OMZ, and examine the biogeochemical and ecological implications of these changes. We show that a warming of the AG that is consistent with future regional climate projections can lead to a substantial intensification of the OMZ in the northern Arabian Sea. To this end, we performed a series of eddy-resolving regional simulations of the Arabian Sea and its marginal seas using the Regional Ocean Modeling System (ROMS) coupled to a nitrogen-based nutrient-phytoplankton-zooplankton-detritus (NPZD) ecosystem model. We find that when a moderate (+2°C) surface warming is applied to the AG, the volume of suboxic water in the Arabian Sea increases by 20% while denitrification increases by 19%. This is caused by a reduction of the ventilation of the Arabian Sea OMZ by the AG waters that gain buoyancy and lose oxygen due to surface warming. A stronger warming (+4°C) of the AG produces, however, a weaker increase in suboxic volume (+11%) and denitrification (+12%). This is because denitrification rates increase in the top 150m almost twice as fast as under moderate warming. This enhances nitrate depletion in the upper northeastern Arabian Sea and results in a reduction of NPP (-6%) that limits oxygen consumption at depth and weakens the intensification of OMZ below 200m. Our findings indicate that perturbations of the AG can have important consequences not only for its local ecosystem but also for the large-scale biogeochemistry of the Indian Ocean. These results also stress the need for improving the representation of marginal and semi-enclosed seas in the current generation of climate models.

POSTER PRESENTATIONS

(13) The role of atmospheric feedbacks in simulated ENSO and their influence on the Pacific OMZ

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Simulated ENSO in climate models of the CMIP5 data base is still too divers to allow reliable predictions, how ENSO will change under global warming (Stocker et al. 2013). The atmospheric component of CGCMs was identified as major source of diversity (Lloyd et al. 2011). In many state-of-theart CGCMs the positive (amplifying) atmospheric Bjerknes feedback and the negative (damping) heat flux feedback are both underestimated, leading to an error compensation (Bellenger et al. 2014, Bayr et al. 2018). Therefore, many CGCMs have biased ENSO dynamics, which hamper the simulation of strong El Niño events. During El Niño events the upwelling in the eastern Pacific is reduced and the thermocline is deeper than normal. Especially during strong El Niño events oxygen rich water is brought from the top into the OMZ (up to 300m depth), as observed during the strong El Niño in 1997 close to cost of Peru (Levin et al. 2002). As climate models with weak atmospheric feedbacks have problems in simulating strong El Niño events, this leads to a much weaker inflow of oxygen rich water into the

**14) Mesoscale ventilation of oxygen minimum zones in a global high resolution climate model**

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The global oxygen concentration in the ocean is expected to decrease as the ocean warms due to anthropogenic release of carbon dioxide. However, the fate of tropical oxygen minimum zones (OMZs) is less clear. Observations show an expansion of the OMZ while earth system models and proxy studies suggest longer-term variability with substantial uncertainty about trends in OMZ volume. Recent studies showed that this uncertainty arises since the extent of the OMZ is controlled by the small difference between large contributions from solubility, biological consumption, and ventilation, all of which are likely to be affected by a changing climate, but on possibly different spatial and temporal scales. Due to the sluggish circulation away from the equator, mesoscale eddies are expected to play a major role in supplying oxygen to tropical OMZs. A comprehensive assessment of the effect of eddies from observations is however difficult, due to sparse coverage at the subsurface. Here, we present results from a high resolution, global coupled climate-model (GFDL CM2.6) with a simplified biogeochemical model (miniBLING). We examine the large scale and eddy components of the flow and analyze the role of eddies in oxygen transport, with a focus on OMZs in the Atlantic and Pacific. We find that eddy ventilation plays a dominant role in ventilation below the OMZ core. Results are compared with existing estimates and the relative contribution of eddy advection and diffusion will be discussed.
(15) Quantifying thermocline oxygen and nitrate supply by Subantarctic Mode and Antarctic Intermediate Waters

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Subantarctic Mode Water (SAMW) and Antarctic Intermediate Waters (AAIW) are major sources for the ventilation of the subtropical thermocline and of the shadow zones, as well as for the nutrient supply of the lower latitudes. Hence, variability of the formation rate and properties of these water masses, and the oxygen ($O_2$) and nitrate (NO$_3$) they transport, may significantly affect subtropical productivity and oxygen minimum zones. We analyze the results of an ocean-sea ice data-assimilating Southern Ocean State Estimate (SOSE) and biogeochemistry model for the years 2008-2012. This time period is characterized by large interannual variability. We use a water mass framework applied to five day averaged SOSE output in order to understand and quantify the processes controlling $O_2$ and NO$_3$ inventories, transport and variability in the SAMW and AAIW density range. In particular, we want to understand the relative importance of physical processes (such as buoyancy fluxes and diapycnal mixing) and biogeochemical processes (such as productivity, gas exchange and tracer mixing) to drive inventories, northward export and variability. We discuss potential downstream effects on low latitude productivity and thermocline ventilation.

(16) Impact of mesoscale eddies on water mass and oxygen distribution in the eastern tropical South Pacific

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The influence of mesoscale eddies on the flow field and the water masses, especially the oxygen distribution of the eastern tropical South Pacific is investigated from a mooring, float and satellite data set. Three different types of eddies, one mode water (MWE), two anticyclonic (ACE1/2) and one cyclonic eddy (CE), are identified and followed in detail with satellite data on their westward transition with velocities of 3.2 to 6.0 cm/s from their generation region, the shelf of the Peruvian and Chilean upwelling regime, across the Stratus Ocean Reference Station (ORS) (~20°S, 85°W) to their decaying region far west in the oligotrophic open ocean. Velocity, hydrographic, and oxygen measurements at the mooring show the impact of eddies on the weak flow region of the eastern tropical South Pacific. Strong anomalies are related to the passage of eddies and are not associated to a seasonal signal in the open ocean. The mass transport of the observed eddies across 85°W is between 1.1 and 1.8 Sv. The eddy type dependent available heat, salt and oxygen anomalies are 8.1x1018 J (ACE), 1.0x1018 J (MWE), -8.9x1018 J (CE) for heat, 25.2x1010 kg (ACE2), -3.1x1010 kg (MWE), -41.5x1010 kg (CE) for salt and -3.6x1016 μmol (ACE2), -3.5x1016 μmol (MWE), -6.5x1016 μmol (CE) for oxygen showing an imbalance between anticyclones and cyclones especially for salt transports probably due to seasonal variability of water mass properties in the formation region of the eddies. Heat, salt and oxygen fluxes out of the coastal region across the ORS region in the oligotrophic open South Pacific are...
estimated based on these eddy anomalies and on eddy statistics (gained out of 23 years of satellite data). Furthermore, four profiling floats were trapped in the ACE2 during its westward propagation between the formation region and the open ocean showing a weakening of the anomalies of the water mass properties transported within the eddy pointing towards mixing processes with the surrounding waters between the seasonal thermocline and the eddy core during the first half of their lifetime.

(17) Subsurface coherent eddies: Tracer cannonballs, hypoxic storms, and microbial stewpots?

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Subsurface eddies are known features of ocean circulation, but the sparsity of observations prevents an assessment of their importance for biogeochemistry. Here we use a global eddying (0.1°) ocean-biogeochemical model to carry out a census of subsurface coherent eddies originating from eastern boundary upwelling systems (EBUS) and quantify their biogeochemical effects as they propagate westward into the subtropical gyres. While most eddies exist for a few months, moving over distances of hundreds of kilometers, a small fraction (<5%) of long-lived eddies propagates over distances greater than 1,000 km, carrying the oxygen-poor and nutrient-rich signature of EBUS into the gyre interiors. In the Pacific, transport by subsurface coherent eddies accounts for roughly 10% of the offshore transport of oxygen and nutrients in pycnocline waters. This “leakage” of subsurface waters can be a significant fraction of the transport by nutrient-rich poleward undercurrents and may contribute to the well-known reduction of productivity by eddies in EBUS. Furthermore, at the density layer of their cores, eddies decrease climatological oxygen locally by close to 10%, thereby expanding oxygen minimum zones. Finally, eddies represent low-oxygen extreme events in otherwise oxygenated waters, increasing the area of hypoxic waters by several percent and producing dramatic short-term changes that may play an important ecological role. Capturing these nonlocal effects in global climate models, which typically include noneddying oceans, would require dedicated parameterizations. Without such parameterizations, models may miss potential non-linear effects of subsurface coherent eddies under global warming, for instance arising from the interplay of changes of productivity, the depth of the oxygen minimum zones, and the depth of the density layer hosting such eddies.
(18) Mechanisms that determine the dynamics of oxygen in the eastern equatorial Pacific in an Earth system model

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Until now, biogeochemical ocean models have generally failed to reproduce the observed oxygen decline in the eastern equatorial Pacific (EEP) over the last decades. We here give an overview about mechanisms that determine the sensitivity of oxygen dynamics in an Earth system model of intermediate complexity in the EEP to climate change. Earth System Climate Models generally overestimate nutrient concentrations in the deep eastern equatorial Pacific. This problem, dubbed “nutrient trapping” by Najjar (1993) already, causes spurious suboxia in the tropical oceans of typical coarse-resolution models. Parameterizing the effect of the unresolved Equatorial Intermediate Current System (EICS) by an (anisotropically) increased zonal isopycnal diffusivity in the tropics improves the simulation of oxygen and nutrients globally. Notably “nutrient trapping” and associated model deficiencies are reduced. Climate projections of low-oxygenated waters change sign and become more plausible if the effect of the EICS is parameterized. In addition to the effects of the EICS we elucidate the effects of changing winds on oxygen levels in the tropical Pacific: Investigating the impact of observed past and anticipated future wind changes in the Southern Hemisphere, we distinguish effects due to a strengthening of the westerlies from effects of a southward shift of the westerlies that is accompanied by a poleward expansion of the tropical trade winds. The poleward shift of the trade-westerlies boundary triggers a significant decrease of oxygen in the tropical oxygen minimum zone. In a business-as-usual CO₂ emission scenario, the poleward shift of the trade-westerlies boundary and warming-induced increase in stratification contribute equally to the expansion of suboxic waters in the tropical Pacific. Further we apply different wind climatologies (NCEP/NCAR and CORE-normal-year) and observed wind fields (CORE, 1947-2007) to a coupled biogeochemistry circulation model. The Equatorial Undercurrent (EUC) shows significant differences in strength and structure depending on the applied wind forcing. On multi-decadal time scales, changes in oxygen concentrations in the upper 1000m of the EEP are predominantly forced by wind driven changes of the EUC, whereas preconditioning of the oxygen fields during the model's spin up plays a minor role. For future projections of the oxygen deficient water volume in the EEP the reliability of projected wind fields are of key importance.

(19) Local and remote controls on oxygen content: early results from an adjoint sensitivity study

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Oceanic oxygen content is influenced by many physical and biogeochemical factors, representing the integrated effects of local and remote drivers across a wide range of timescales. In this study, we use a global ocean adjoint model to quantify the sensitivity
of the oxygen content in the tropical Pacific oxygen minimum zone (OMZ) to local and remote (i.) surface forcing (e.g. wind stress, heat flux) and (ii.) biogeochemical anomalies on annual-to-decadal timescales. Adjoint sensitivity fields can potentially inform the development of future observational networks by highlighting locations that remotely influence oxygen values in the OMZ. In addition, sensitivity fields may help with the diagnosis of Earth System Model output by identifying key local and remote drivers of OMZ variability.

(20) Interannual variability of the Eastern South Pacific OMZ off Chile (30°-38°S): a modelling study

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One of the most large oxygen minimum zone (OMZ) is located in the Eastern South Pacific. It extends southward along the Chilean coast due to the Peru-Chile Undercurrent (PCUC), which transports Equatorial Subsurface Water (ESSW) (characterized by low dissolved oxygen, high nutrients and relatively high salinity) along the slope. Despite the importance of this OMZ on the biogeochemical cycles and regional oceanographical conditions, the main processes controlling its variability remain rather unknown. Here, we assess the interannual variability of the southern tip of the OMZ off Chile (30-38°S) using a high-resolution regional physical-biogeochemical coupled model simulation for the period 2000-2008. First, we describe the main features of the OMZ: its volume, the mean DO, its spatial variability and mean depth. Then, we relate these characteristics with some relevant climatic indices for the Pacific, like different ENSO indices, including the El Niño Eastern Pacific (EP), El Niño Central Pacific (CP), and the Pacific Decadal oscillation (PDO) and the Southern Annular Mode (SAM). Additionally, we contrast the periods of more intense (lower values of DO) and weaker OMZ during the study period, and we analyze the mechanisms that would be associated to these extrema. The OMZ volume showed a significant correlation (r=0.6) with the equatorial indices (ONI, CP and MEI) and with PDO (r=0.5), but a lower correlation (r<0.3) with SAM. Maximum and minimum values of the OMZ-volume anomalies were observed during 2001 and 2007 respectively. In 2001, the OMZ-volume increase up to ~33% related to the mean value for the study period, displaying a large decrease in the mean oxygen concentration, together with a greater offshore and southward extension, as well as an increase in temperature and salinity. In contrast, in 2007, the OMZ volume was reduced by ~23% and became more oxygenated, showing a lesser offshore and southward extension, together with a decrease in temperature and salinity. These changes of the OMZ were related to changes in the PCUC transport, i.e., positive (negative) OMZ volume anomalies were mostly related with the intensification (weakening) of the PCUC. We observed that highest correlation (r=0.8) between the PCUC and the oxygen concentration inside the volume rather than with the volume itself variability. An important fraction of the interannual variability of the PCUC off central Chile, and thus the southern tip of the OMZ, is of equatorial origin and it covaries with the ENSO, and likely with other fluctuations that modulate the tropical Pacific.
(21) Sensitivity of the oxygen levels to the CORE-II and JRA55 forcing dataset in a high resolution model of the tropical Atlantic Ocean

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Along the eastern boundaries of the eastern tropical Atlantic (ETA), intense oxygen minimum zones (OMZs) at intermediate depth result from the large remineralization of organic matter and the weak interior ventilation. The ETA is ventilated in the upper thermocline by the equatorial undercurrent (EUC). A part of the water transported by the EUC originate from the oxygen-rich subtropical regions, where subduction processes occur. The connection between subtropics and tropics is effectuated by wind driven shallow circulation cells, called subtropical-tropical cells (STC). To quantify the importance of the oxygen supply (in particular by the EUC and the STC) and the biological consumption, we perform simulations using an eddy resolving (1/10°) ocean model, embedded by a two-way nesting approach in a global coarse resolution model and coupled to a previously calibrated biogeochemical model that simulates phosphorus, oxygen, and nitrogen fluxes (MOPS-1.0). We perform two inter-decadal (1948 – 2007) experiments using two different atmospheric forcing data sets, CORE-II and JRA55-do. We show that the strength of the wind stress has a significant impact on the ocean circulation, the respiration rate and ultimately the oxygen levels.

(22) Ventilation of the oxygen minimum zone in the Arabian Sea

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In the Arabian Sea, at intermediate depth an open ocean oxygen minimum zone (OMZ) is predominant throughout the year. However it is shifted eastward away from the region of high biological productivity. It is still under debate which physical and biogeochemical mechanisms are causing the maintenance of the Arabian Sea OMZ. The presented analysis improves the understanding of oxygen supply into this region. The ventilation pathways of source waters from the marginal seas and their temporal as well as spatial variability are analyzed based on reanalysis velocity data from the dynamic ocean model Hycom (Hybrid Coordinate Ocean Model). A model based simplified backward trajectory analysis on isopycnals reveals that the eastern part of the Arabian Sea OMZ is ventilated by Red Sea Water as well as Persian Gulf Water that circle clockwise the perimeter of the basin. It is notable that there is no evidence for a more direct pathway into the interior basin. Ventilation time scales into the east exceed those into the western basin. Beside seasonal variability in the mean current location and strength, also eddy mixing plays an important role in the ventilation.
(23) Ventilation variability of Labrador Sea Water and its impact on oxygen changes

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In a recent review paper we provided an overview of the changes of Labrador Sea Water (LSW) from observations in the Labrador Sea and the southern boundary of the subpolar gyre along a transect at 47°N. The strong connection with reduction/intensification of convection and reduction/intensification of oxygen supply in the LSW, due to reduction/intensification of ventilation was showed for the time period 1996-2016. Intense and deep convection like the one in the early to mid-1990s in the Labrador Sea, produced thick, dense and well oxygenated LSW, while weak convection like the one in the following years (1997-2005) produced shallower, thinner and less oxygenated LSW. The latter time period deep convection was resumed and starting in winter 2013/2014 production of denser, thicker and more oxygenated LSW was resumed. All these changes can be followed with some delay in the western boundary currents at 47°N along the pathway of the LSW. On multi-decadal time scales climate models predicts a weakening of the Atlantic Meridional Overturning Circulation (AMOC), followed by a weakening of convection and thus deoxygenation of the LSW. Here we will extend the analysis by including the latest cruises in 2017 and 2018.

(24) A 12-years transient tracer time series to detect changes in ventilation in the Eastern Tropical North Atlantic oxygen minimum zone

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Significant decadal variability in ventilation has been documented from a time series of nine hydrographic surveys with transient tracer measurements in the Eastern Tropical North Atlantic Oxygen Minimum Zone (ETNA-OMZ) between 2006 and 2018. The changes in ventilation were identified by using transient tracer (CFC-12 and SF6) measurements and the mean age was calculated by using the Transit Time Distribution (TTD) method with standard parameterization. The changes of the tracer concentrations were calculated on density surfaces in the OMZ core at σθ=27.0 kg m⁻³ as well as above and below at 26.8 and 27.2 respectively. The survey area was separated into four sub-areas (NE, NW, SE and SW) and each sub-area into 5 by 5 fields for statistical purpose to resolve the changes in a spatial perspective. Furthermore, the data was separated into specific salinity ranges to track the relation of the two main water masses in this density range. The tracer distribution on density surfaces shows an overall trend of increasing tracer concentration throughout the water column over time. However, the concentration increase is non-monotonic and shows clear temporal variability on all density surfaces. The highest spatial variability is shown in the OMZ core with a clear north-south and west-east gradient from high to low concentrations. The mean age, on the other hand, appears to be relatively
constant over time except for the last three years where the water masses got younger with most significant changes in the NW area on all density surfaces. The spatial variability shows a general trend of increasing ages from north to south and west to east. The water mass perspective by salinity ranges shows a more steady change in ventilation with less decadal variability. The increase in ventilation and thus the decrease in mean age is also most prominent for the Eastern North Atlantic Central Water (ENACW). The oxygen distribution however is decoupled from the mean age distribution. A decrease in ventilation is not necessarily manifested as a decrease in the oxygen, and vice versa. The oxygen budget is thus not only related to the changes in ventilation. The variability in oxygen consumption within the OMZ or the oxygen utilization rates along the flow pathway modulates the oxygen budget independent of ventilation.

**(25) Drivers of long-term oxygen changes and influence on nutrient changes in the Pacific Ocean**

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For recent decades a rather rapid change in dissolved ocean oxygen (DO) was found in observations and numerical models respectively. Tropical and subtropical DO decreased in most regions of the world ocean. These DO trends are a combination of long-term trends superimposed with (multi-) decadal and short-term variability. The exact processes at play remain elusive. Here we show some of the identified drivers of deoxygenation separated for the upper ocean above 1200 m as well as for the deep ocean below 1200 m. The marked drivers are solubility and stratification, decline and increase in source waters, (overturning) circulation changes, nutrient stimulation via upwelling and multidecadal variability like the Pacific Decadal Oscillation (PDO). Observed nutrient changes seem to be related to oxygen changes modified by local and eddy processes. In addition the oxygen and nutrient changes in some regions of the Pacific Ocean where longer time series exist are investigated in relation to the PDO for the period since 1950. In subsurface layers (e.g. 50-300 m) in the eastern Pacific the oxygen content increased often during the cold PDO phase until 1976 and decreased after 1977. Nutrient trends are more variable related to local processes; however nutrients often show a reversed trend to the oxygen trend. El Niño and La Niña events modify the measured oxygen and nutrient content during the year of these events. Anticyclonic eddies e.g. off Peru carry oxygen-poor, nitrate-poor and nitrite-enhanced water westward into the open South Pacific Ocean. Silicate and phosphate in anticyclonic eddies show a vertical expansion of their characteristics at the depth of core layer of the eddy.
**Microbial Communities and their Impact on Biogeochemical Cycles in Oxygen Minimum Zones**

**Topic abstract**

Oxygen minimum zones (OMZs) in the ocean are created by microbial respiration during organic matter degradation. They host a diverse range of microorganisms that are capable to grow under reduced oxygen or even anoxic conditions. Depending on the availability of oxygen and other electron acceptors, microbial communities display a variety of heterotrophic and autotrophic processes that influence marine element cycling, notably of carbon, nitrogen and sulfur, but also for trace metals. Understanding the complex interplay between oxygen sensitivity of microbial processes and other controlling factors, such as the availability of organic and inorganic substrates, temperature and pH, is essential to estimate the role of OMZs in biogeochemical cycling. This session invites presentations on all aspects of microbial life under reduced oxygen conditions. We welcome field, experimental and modelling studies that give insight into the role of bacterial and archaeal communities in OMZs, their growth and losses, contribution to biogeochemical transformations, as well as technical innovations to investigate microbial life under hypoxic conditions.

**Conveners:**
- Anja Engel // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
- Klaus Jürgens // Leibniz Institute for Baltic Sea Research Warnemünde, Germany
- Tina Treude // University of California, Los Angeles, USA

**KEYNOTE SPEAKERS**

**04.09. TUESDAY | 10:45**

**New microbial players in oxygen minimum zone biogeochemistry**

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Key microbial players from oxygen minimum zones (OMZs) have been identified, but the majority remains unrecognized or uncharacterized. The application of single-cell genomics – in combination with microbial-community gene content, transcription, and process rate measurements – offers the possibility to gain some insight into the distribution, metabolic potential, and activity of previously uncharacterized bacterial and archaeal groups. Such approach is revealing new potentially import players for OMZ biogeochemistry, as well as the presence of some apparently overlooked pathways. Quantifying the importance of such microbial processes at the local and global scale and putting them into a general ecological framework remain a challenge.
Osvaldo Ulloa | Osvaldo Ulloa received his Master’s (1987) and his PhD (1992) from Dalhousie University, Canada, working in phytoplankton ecology and marine bio-optics, respectively. His postdoctorate work was carried out at the Niels Böhr Institute of the University of Copenhagen, where he worked on the carbon cycle.

Ulloa returned to Chile in 1997 and joined the University of Concepcion, where he is currently a full Professor at the Department of Oceanography and director of the Millennium Institute of Oceanography (IMO). He has trained undergraduate and graduate students in marine biology and oceanography. He has received several postdoctoral fellows, from Chile and abroad, in his lab. For over a decade, he has been one of the organizers and co-directors of the international course “Ecology and Diversity of Marine Microorganisms (ECODIM)” which has proven to be fundamental in the creation of a new generation of marine microbial ecologists in Latin America.

His most relevant scientific contributions have been in the area of biological oceanography, particularly in the study of the factors that determine the distribution patterns of phytoplankton and the microbial diversity and biogeochemistry of oxygen deficient marine environments. Ulloa’s research focus are microbial communities in marine oxygen minimum zones, particularly those of the eastern tropical south Pacific, and he and his group have contributed numerous new insights on their diversity, role in biogeochemical cycles and their genomic adaptations to this environment. Osvaldo Ulloa participates also since long in international working groups (e.g. SCOR), dealing with marine deoxygenation and the response of the microbial communities in those systems.

04.09. TUESDAY | 11:20

Nitrogen biogeochemistry of oxygen minimum zones: what controls the distribution of microbes and N transformation reactions?

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Oxygen minimum zones are distinguished by characteristic distributions of the inorganic nitrogen compounds nitrate, nitrite, and nitrous oxide. Although many of the reactions that produce and consume these compounds are known, the mechanisms by which characteristic features, such as the secondary nitrite maximum and the subsurface nitrous oxide maximum, are maintained are not clear. Oxygen is one of the most important constraints on the distributions of chemistry and microbial reactions. Nevertheless, there is evidence for “incompatible reactions”, such as oxidation of nitrite in the absence of oxygen and consumption of nitrous oxide in the presence of oxygen. Data from stable isotope tracer incubation experiments, distributions of natural abundance of stable isotopes, and molecular data on the composition, diversity and distribution of microbes and their key functional genes
related to these processes will be considered. These data will be used to characterize the functional response of microbial N transformations involved in nitrite and nitrous oxide production and consumption in relation to oxygen concentration and other variables. Relationships between rate measurements and molecular data will be used to investigate the depth distribution of microbes, processes, and chemistry, and to develop hypotheses about control of the “incompatible reactions”.

Bess Ward | Since 2006, Bess Ward is the Chair of the Department of Geosciences at Princeton University, New Jersey, USA. She received her Ph.D. in Biological Oceanography from the University of Washington, Seattle, focusing on the process of nitrification. During her postdoctoral years at Scripps Institution of Oceanography, Ward continued to study nitrification, but also turned her attention to the oxidation of methane. Both methane and the traces gases produced during nitrification are powerful greenhouse gases and their fluxes from the ocean are largely unknown. Ward taught and did research in the Ocean Sciences Department at the University of California, Santa Cruz for nine years before moving to Princeton University in 1998. Her current interests include many aspects of the marine nitrogen cycle, especially nitrification, denitrification and anammox, nitrous oxide cycling, phytoplankton nitrogen assimilation and new production. Ward's research program involves molecular biological research in the laboratory, as well as research expeditions in pursuit of samples and field experiments. Her current programs involve everything from stable isotope experiments to the development of DNA microarrays to investigate N assimilation by phytoplankton. She is a fellow of the American Academy of Microbiology, a Fellow of the American Geophysical Union, and the youngest and first female winner (1997) of the G. Evelyn Hutchinson award.

04.09. TUESDAY | 11:55

Anaerobic methane oxidation is an important sink for methane in the ocean’s largest oxygen minimum zone

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The eastern tropical North Pacific (ETNP) harbours the largest of the oceans' three major oxygen minimum zones and is further characterized by what appears to be the largest open-ocean accumulation of methane, with peak concentrations located in the anoxic core. Benthic methanogenesis is a major methane source in the ETNP OMZ but it remains unknown to which extent methane is cycled within the OMZ or released to the surrounding oxic waters, thus representing a source of methane to the
atmosphere. However, the recent discovery of transcriptionally active bacteria closely related to the anaerobic methanotroph “Candidatus Methylomirabilis oxyfera” of the NC10 clade in OMZs, suggests that the OMZ methane pool might be more dynamic than previously recognized. We measured methane oxidation rates in anoxic incubations of ETNP OMZ waters using tritium-labelled methane. The highest rates were found at depths intermediate between the secondary nitrite maximum and the deeper peak in methane concentrations within the OMZ core. By contrast, activity was at or below detection in the lower oxycline and at the oxic/anoxic interface. In oxygen addition experiments the process was inhibited by low micromolar oxygen concentrations, which further indicated an anaerobic metabolism, possibly performed by nitrite-dependent NC10 bacteria. The rate constant of anaerobic methane oxidation was approx. 0.3 y⁻¹. Given available estimates of water residence time, this implies that anaerobic methane oxidation is a substantial methane sink in the ETNP OMZ and hence attenuates the emission of methane from this and possibly other oxygen minimum zones.

Bo Thamdrup | Bo Thamdrup is Professor for geomicrobiology at the Department of Biology, University of Southern Denmark in Odense. Bo completed a M.Sc. in biology and chemistry, and a Ph.D. on the biogeochemical cycling of manganese, iron, and sulfur in marine sediments, at the University of Aarhus, Denmark, and subsequently worked for five years as a researcher with Bo Barker Jørgensen at the Max Planck Institute for Marine Microbiology in Bremen. He moved to Odense in 1998 where he was associated to the Danish Centre for Earth System Science and, subsequently, the Nordic Centre for Earth Evolution. Bo is known for his explorations of how microbes through their diverse metabolisms contribute to element cycling on local to global scales, and to Earth’s biogeochemical evolution. Bo’s contributions include quantification of the role of microbial iron and manganese reduction in the aquatic sediments, discovery of a new microbial metabolism: disproportionation of elemental sulfur as an important link in oxidative sulfur cycling, and the discovery, that anaerobic ammonium oxidation by anammox bacteria is an important sink for fixed nitrogen in natural environments. During the past decade, much of Bo’s research has focused on the geomicrobiology of oceanic oxygen minimum zones, particularly the distribution and interactions of microbial nitrogen transformations and, after the development of the highly sensitive STOX oxygen sensor by Niels Peter Revsbech, how these and other microbial processes are controlled by oxygen at nanomolar levels.
Nitrogen (N) is an essential nutrient that limits productivity in large parts of the world ocean. While denitrification and anammox are the major processes responsible for the removal of this nutrient from the oceans, input occurs mainly through nitrogen fixation. Estimates of marine N budgets suggest that losses exceed inputs, while models imply that nitrogen fixation should be enhanced in the vicinity of oxygen minimum zones, where the loss processes occur. Based on analysis of nifH, a key gene in nitrogen fixing microbes, we found that several clades of N-fixers are present and active in the OMZ and surface euphotic waters in the Eastern Tropical South Pacific (ETSP), Eastern Tropical North Pacific (ETNP) and Arabian Sea. These OMZ regions contain substantial nifH diversity, in both surface and anoxic waters. Surface waters contained greater diversity, but that was not due to presence of the well-known diazotroph, Trichodesmium, or other cyanobacteria. Sequences related to Trichodesmium were rare in the combined clone libraries from these three regions and were detected only in surface waters (Cluster I nifH), along with proteobacterial nifH phylotypes. Most of the new sequences in three of the four Clusters of the conventional nifH phylogeny were not closely related to any sequences from cultivated Bacteria or Archaea. Cluster II was not represented in the OMZ samples. The most abundant Cluster I OTUs could be assigned to the Alphaproteobacteria, followed by the Gammaproteobacteria. nifH DNA and cDNA sequences with high identities to those of anaerobic microbes (Clusters III and IV nifH) were found in the anoxic waters. Although similar groups of nifH sequences were present in the three OMZs, strictly anaerobic sequences (Cluster III and IV) were better represented in the ETP ODZs. Most of the OTUs were not shared among regions, depths or DNA vs cDNA and sometimes were restricted to individual samples. While measurements of N2 fixation rates are not reported here, the abundance of cDNA sequences, estimated from quantitative PCR, implies that the genes are expressed and the cells harboring them are active. We previously reported low, but analytically significant, rates in anoxic depths in the ETNP, indicating that non-cyanobacterial N fixation might make a small contribution to the N budget of the ocean. Future work should focus on determining to what extent the diversity we detected actually represents biogeochemically significant reactions and what factors might control the activity of diazotrophs in the dark ocean.

Oceanic N2O emissions to the atmosphere represent up to 35 % of the global natural sources, and oxygen minimum zones (OMZs) are the major sites for net
N₂O production. In order to understand what controls net N₂O fluxes, and whether the magnitude of N₂O production might change in response to global climate and environmental change, it is necessary to determine the factors that influence the major microbial pathways (nitrification and denitrification). The potential niche overlap of nitrifiers and denitrifiers in OMZs makes it difficult to distinguish between these two N₂O sources. We used a combination of qPCR and functional gene microarrays targeting, nirS gene for denitrification and amoA gene for ammonium oxidation, to access how the abundance and structure of the community impacts N₂O production rates. The influence of natural and manipulated oxygen gradients and particulate organic matter on the regulation of different marine N₂O production pathways was investigated in the Eastern Tropical South Pacific (ETSP) using 15N tracer incubation techniques. Highest N₂O production rates from nitrate - up to 11.7 ± 0.9 nM N/d - occurred at the oxic/anoxic interface. Oxygen inhibited N₂O production from nitrate, nitrite and ammonium. The addition of in situ particulate organic matter stimulated N₂O production from nitrite and nitrate by a factor of up to 5.1 and 3.4 respectively. Denitrification is a major source of N₂O in the OMZ of the ETSP. Hence, in the coastal area off Peru, short-term variability in oxygen concentrations and increased organic matter flux leads to imbalances in N₂O production vs. consumption processes, which may result in high net N₂O flux.

**Microbial degradation activity and organic matter lability in the oxygen minimum zone off Peru**

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Within oxygen minimum zones (OMZs) microbial biogeochemical cycling is adapted to limited availability of oxygen (O₂). Earlier studies suggested higher efficiency of carbon export in those regions due to reduced microbial degradation activity. However, previous findings on the effect of O₂ on microbial activity are ambiguous and compared to nitrogen cycling little is known about microbial degradation activity within OMZs. Here, we present first results on bacterial biomass production (estimated by 3H leucine incorporation) and rate measurements of the extracellular enzyme leucine aminopeptidase, for the OMZ off Peru. Additionally, we estimated the uptake of dissolved organic carbon (DOC) and lability of dissolved organic matter, defined by combined carbohydrates and amino acids. We observed no significant reduction in bacterial biomass production (20 ± 26 μmol C m⁻³ d⁻¹), or leucine aminopeptidase rates (49 ± 22 nmol L⁻¹ h⁻¹) and no reduced cell abundance (8 ± 4 x10⁵ ml⁻¹), in core of the OMZ (<5μM O₂) compared to more oxygenated waters (34 ± 44 μmol C m⁻³ d⁻¹ and 34 ± 20 nmol L⁻¹ h⁻¹, 9 ± 2 x10⁵ ml⁻¹) at the upper and lower oxyclines (5-60 μM O₂), suggesting that the microbial degradation rate does not slow down under low O₂ conditions. Additionally, changes in dissolved organic matter composition between the OMZ core and the lower oxycline suggest active microbial organic matter degradation in the anoxic waters. Our results suggest that microbial degradation of organic matter significantly contributes to the formation of the OMZ off Peru and can proceed at relatively high rates within anoxic waters. This indicates
that carbon dioxide production by heterotrophic microbial degradation in the OMZ off Peru is not necessarily reduced under anoxia and driven by anaerobic heterotrophic respiration pathways like denitrification.

**Eukaryotic denitrification pathway of benthic foraminifera thriving in oxygen-depleted environments**

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Foraminifera are a group of amoeboid protists commonly found in various marine habitats. Several benthic foraminiferal species are known to store nitrate and use it for complete denitrification, a unique energy metabolism among eukaryotes. This property and their high density in sediments of oxygen-depleted zones, pinpoint them as important players in the oceanic nitrogen cycle. Recent estimates of the foraminiferal contribution to the total benthic denitrification in the OMZ reach up to 100%; and thus are important to constrain the biologically available nitrogen in coastal water. The mechanisms of foraminiferal denitrification are however still unknown and a contribution of associated bacteria is discussed. Here we present evidence for a novel eukaryotic denitrification pathway that is encoded in the foraminifera genomes. The presence of a denitrification pathway in ten Peruvian species thriving in oxygen minimum zones and two further species populating oxygen-depleted environments in Sweden was revealed by a large-scale sequencing of genomes and transcriptomes. These pathways include the enzymes nitrite reductase (NirK) and nitric oxide reductase (Nor) as well as a wide range of nitrite/nitrate transporters (Nrt). Furthermore, we uncovered evidence for a prokaryotic origin of the foraminiferal denitrification pathway and an ancient emergence of this trait via phylogenetic reconstruction. We propose a model for foraminiferal denitrification where a common electron transport chain is used for anaerobic and aerobic respiration. The evolution of hybrid respiration in foraminifera likely contributed to their ecological success that is well documented in paleontological records since the Cambrian.
Isotopic fingerprints of benthic nitrogen cycling in the Peruvian oxygen minimum zone

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Stable isotopes ($^{14,15}$N, $^{16,18}$O) of dissolved inorganic nitrogen (N) were measured in sediment porewaters and benthic flux chambers across the Peruvian oxygen minimum zone (OMZ) from 74 to 1000 m water depth. Sediments at all locations were net consumers of bottom water NO$_3^-$ in waters shallower than 400 m, this sink was largely attributed to dissimilatory nitrate reduction to ammonium (DNRA) by communities of filamentous nitrate-storing bacteria (Marithioploca and Beggiatoa) and to denitrifying foraminifera. The $\delta^{15}$N of their collective intracellular NO$_3^-$ pool was >30 ‰. The apparent N isotope effect of benthic NO$_3^-$ loss was 7.4 ± 0.7 ‰ at microbial mat sites and 2.5 ± 0.9 ‰ at the lower fringe of the OMZ (400 m) where foraminifera were abundant. Model simulations of the data generally support a previous hypothesis (Prokopenko et al., 2013) attributing the $^{15}$NH$_4^+$ enrichment to a close coupling of DNRA and anammox (DAX) using NO$_2^-$ supplied by Marithioploca and NH$_4^+$ form the porewater. The model predicts that 40 % of NO$_3^-$ actively transported into the sediment by Marithioploca is lost as N$_2$ by DAX. This enhances N$_2$ fluxes by a factor of 2 – 3 and accounts for 70 % of fixed N loss to N$_2$. By limiting the flux of $^{15}$NH$_4^+$ back to the ocean, DAX tends to decrease overall benthic N fractionation. Knowledge of the sink of NH$_4^+$ once it leaves the sediment is critical for understanding how the benthos contributes to the N isotope effect in the water column.

Untangling the key drivers in oxygen minimum zone (OMZ)-influenced waters that shape natural plankton assemblages

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The eastern tropical South Pacific Ocean (ETSP) contains one of the largest oxygen minimum zones (OMZ) in the world, with a pronounced impact on nutrient cycling and stoichiometry in the region. Low oxygen concentrations support nitrogen loss and release of sedimentary phosphorus, leading to inorganic macronutrient nitrogen to phosphorus ratios (N:P) in upwelled waters well below the Redfield ratio (16:1). Field studies and bioassays indicate that inorganic macronutrient N:P influences phytoplankton community composition, which will likely influence trophic transfer and organic matter partitioning. However N:P in inorganic nutrients is not the only defining characteristic of upwelled waters from subsurface layers. In addition, dissolved organic matter (DOM) concentration and composition, trace
metal concentration and bioavailability, and the seed microbial community will also depend on the origin of a water parcel and its history of oxygenation. In this study, our aim was to distinguish key drivers (inorganic nutrient N:P, seed microbial community, DOM/trace metal availability) of the lower food web response to water influenced by the OMZ in the ETSP. We collected water with two distinct nutrient signatures (N:P~4 and 1 for moderate and strong OMZ, respectively) from different locations in the coastal Peruvian upwelling region. These waters were then added to a surface phytoplankton community resulting in 3 treatments for each N:P ratio (filtered, unfiltered, inorganic nutrient addition). Here, we report on the key drivers of particulate and dissolved matter dynamics and the response of the phytoplankton community biomass and composition during this short-term incubation study.

A metatranscriptomics/metagenomics approach to obtain insights into the biogeochemistry of the suboxic zone of the Black Sea

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The Black Sea has a characteristic “suboxic” transition zone at the interface between the oxic and anoxic water layers that is known as an important site of element transformations. However, the interaction between the biogeochemical structure of the water column and the depth zonation of microbial activities is not yet understood. We used high-resolution chemical profiling together with an analysis of prokaryotic community structure (16S rRNA genes), heterotrophic and chemoautotrophic production, metagenomics analysis of dominant prokaryotes, and expressed genes (metatranscriptomics) to gain insights into the stratification of specific activities as well as the responsible prokaryotic key players. For unbiased gene expression profiles, an automated in situ fixation sampler was used. The dominant prokaryotes included several groups globally distributed in oxygen minimum zones, such as Thaumarchaeota, SUP05 cluster, Marinimicrobia, and Sulfurimonas, but also several taxa that seem to be characteristic for the Black Sea redoxcline. Quantitative analysis of expressed functional genes reflected a distinct vertical zonation of major biogeochemical transformations, including archaeal ammonia oxidation, anammox, and chemoautotrophic denitrification in conjunction with sulfur oxidation. However, for several transformations suggested by functional gene expression the underlying redox reactions remain unclear because the respective depths were devoid of known substrates for some of the processes (e.g., denitrification).
Ecological strategies of sulfur-oxidizing bacteria in responses to the changing marine environment

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Sulfur (S) is a major element on Earth. It is also a bioessential element for all living organisms. The transformation and mobilization of sulfur in biosphere, lithosphere, atmosphere, and hydrosphere constitute the Earth’s S cycle, which are mainly driven by microorganisms. Sulfur oxidation is a major process in the cycling of S that involves diverse redox reactions. Diverse marine bacteria and archaea have been found to carry out this environmentally and biogeochemically important function. Element S and reduced inorganic sulfur compounds are excellent energy sources and electron donors that support phototrophy and chemotrophy in sulfur-oxidizing bacteria (SOB). Recently, some bacteria originally thought to carry out sulfate reduction were found to actually perform sulfur oxidation instead, expanding the SOB diversity by including the Deltaproteobacteria and Thermodesulfobacteria lineages. Besides using O₂ as a terminal electron acceptor, many SOB can also use nitrate and nitrite as terminal electron acceptors for carrying out sulfide oxidation under anoxic condition. The diverse SOB and their metabolic pathways adds more motives for their research. With the expansion of coastal hypoxia and open ocean OMZs under the impacts of increased anthropogenic activities and global change, SOB may play more important roles in the biogeochemical cycling of carbon, nitrogen and sulfur in the future ocean.

Pathways of gravitational particle export in the peruvian OMZ

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Oxygen minimum zones (OMZs) may expand in the future with important consequence on biogeochemical cycles. In well-oxygenated waters, temperature and plankton community structure are known as the main factors affecting the magnitude of the biological carbon pump, an ecosystem service that buffers the atmospheric CO₂ concentration. In oxygen deficient waters, observations suggest that the efficiency with which the POC is transported to depth is larger relative to oxygenated waters regardless of the temperature or the plankton community. The expansion of OMZ could therefore increase the global magnitude of the biological carbon pump. The underlying mechanisms by which low O₂ concentrations enhance the flux of POC are however poorly understood or partially demonstrated. Several explanations were proposed: (1) the absence of zooplankton leading to less consumption on particles and a limited presence of fast sinking carbon rich fecal; (2) the quality of the organic matter exported as particles differs in OMZ; (3) the reduced efficiency with which heterotrophic prokaryotes respire organic matter (OM) and (4) the potential addition of OM produced from dissolved inorganic carbon by chemoautotrophic prokaryotes attached to sinking particles. Although all the above mechanisms do enhance the flux of POC in O₂ deficient regions, they were only established and tested individually in various OMZ. This prevents the unequivocal identification of the prevailing mechanism. Moreover, the extent to which empirical relationships between
temperature and flux attenuation remains valid in low O₂ regions is unknown. Recently, (Cisternas-Novoa et al., companion paper) made extensive measurements of mesopelagic POC fluxes in the Peruvian OMZ. Locally, flux attenuation coefficients yielded to a wide range of values (from 0.3 to 1.0) despite the small ranges of top 500m median temperatures and O₂ concentrations (from 11 to 14°C and 2.0 to 2.4 μmol kg⁻¹ respectively). This suggests that other factors may shape the variability of the flux attenuation in this region. We will further examine this pattern by examining and quantifying the carbon fluxes carried by various ecological routes (phytodetritical aggregates vs fecal pellets) using polyacrylamide gels placed in two drifting sediment traps. We couple this novel approach to traditional information on the biogeochemical quality/quantity of the particle flux. In essence, we are looking at which gravitational downward export pathway dominates the particle flux from the euphotic zone and through the (partly anoxic) mesopelagic zone. We further confront our results to proposed mechanisms as to why fluxes of C are larger in OMZs.

**The role of marine snow for nitrogen loss from oxygen minimum zones**

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Oxygen minimum zones (OMZs) are regions of the ocean where the depletion of oxygen leads to favorable conditions for microbial nitrogen (N) loss processes. Although OMZs make up less than 1% of the global ocean (oxygen < 20 µM), they host 20-40% of global oceanic N-loss through the processes of denitrification and anammox. Recent studies indicate that marine snow aggregates play a vital role in OMZ N-loss by transporting organic matter from surface layers to the ocean interior. Aggregates are also hotspots of microbial activity, and it is speculated that a large proportion of N cycling occurs within and around aggregates. However, due to their fragile nature and difficulties in sampling, studies on single aggregates are limited and N-loss determinations are mostly based on bulk water incubations, which likely exclude sinking aggregates. To investigate the role of single aggregates in OMZ N cycling, we collected > 200 aggregates with sizes larger than 0.3 mm from the OMZ offshore Peru using a marine snow catcher. The aggregates, together with bulk water samples, were incubated and amended with stable nitrogen isotopes (¹⁵N) to determine anammox and denitrification rates. Based on our bulk water incubations, the areal anammox rates ranged between 1.7 and 10 mmol N₂ m⁻² day⁻¹, with highest rates observed at coastal stations. Denitrification occurred more sporadically than anammox, ranging between 1.0 and 1.9 mmol N₂ m⁻² day⁻¹. In contrast, N₂ production by denitrification was detected in the majority of the single aggregate incubations with rates in the range of picoto nano-mole N per aggregate per day. Denitrification associated with these large (> 0.3mm) marine snow aggregates contributed between 2.5% and 50% to total N-loss from the investigated OMZ waters. Anammox rates
Deep Maximum of virus-bacterial ratio in oxygen minimum zone in the South China Sea: preliminary evidence for viral control of bacterial depletion of oxygen

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The oxygen minimum zone (OMZ) in deep water column of the oceans is over hundreds of years old and receive constant supply of organic matter from water above, but oxygen does not reach anoxia. Bacterial respiration is largely responsible for oxygen consumption in the OMZ and hence, any process that limits bacterial abundance and respiration contributes to the variation of OMZ. We hypothesize that viruses play an important role in limiting bacterial abundance in the OMZ and regulating the consumption of oxygen in the OMZ. We tested the hypothesis during a cruise conducted in September 2005 in the deep South China Sea. The results revealed the double maxima in the ratio of viral to bacterial abundance (VBR) in the water column: the deep maximum at 800-1000 m in the OMZ and the subsurface maximum located at 50-100 m near the subsurface chlorophyll maximum (SCM) layer. At the deep maximum of VBR, both viral and bacterial abundance were reduced with viral abundance being reduced less than bacterial abundance, whereas at the subsurface maximum of VBR, both viral and bacterial abundance increased to the maximum, with viral abundance increasing more than bacterial abundance. The evidence suggests that the two VBR maxima are formed due to different mechanisms. When abundant supply of organic matter at the chlorophyll maximum increases bacterial growth, viral abundance is stimulated and can increase faster, resulting in the VBR maximum. In contrast, in the OMZ, organic matter has been consumed and limits bacterial growth, but viruses are less limited by organic matter and continue to infect bacteria, leading to the maximum VBR. Such viral control of bacterial abundance is a potential mechanism responsible for slowing down the decrease to anoxia in oxygen in OMZ. Our finding provide a piece of evidence that viruses are an important player in controlling bacterial abundance when bacterial growth is organics-limited, and thus, regulate decomposition of organic matter, oxygen consumption and nutrient remineralization in the deep oceans.
POSTER PRESENTATIONS

(26) Lipidomics of microbial communities associated with the oxygen minimum zone of northern Chile

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Marine oxygen minimum zones (OMZs) harbor diverse microbial communities that play a major role in global biogeochemical cycles. The Eastern Tropical South Pacific designates a dynamic yet persistent OMZ driven by strong upwelling that replenishes the surface nutrient supply and fuels primary production. A rapid flux of detrital organic matter from the surface drives strong vertical chemical gradients as well as changes in redox conditions through the water column. These gradients have been associated with significant restructuring of extant microbial communities in addition to indications of physiological responses to changing conditions. Microbial dynamics are relevant to understanding the trophic states of broad expanses of oxygen deficient waters, in addition to the cycling of biologically relevant elements such as nitrogen and carbon. The taxonomic composition of microbial communities can be described through analysis of the composition, distribution, and structural characteristics of cell membrane lipids also known as intact polar lipids (IPLs; a form of biomarker) in suspended particulate organic matter. In this study, we present the vertical distribution of IPLs through water columns experiencing varying chemical gradients associated with the OMZ off the coast of Iquique, northern Chile. Our analysis shows a great diversity in membrane lipid production and denotes transitions in IPL distributions between distinct microbial assemblages in relation to increasing oxygen deficiency and varying nutrient availability from two nearshore sites along the Humboldt Current system. We discuss the implications of these results in the study of microbial communities of modern OMZs using gene-independent techniques, as well as the potential application of these biomarkers to study microbial processes in the past as preserved in sedimentary records.

(27) Offshore transport of a key sulfur oxidizing bacteria from the SUP05 clade sustains ‘cryptic sulfur cycling’ in the the oxygen minimum zone of the Peru upwelling

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Members of the gammaproteobacterial clade SUP05 couple water column sulfide oxidation to nitrate reduction in sulfidic oxygen minimum zones (OMZs). Their abundance in offshore OMZ waters devoid of detectable sulfide has led to the suggestion that local sulfate reduction fuels SUP05 mediated sulfide oxidation in a so-called ‘cryptic sulfur cycle’[1]. We examined the distribution and metabolic capacity of SUP05 in Peru Upwelling waters, using a combination of oceanographic, molecular, biogeochemical and single-cell techniques, and thus obtained the first direct data on the in situ activity of a sulfide-oxidizing, nitrate reducing organism in OMZ waters. A single SUP05 species, Uncultured Thioglobus perditus, was found to be abundant and active in both sulfidic shelf and sulfide-free offshore OMZ waters. Our combined data indicated that mesoscale eddy driven transport led to the dispersal of U. T. perditus and elemental sulfur from the sulfidic shelf waters into the offshore OMZ region. This offshore transport of shelf waters provides an alternative explanation for the abundance and activity of sulfide-oxidizing denitrifying bacteria in sulfide-poor offshore OMZ waters.


(28) Impact of nutrient stoichiometry on the microbial community structure in an in situ pelagic mesocosm experiment simulating a Peruvian coastal upwelling event

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Coastal upwelling introduces nutrient-rich bottom waters into the sunlit surface waters and thereby stimulates high biological productivity. The Peruvian upwelling system in particular is one of the most productive coastal upwelling systems (Lachkar, Gruber 2012; Espinoza-Morriberón et al. 2017). An upwelling event was simulated in an in situ mesocosm study in the coastal region off Callao, Peru, in close proximity to the oxygen minimum zone by the addition of selected anoxic bottom waters with different nutrient concentrations to surface waters enclosed in the mesocosms. By this approach, two conditions with different N/P-ratios and nutrient concentrations were produced in a replicated setup and sampled over 40 days. The microbial community in the experiment was sampled by consecutive filtration using different pore sized filters to differentiate between particle associated and free living microbes. Next-generation 16S rRNA gene amplicon sequence analysis was used to analyze the microbial community composition and its changes over time (Roy et al. 2012). The influence of nutrient availability and stoichiometry on the development of the microbial community during the course of the experiment will be presented with a special focus on the differences observed between the particle-associated and free microbial community. Additionally, the analysis of the genetic potential within these two fractions will allow us to infer on the metabolic potential of the

(29) Sampling in oxygen minimum zones: the deviation from anoxic conditions

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The study of Oxygen Minimum Zones (OMZs) is coupled directly or indirectly to the distribution of oxygen in the water column. Oxygen, even at very low concentrations controls to a large extent the presence and magnitude of diverse microbially mediated transformations in these areas. The former trivial separation between oxic and anoxic conditions was progressively redefined as a blurry range in which aerobic and anaerobic processes coexist. During laboratory incubations, aerobic and anaerobic processes have thus been measured under both apparent suboxic (few micromolar) and anoxic conditions. However, the oxygen concentrations during sampling and incubation periods have commonly be assumed, but rarely measured. In order to evaluate the oxygen concentration present in samples collected in OMZs, a series of oxygen measurements with high-resolution sensors were performed in the East Tropical North and South Pacific OMZs. Oxygen concentrations were measured in Niskin bottles and in the outflow of a Profiling Pump System (PPS) with 400 m cable. The oxygen concentration in Niskin bottles was determined by direct measurements with STOX sensors and results were compared with subsequent measurements with the Winkler method. Oxygen in the PPS outflow was measured in glass vials or bottles that were filled with a large overflow. Water samples were collected from Niskin bottles in full glass bottles in which oxygen was measured with high-resolution optical sensors. The effect of an anoxic atmosphere versus multiple bottle volume overflows on the final oxygen concentration was evaluated. For all the tested procedures, our results showed a significant deviation from in situ anoxic conditions, resulting in values closer to 1 micromolar when samples had been retrieved on deck than the maximum of a few nanomolar that might be present in the anoxic core of these OMZs.
**(30) Siderophore distributions in the Eastern Tropical South Pacific**

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Siderophores are iron binding complexes produced by bacteria as part of a high affinity iron uptake mechanism. They are thought to liberate iron from mineral particles and iron proteins and thus increase the amount of iron available to the producing bacteria, giving them a competitive advantage in environments where iron is scarce. Iron concentrations are extremely low in the ocean and siderophores have been identified in surface waters of the Atlantic(1) and Pacific Ocean(2), including the Eastern Tropical South Atlantic. However, little is known about the depth distribution of these compounds in the ocean or how oxygen abundance influences their distributions. Here we report results from an investigation into siderophore distributions in surface and sub surface waters of the Peruvian upwelling, undertaken on a cruise in the austral spring of 2015. We investigated the diversity of dissolved siderophores in seawater at depths of up to 150 m. We further quantified the abundance of hydroxamate siderophores and examined their distribution in the context of the prevailing iron and oxygen conditions. To our knowledge this is the first investigation into the influence of oxygen concentrations on siderophore distributions, and we consequently reassess the current paradigm that siderophores are only produced in fully oxygenated environments.  


**(31) Parametrisation of particle aggregation determines the representation of oxygen minimum zones in MOPS**

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Particle export is important for the ocean’s interaction with the atmosphere, for the deep ocean biota feeding, as well as for the volume of oxygen minimum zones (OMZs) in the ocean. The biological pump removes photosynthetically-produced organic matter from the surface layer into the deep ocean by particle sinking, vertical advection and mixing as well as transport by zooplankton. The sinking speed depends on particle size. Large particles favour high sinking speed, low remineralisation in the water column and thus a limited OMZ volume, and vice versa. Particle aggregation in
the water column, and the resulting increase in particle sinking speed can enhance organic matter flux to the deep ocean, and therefore alter the size of OMZs. To explore this relationship, this study uses the global three-dimensional Model of Oceanic Pelagic Stoichiometry (=MOPS; Kriest et al., 2015) with an integrated aggregation module (Kriest et al., 2002), which parametrises the particle size distribution via the spectral slope. A first optimisation of MOPS using an estimation of distribution algorithm (Covariance Matrix Adaption Evolution Strategy, CMAES) against the root mean square error (RMSE) to observed annual mean phosphate, nitrate and oxygen showed an improvement of simulated biogeochemical fluxes (Kriest et al., 2017). The next step consists in optimizing the model against the extent and location of OMZs as well as against number and size of organic particles. For this latter purpose, we will use the global dataset of the World Ocean Atlas and particle data of the Underwater Vision Profiler 5 (UVP 5). First twin experiments against synthetic data, that exhibit the same spatial coverage as the observations, have shown a good rate of recovery of parameters relevant for the aggregation module.

(32) Bacterial sulfate reduction associated with marine snow particles in the water column of the Peruvian oxygen minimum zone?

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During the SFB754 expedition M137 to the Peruvian Oxygen Minimum Zone, bacterial sulfate reduction activity was determined with radiotracer techniques (35S) in samples collected from the water column at four stations (74, 128, 244 and 824 m) along a 12 degree South depth transect. In order to capture pelagic sulfate reduction in marine snow, water-column particles were first accumulated on filters (Whatman Nuclepore polycarbonate track-etch membrane filters, diameter 293 mm, pore size 1 μm) using in-situ pump systems (McLane Research Laboratories, Inc.), and then filter sub-samples were incubated with in-situ water collected by CTD/Rosette. Sampling depths at each station were selected according to O2 profiles. Three redox zones were targeted at each station: (1) the shallow oxic/hypoxic transition, (2) the central OMZ, and (3) the deep hypoxic/oxic transition or (if hypoxia reached the seafloor) the zone close to the seafloor (ca. 10 m above ground). Each station was sampled with three in-situ pumps simultaneously. Results revealed detectable sulfate reduction activity only at the 74 m station. Activity was low (10-58 pmol/L/d), but distinct from control samples (2- 3x average control value and >3x method detection limit) in five out of six sub-samples collected from the shallow oxic/hypoxic transition (30 m, [O2] ca. 13 μM). From the six sub-samples collected close to the seafloor (60 m, [O2] ca. 6 μM) one showed sulfate reduction activity (182 pmol/L/d), but given the lack of reproducibility, the environmental relevance of this sample is questionable. No sulfate reduction activity was detected in the central OMZ at this station (45 m, [O2] ca. 6 μM). In this poster presentation, we will compare the observed sulfate reduction activity with environmental parameters (e.g., O2, stratification, particle density, Corg) and molecular data from the four stations to discuss the following...
questions: Why was sulfate reduction only detectable at the 74 m station? Why was the activity concentrated at the shallow oxic/hypoxic transition (30 m)? Were other depths/stations devoid of sulfate-reducing bacteria or are sulfate-reducing bacteria present but inactive? What is the environmental relevance of the observed sulfate reduction activity?

(33) Anammox bacterial abundance, diversity and distribution across surface sediments underlying oxic, hypoxic and suboxic zones of Northern Indian Ocean

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The oxygen-depleted environments (ODEs) are reported sites of oceanic fixed nitrogen loss mediated by major microbial pathways like denitrification and anaerobic ammonium oxidation (anammox). The aim of the present study was to understand the diversity, abundance, and distribution of anammox bacteria across surface sediments of the northern Indian Ocean using PCR-based molecular tools. A total of 22 sediment samples were collected from three transects (off Goa, off Mangalore and off Kochi) in Arabian Sea and off Paradip transect in Bay of Bengal, underlying oxic, hypoxic or suboxic water column having a depth of 20 to 2000 m. Multiple molecular proxies such as 16S rRNA, hydrazine synthase (HzsA) and hydrazine oxidoreductase (Hzo) gene partial fragment were targeted for characterization of anammox community. Gene abundance was quantified using standard curve method, while for diversity studies a combination of tools such as nested PCR, DGGE, pyrosequencing and metagenomic library construction was used to identify all possible anammox communities. Anammox gene diversity was high in the suboxic zone and dissolved oxygen and salinity could contribute ~89 to 90 % variability. The anammox specific 16S rRNA gene diversity study was able to identify only genus Scalindua, though belonging to diverse clades. On the other hand, functional diversity studies targeting hydrazine gene and phylogenetic diversity studies using universal primer suggest the possibility of occurrence of novel anammox community with high diversity and abundance. The gene copy number ranged between 1.5E+04 and 1.9E+05 per gram sediment and did not show significant correlation with dissolved oxygen in the overlying water-column. Anammox abundance was high in the coastal stations in comparison to the offshore stations. Within suboxic zones, a noticeable increase was observed in off Kochi transect which is outside the secondary nitrite maxima zone in the eastern Arabian Sea. Our study reports the widespread prevalence of anammox bacterial community across the sampling sites, but not in very high abundance, suggesting a less significant role for anammox in the northern Indian Ocean. However, the positive correlation of anammox gene abundance with temperature poses a serious concern due to a reported expansion of coastal hypoxia induced by global warming.
Foraminifera as bacterial microniches in benthic biochemical processes?

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Foraminifera are unicellular macroscopic eukaryotes found in a wide range of marine environments. Benthic species reach high abundance up to >500 individuals per square centimetre at sea floor sediments and exceed metazoan (i.e., animal) population density and biomass in certain habitats. Several foraminifera were reported to host a substantial amount of bacteria in their cytoplasm, either representing symbionts, food or just sharing the same habitat. Bacterial lineages are key players in marine biochemical cycles, especially in oxygen-depleted environments. However, the bulk of bacteria associated with foraminifera has never been characterized and has not been considered for benthic biochemical processes yet. Here we study metabolic pathways encoded in the genomes of bacteria associated with foraminifera and evaluate their contribution to biochemical cycles in oxygen-depleted sediments. From large-scale metagenome sequencing of the benthic foraminifera *Globobulimina* in a hypoxic fjord, we retrieved 26 draft genomes of foraminifera-associated organisms. Most of these genomes represent Gammaproteobacteria, while also Alphaproteobacteria and members of the phylum Bacteroidetes were identified. Their genetic content covered complete and partial metabolic pathways typically associated with oxygen-depleted environments and therefore were in line with the facultative anaerobic lifestyle of their foraminiferal host. Furthermore, multiple strains identified were related to bacteria previously found in host-association or as endosymbionts of marine eukaryotes. Several benthic foraminifera are capable to migrate deeper into sediments to avoid competition and to seek specific food sources. We hypothesize that foraminifera represent microniches for bacteria, bringing metabolic processes at the benthic interface into deeper sediment layers. Thus, our results expand the role of foraminifera in marine biochemical cycles by considering the bacterial community in their cells.
Major Upwelling Systems

Topic abstract

Coastal upwelling systems (including eastern boundary and northern Indian Ocean upwelling systems, EBUS and NIOUS, respectively) play a key role in the global carbon and nitrogen cycles and are of local relevance due to their high productivity and the associated fisheries. The major coastal upwelling systems are usually associated with pronounced oxygen minimum zones (OMZ) and are characterized by a complex interplay of physical, biological and chemical processes (in sediments, water column and atmosphere). These systems are driven by various physical processes ranging from mesoscale eddies, submesoscale filaments and fronts down to internal waves and microscale turbulence which are important for the transport of oxygen and thus ventilation of the OMZ. This, in turn, determines occurrence of O₂-sensitive biogeochemical processes in the water column and sediments of OMZ. Recent increase in computational power and new techniques such as multi-nesting approaches made it possible to increase the resolution of regional ocean general circulation models down to some hundred meters. New observational techniques such as airborne, underway, and autonomous technologies allow for high-resolution adaptive multidisciplinary campaigns. Recent progress in biological/microbial techniques and application of new chemical sensor techniques allow deciphering of biogeochemical patterns with unprecedented high resolution. Both observational and modelling studies investigating all physical, biological and chemical aspects of the major coastal upwelling systems and associated OMZ (incl. EBUS and NIOUS) are welcome.

Conveners
Hermann W. Bange // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
Sören Thomsen // LOCEAN-IPSL (UPMC Paris 6/CNRS/IRD/MNHN), France
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KEYNOTE SPEAKERS

05.09. WEDNESDAY | 09:00

Factors affecting the variability of the Arabian Sea OMZ over seasonal, interannual and climate-change time scales

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The combination of high biological production and weak oceanic ventilation over coastal upwelling systems cause large-scale oxygen minimum zones (OMZs) that profoundly affect marine habitats and alter key biogeochemical cycles. These low subsurface oxygen levels are determined by a balance between remineralization and ventilation, which both vary over multiple time-scales and have local as well as remote sources. In this presentation, I will highlight key factors affecting the variability of the Arabian Sea OMZ over seasonal, interannual and climate-change time scales, using high-resolution model simulations of the Northern Indian Ocean
performed using a range of physical (NEMO, ROMS) and biogeochemical (NPZD, PISCES) models. The Arabian Sea OMZ has unusual characteristics compared to the two other main OMZ, which are found in Eastern Boundary Upwelling Systems, along the eastern Pacific and Atlantic, respectively. In the Arabian Sea, the strongest coastal upwelling is driven in summer by southwest monsoon winds and is located along the western coast, while the OMZ is shifted eastward from this region of highest productivity and reaches the Indian coastal waters. Furthermore, the Arabian Sea OMZ is the thickest of the three oceanic OMZ, with near-total depletion of oxygen (suboxia) at depths 200-1000m associated with intense denitrification. Suboxic events are particularly dramatic when they occur along coastal areas, as they induce episodes of fish mortality and shorter fishing season, inducing a sharp decline in fish catches. The economy based on fisheries of these dense population regions is thus highly vulnerable to the variability in the strength of this OMZ and to the frequency of suboxic events. I will examine several factors that were found to prevent and/or limit anoxia, over intra-seasonal to interannual time-scales. First, eddy-driven ventilation strongly limits their extent, limiting the associated denitrification. This has a positive feedback on primary production with the counter-intuitive consequence of increasing the extent of hypoxia. Second, anoxia occurs when the OMZ is raised toward the surface. This is reinforced by remineralisation fluxes that occur essentially in the upper twilight zone. Over inter-annual time-scales, the strongest coastal anoxic events occur essentially during negative Indian Ocean Dipole events which are associated with an upwelling of the thermocline and of the oxycline. Finally, over climate change time scale, variations in monsoon wind intensity and large-scale ventilation both affect the volume occupied by the OMZ.

Marina Lévy | Marina Lévy started her scientific career with a master in Oceanography, Meteorology and Environment (1993) followed by a PhD in Oceanography (1996) at Université Pierre et Marie Curie, Sorbonne Université, in Paris. Marina was a Postdoc fellow at Lamont-Doherty Earth Observatory, Columbia University between 1997 and 1998. Since 1998 she is back in Paris at LOCEAN-IPSL, working for CNRS. In parallel to her research activities, she is now the Deputy Director of the Ocean, Climate and Ressources Department of the French Research Institute for Sustainable Development, IRD.

Marina studies the interactions between ocean physics, biogeochemistry, plankton and marine ecosystems, with a particular focus on the role of ocean turbulence, and with the final goal of being able to make better predictions for the future, particularly with regard to the carbon cycle. Her primary research tools are regional, bio-physical models which Marina uses and develops to guide her interpretations of satellite and in-situ observations. Most of her work on oxygen is through long-term collaborations with the NIO in India, IMARPE in Peru, NYU-Abu Dhabi and Princeton University.
The “bad” breath of the ocean: greenhouse gas emissions from Eastern Boundary Upwelling Ecosystems

Damian Arévalo-Martínez // darevalo@geomar.de

Eastern Boundary Upwelling Ecosystems (EBUS) are well-known “hotspots” for production of greenhouse gases (GHG). Although each year tons of GHG are emitted out of the global ocean, EBUS are focal points with a disproportionally high share of the total efflux of these gases. Given that EBUS are a fundamental component of the socio-economic development of the bordering countries, the associated anthropogenic activities bear the potential to exacerbate the already increasing GHG emissions. Since GHG-driven warming is thought to be the major cause for ocean deoxygenation, it is of utmost importance to understand the distribution and variability of these gases over wide temporal and spatial scales. Throughout the last decade great progress has been achieved in the development of methods for continuous in situ monitoring of GHG, which not only contributes to fill the existing gaps in data coverage but also helps improving modelling approaches for predicting the emission trends of GHG with future climate change. In this talk I will present observational trends of GHG in all four EBUS and discuss how to find reasonable temporospatial scales for linking observational and modelling programs. Likewise I will address some of the major environmental problems leading to increased deoxygenation and how they influence the emissions of the major GHG in EBUS.

Damian L. Arévalo-Martínez | Dr. Damian L. Arévalo-Martínez is a sea-going chemical oceanographer working at the GEOMAR Helmholtz Centre for Ocean Research Kiel (Germany). His research is focused on biogeochemistry and air-sea gas exchange of climate-relevant trace gases. Over the last years he investigated the distribution and emissions of CO₂, N₂O and CO in different regions of the tropical Pacific, Atlantic and Indian Oceans, with particular emphasis on coastal and equatorial upwelling ecosystems and their associated oxygen minimum zones. Between 2012 and 2015 he was part of the ocean component of the EU-funded Integrated non-CO₂ Greenhouse gas Observing System (InGOS), and since then he has participated in several field campaigns within the framework of the Surface Ocean Processes in the Anthropocene (SOPRAN) project, the SCOR Working Group 143, and the Collaborative Research Centre SFB 754. Damian’s work encompasses the development and field deployment of state of the art, high-resolution spectroscopic analytical systems for gas measurements, as well as strong cooperation with physical oceanographers and biologists in order to perform detailed studies of the marine pathways and distribution of increasingly important gases like N₂O. Recently he has set focus on investigating the N₂O cycling and emissions from polar and sub-polar ecosystems, as well as on the development of autonomous, long-term observational tools for monitoring air-sea fluxes of greenhouse gases. He holds a PhD in Chemical Oceanography and a MSc in Biological Oceanography from Kiel University, as well as a BSc in Marine Biology from the Universidad Jorge Tadeo Lozano (Colombia).
Does the Ocean lose its breath?

Carolin Löscher // cloescher@biology.sdu.dk

Oxygen (O₂) plays a critical role for life on Earth, but over the last 50 years, O₂ concentrations in the Ocean have decreased massively as a consequence of human activity. These activities include greenhouse gas emissions and nutrient discharge to coastal waters, with major impacts on Ocean biogeochemistry and ecology. This effect is particularly intense in O₂ depleted tropical Ocean areas, also referred to as oxygen minimum zones (OMZ). These are sensitive areas as OMZs are connected to nutrient-rich coastal upwelling systems and support some of the world’s most prolific fisheries. While continuous OMZ expansion would lead to a decreasing habitat for fish and other organisms, feedback mechanisms which counteract O₂ depletion and stabilize the system’s ecological functionality may however explain and sustain high productivity. Microbes are essential to regulating ocean biogeochemistry, oxygen and nutrient turnover and may those hold the key to stabilizing the oxygen budget to a certain extent. In this talk, I will discuss the potential of microbes involved in the nitrogen cycle to mitigate against Ocean oxygen depletion via feedback cycling from an integrated molecular, biogeochemical, and modeling perspective.

Carolin Löscher | Dr. Carolin Löscher is a Junior Professor of Geobiology at the Danish Institute for Advanced Study, and the Nordic Center for Earth Evolution at the University of Southern Denmark. Her research is focused on understanding and reconstructing the relationship between environmental change and biological evolution. The general theme linking her research projects is the impact of extremes of productivity and oxygen distribution, and the transition between qualitatively different nutrient-limitation states. Carolin studied biology and marine sciences in Berlin, Kiel and Bremen, and holds a PhD from the University of Kiel. She was a Postdoc at the University of Kiel and at GEOMAR, organized several research cruises and led various smaller projects. Over the last years, she received a Marie Curie fellowship from the European Union, a DIAS young investigator start-up grant, and a fellowship from the Templeton Foundation.

While her earlier studies were mostly centered around resolving patterns of nitrogen cycle processes and primary production in the modern Ocean, her current research is focused on biomarker identification and simplistic modeling of those processes in order to resolve major biogeochemical and ecological response patterns to climate change in a deep time perspective. A specific focus is to understand Gaian feedback cycles, their limitations in the modern Ocean, and through Earth history.
Dispersion of a tracer in the Eastern Tropical South Pacific

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Anoxic marine sediments release significant amount of ammonium, phosphorus, reduced iron and silicate (e.g. Bohlen et al. 2011 & Noffke et al. 2012). Therefore the water layer directly influenced by the sediments, the bottom boundary layer (BBL), contains high concentrations of nutrients and is particular dynamic in terms of N-cycling (e.g. Kalvelage et al. 2013). The nutrient flux from the BBL to the interior ocean is potential important for the development of Oxygen Minimum Zones (OMZ). There is a lack of understanding about the complex dynamic processes responsible for dispersion of nutrients from the BBL to the interior ocean. To investigate integral aspects of these processes, a deliberated Tracer Release Experiment (TRE) was conducted. In October 2015 the Peruvian Oxygen-minimum-zone System TRE (POSTRE) was initiated to detect the pathways connecting the BBL with the OMZ and to investigate the biogeochemically important BBL ocean interface processes. The tracer was released in 250 m on the Peruvian shelf, which is in a potential density range from 1026.24-1026.38 kg m\(^{-3}\). It is the first TRE, where the tracer is injected directly in the BBL, i.e. onto a fixed depth rather than a target density layer. The tracer survey took place in March 2017, about 17 months after injection. From the lateral distribution a tracer advection of at least 2000 km southeastward along the coast was observed. This is related to the Peru Chile Undercurrent, into which the tracer was partly injected. Due to the zonal eddy transport the tracer is also found more than 1400 km offshore. In the vertical distribution Gaussian shaped profiles are found for off-shore stations. An open ocean diapycnal mixing estimate from the advection-diffusion equation over the entire period has an order of 10\(^{-5}\) m\(^2\) s\(^{-1}\), which is consistent with the results from several open ocean TREs. In the coastal area the profiles have equally high tracer concentration throughout the water column. This shape indicates enlarged mixing due to boundary influence. Moreover the overall center of the tracer was found on lighter isopycnals than the injection densities. There had to be high upward diffusivity on the shelf, when the experiment was started. This indicates that the represented nutrients can reach euphotic zones.

The role of filaments for ventilating the oxygen minimum zone off Peru

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Filaments and the associated submesoscale frontal processes are known to play a crucial role for the offshore and downward transport of biogeochemical tracers
in Eastern Boundary Upwelling Regions (EBUS). These fluxes modulate subsurface oxygen concentrations directly but also indirectly through changes in biological production and subsequent remineralisation of organic matter. So far most studies are either based on observations or model simulations but seldom are both approaches combined to assess the importance of filaments for the biogeochemical cycling in upwelling systems. Here we combine targeted interdisciplinary shipboard observations of a cold filament in the Peruvian upwelling region with submesoscale-permitting coupled physical (ROMS) and biogeochemical (PISCES) model simulations to (i) evaluate the model simulations in detail, (ii) investigate the pathways and timescales of biogeochemical modification of the newly upwelled water and (iii) quantify the net effect of filaments on biogeochemical tracer distributions in the oxygen minimum zone off Peru. Enhanced nitrate concentrations of and offshore velocities of up to 0.5 m/s within the observed filament suggest an offshore transport of nutrients. Despite low chlorophyll a concentrations in the core of the filament, depth integrated primary production is 40% higher than at the upwelling front and 25% higher than offshore. The model simulation exhibits filaments that are similar in horizontal and vertical scale and structure compared to the observed filament. Nitrate concentrations and primary production within filaments are comparable to observations, suggesting these processes are well represented in the model. Our simulations further suggest that the net effect of submesoscale frontal processes is to increase subduction and offshore export of nitrate which leads to reduced primary production. An increase in oxygen that resembles the pattern of the decrease in nitrate suggests a ventilation of the shallow oxygen minimum zone off Peru by horizontal and vertical eddy-fluxes.

**Impact of non-linear internal waves on the cross slope circulation in the Peruvian upwelling region**

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Non-linear internal waves (NLIWs) are a prominent feature on the continental slope and shelves of all major upwelling regions. They are known to enhance diapycnal mixing and associated nutrient fluxes, thereby fueling biogeochemical cycles. Additionally, they cause elevated near-bottom velocity variability which affects sedimentation rates and benthic distribution of biota. NLIWs are also capable of transporting mass through Stokes drift and are thus potentially contributing to cross-shelf exchange. During a measurement program at 11°S off Peru in austral summer 2013, particularly elevated onshore-propagating NLIWs were observed in velocity records from moorings and landers as well as hydrographic and turbulence profiles collected by research vessels and autonomous platforms. The generation and cross-slope evolution of NLIWs along 11°S is investigated using a fully nonlinear two-dimensional very high-resolution model (8m horizontally, 0.25m vertically) with observed topography that is forced with a cross-shore barotropic tide having amplitudes taken from the moored velocity records. Many features of the simulations are consistent with the collected data set.
A first vertical mode baroclinic tide forms at a water depth of about 500m due to tidal beams of small vertical extend that originate from a critical continental slope section between 800 and 600m depth. While the baroclinic tide propagates into shallow waters, amplitude dispersions generates trains of NLIWs at a water depth of about 300m, having near N frequencies. Particle displacements due to NLIWs determined from the observations and from solutions to the Dubreil-Jacotin-Long model giving NLIW phase speeds yield an onshore transport of 0.3m^2/s in shallow waters. This onshore transport exceeds offshore Ekman transport averaged to 0.18m^2/s from direct wind measurements during the observational period. Distributions of diapycnal mixing due to tide-topography interaction and upwelling patterns due to divergent cross-shore flow are discussed. Finally, we offer an alternative explanation for the observed cold near-shore surface temperatures relative to warmer surface temperatures offshore and provide reasoning for sulfidic events that frequently occur off Peru inshore of the 150m-isobaths during austral summer.

**Linking upwelling, export production and nitrogen cycling processes in the OMZ waters of the ETSP**

**Gaute Lavik // Max Planck Institute for Marine Microbiology, Germany // glavik@mpi-bremen.de**

Upwelling of nutrient-rich water fuels high surface productivity and the resultant export of organic matter stimulates strong microbial respiration in the subsurface waters. Combined with poor ventilation, O₂-deficient waters called oxygen-minimum-zones (OMZs) develop. Under these low oxygen conditions fixed nitrogen is lost as N₂-gas via the anaerobic processes of anammox and denitrification. Although constituting only ~1% (O₂ ≤ 20 μmol kg⁻¹) of global ocean volume, OMZs account for ~20-40% of the global oceanic N-loss. Thus, processes removing fixed nitrogen in OMZ waters partly regulate the availability of nutrients for primary production in the photic zone. As the organic matter exported from primary production is the main source of substrates for N-loss processes, there is a tight coupling between the physical processes bringing nutrients to the surface waters and microbially driven nitrogen cycling in the underlying OMZ waters. The eastern tropical South Pacific (ETSP) OMZ is one of the ocean's largest sinks of fixed nitrogen where one-third of nitrogen loss occurs in productive shelf waters stimulated by organic matter export as a result of eastern boundary upwelling. Further off shore mesoscale eddies have been suggested to enhance vertical nutrient transport and thereby regulate primary productivity and organic matter export. For offshore mesoscale eddies, both depth-integrated chlorophyll content and anammox activity increase at the periphery, relative to the eddy center; suggesting enhanced organic matter export along the periphery supports nitrogen loss activity. In the central ETSP-OMZ, the formation of eddies, as a result of a topographic bend on the shelf edge, can also influence the coastal currents and transport coastal waters towards the open ocean OMZ with important implications for the fixed nitrogen budgets. Furthermore, the physical processes causing upwelling of nutrients to the surface waters can also bring oxygen into the OMZ waters and thereby support microaerobic processes. The occurrence of aerobic processes in waters seemingly devoid of free oxygen is supported by the high presence of obligate aerobic microbes and gene transcripts in OMZ water. In the upper part of the OMZ waters, microaerobic respiration was shown to be the
dominant source of the ammonia which sustains fixed nitrogen loss by anammox. The co-occurrence of aerobic and anaerobic N-cycling processes under low oxygen conditions has been described in several studies. However, the production of N₂O, an important greenhouse gas, in direct comparison to other N-cycling products like N₂-gas under these conditions has been less systematically studied.

**Measurements of biogenic volatile organic compounds (BVOCs) in marine boundary layer of Arabian Sea (OMZ): Role of carbon cycle in pre-monsoon season**

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Global oceans play important role as a sink of atmospheric carbon dioxide (CO₂). Dissolved organic carbon (DOC) in the sea waters is an important source of many biogenic volatile organic compounds (BVOCs). Globally, BVOCs are emitted from plants and organisms from both terrestrial and oceanic reservoirs. However, spatial and temporal variations in emission and factors controlling production of BVOCs in oceanic regions are poorly understood. Therefore, the reported estimates of a global oceanic flux of reactive carbon species contain great uncertainties. BVOCs play important role in the enhancement of oxidants and climate change. Northern tropical Indian Ocean is expected to be a strong source of many BVOCs due to relatively high productivity (phytoplankton). Arabian Sea is one of the most productive regions of the world where studies of BVOCs emissions from sea waters are scarce. The present study is based on the measurements of BVOCs including alkenes and isoprene in the marine boundary layer of Arabian Sea during a cruise campaign onboard Sagar Sampada #19 from 18 April to 02 May 2017. The objective is to determine the relation between the emissions of oceanic VOCs (particularly isoprene) with phytoplankton in surface sea waters of the Arabian Sea. The concentrations of BVOCs were measured using a thermal desorption-gas chromatography with a flame ionization detector (TD-GC-FID) instrument. The concentrations of isoprene over open and coastal regions were 0.47±0.13 and 0.80±0.18 ppbv, respectively. However, we do not find significant differences in key meteorological parameters such as temperature and solar radiation observed over both regions of Arabian Sea. Therefore, large gradient and heterogeneity in fluxes of BVOCs could be mainly controlled by the distribution of DOCs in the pre-monsoon season. In consistent with distribution of isoprene concentration the satellite based ocean color map (chlorophyll concentration) shows much higher productivity in coastal regions compared to open oceanic region. The spatio-temporal variation of BVOC is consistent as the high primary production which could cause low surface pCO₂ and higher DOCs observed over the Arabian Sea. This result is an important for further understanding of different processes controlling the oceanic emissions of alkenes from the oxygen minimum zone (OMZ) of tropical Indian Ocean. A detailed result of different BVOCs including their latitudinal dependence and role of biogeochemistry in view of carbon cycle over Arabian Sea will be presented.
Variability and trends of the oxygen minimum zone at the coastal upwelling system off Peru

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The Humboldt Current upwelling ecosystem, particularly the northern component off the coast of Peru is considered a hot spot for the scientific community because of its unique characteristics: it is the upwelling system with the biggest catch productivity despite the fact it is embedded in a shallow and intense oxygen minimum zone (OMZ). It is also an area of intense biogeochemistry activity and experiences one of the large interannual variability associated with the equatorial remote forcing. The present work aims to present a detailed study of the spatial and temporal distribution of dissolved oxygen off Perú since 1960 to recent years. The dataset offers the unique opportunity to explore longer timescales of variability expected from the complex of processes involved. Overall, our results illustrate the rich spectrum of OMZ variability. In particular suggests the strong connection at seasonal scale with the coastal upwelling dynamics, water masses distribution, and biology; while at interannual scale but also a low-frequency a connection with the equatorial forcing and the El Niño events. The spatial analysis of the OMZ time series put in evidence the large amplitude of the oxygen variability in the northern zone compared with a more stable environment in the center and south of Peru. Important decadal changes associated with the OMZ contraction or expansion appears associated with the Pacific Decadal Oscillation (PDO) and the variability of the El Niño events. From 2000 a long-term deepening of the oxygen-deficient waters appears in the data in contrast to the long-term open ocean deoxygenation trend observed over the last decades in the eastern tropical Pacific. This suggests that either the oxygen variability in the coastal area could be not representative of the changes in the offshore OMZ. This would deserve further investigation. A better understanding of the natural variability is essential to understand changes in nutrients and finally predicting the productivity and distribution of marine resources. In addition, maintain monitoring and fix points are essential in the context of the Climatic variability and Climate change and need to be coupled with experimentation design and modeling which needs to be taken into account for future work.
Intra-seasonal variability of the eastern boundary circulation off Peru and biogeochemical consequence

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Dissolved oxygen (O$_2$) and nutrient concentrations at the continental margin of the eastern tropical south Pacific (ETSP) exhibit elevated intra-seasonal, seasonal and inter-annual variability. Here, we discuss the impact of remotely forced and locally generated intra-seasonal variability of the eastern boundary circulation at 12°S. Data from a multi-cruise physical and biogeochemical measurement program conducted during the declining phase of the 2017 Coastal El Niño event between April and June (austral autumn) are used. Upper ocean temperatures were anomalously high and during the latter cruises the oxycline was displaced downward compared with previous observations in austral summer 2008/09 and 2012/13. We observed the offshore propagation of a freshly generated eddy and an associated phase of weak poleward flow. After the reestablishing of the poleward Peru-Chile Undercurrent (PCUC) the passage of a remotely-generated downwelling coastal trapped wave (CTW) causes an intensification of poleward velocities exceeding 50 cm s$^{-1}$. Warm temperature anomalies persisted during the intensified PCUC while sea surface temperature anomalies declined after the peak of the Coastal El Niño event. During the period of PCUC acceleration, nitrate concentrations increased while the nitrogen deficit became reduced. This suggests the advection of water less affected by anoxic biogeochemistry whereas during the period of weak poleward flow the water was biogeochemically altered more. The upper boundary of anoxic water was displaced downward increasing the depth range where bottom waters were ventilated while nitrite was depleted concurrently. We will analyze the different response of temperature, nutrients, and O$_2$ to the varying circulation and discuss the implications for the biogeochemical element cycling in the water column and the sediments.
Spatial heterogeneity of dissolved oxygen and hypoxia events in shallow waters of central Chile: Diurnal and seasonal patterns in an upwelling ecosystem

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Several field studies have demonstrated that shallow waters on the inner-shelf can commonly experience low oxygen conditions, especially in upwelling ecosystems. However, the frequency and intensity of hypoxia events, as well as the physical and biological drivers of such conditions in coastal shallow waters (<30m deep) are still scarcely studied. We used high frequency records obtained between Nov-2015 and Oct-2016 to characterize shallow (15-23m deep) near-bottom dissolved oxygen (DO) at 6 sites (Valparaiso, Quintay, Quisco, ECIM, Matanzas, Pichilemu) exposed to contrasting levels of upwelling intensity and spread over a distance of 170 km along central Chile. Here we analyze short-period oscillations in oxygen concentration and their potential drivers. High-frequency fluctuations were observed at all sites, particularly during spring and summer months. DO at all sites fluctuated between 0.2 mg/l and 13 mg/l, and daily ranges in DO reached values around 11 mg/l. A strong diurnal signal was detected at five of the six sites, with the lowest oxygen concentrations occurring at night and peaks of oxygenated waters during the afternoon. Valparaiso showed a strong semidiurnal signal instead, with peaks of maximum DO occurring early morning (6:00) and afternoon (15:00). Days with hypoxic events (< 2.8 mg/l for > 20 min) were observed along the whole study period, however they were more frequent during spring and summer months and the number of days with hypoxic events differed markedly among sites (from 5.23% of days at the site Quintay to 43.28% of days at Matanzas). At all sites, hypoxic events occurred significantly more often at night hours than daytime, suggesting that community respiration plays a role in driving already low DO levels to hypoxia. Our observations thus showed that shallow waters of central Chile frequently experience low DO and hypoxia conditions, with an important diurnal cycle, and with large variability in frequency and duration of occurrence among sites. Among-site variability is not related to upwelling intensity in a simple manner. Site-specific DO regimes could depend on coastal morphology, local circulation, phytoplankton biomass or river outflow proximity.

Recent biogeochemical trends in the Peru upwelling system

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The Peruvian Upwelling System (PUS) is one of the most important coastal upwelling system in the world ocean because of its intense Oxygen Minimum Zone (OMZ) and high productivity supporting the largest anchovy fishery. Between the 1980s and 2000s, a sea surface cooling, a subsurface deoxygenation and nearshore surface
chlorophyll increase were evidenced from satellite and in situ observations. In the present work we investigate the physical and biogeochemical processes driving the biogeochemical trends from 1979 to 2008 using the physical-biogeochemical coupled ROMS-PISCES model. Numerical experiments were made to evaluate the respective impact of the remote (e.g. equatorial waves) and local forcings (e.g. upwelling favorable winds) on these trends. The model was able to reproduce the alongshore deoxygenation and productivity increase. Deoxygenation (-4 μmol.kg⁻¹.dec⁻¹) was mainly found between 20-100 m depth and a shoaling of the upper limit of the OMZ was also evidenced. The modelled increase of productivity (+0.4 mg Chl.m⁻³.dec⁻¹) was significant in the Northern-Central part off Peru (6°S-10°S). The modelled phytoplankton growth limiting factors indicated that the productivity increase was due to a reduction of nutrient limitation caused by the nutricline shoaling, while no change in light limitation was observed. Sensitivity experiments demonstrated that the remote forcing drove the deoxygenation and productivity increase, due to the more frequent occurrence of central Pacific El Niño (El Niño Modoki) events in the recent period. Upwelling Kelvin waves are generated during the offset of these events, driving the shoaling of the nearshore thermocline, nutricline and oxycline.

Drivers of anoxia in a large embayment of an eastern boundary upwelling system: St Helena Bay

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St Helena Bay is located in the southern Benguela and is a large, highly productive open bay formed by the Cape Columbine promontory. Here we show oxygen depletion to be a function of local drawdown at seasonal and episodic scales. We investigated plankton community metabolism through estimates of net community production [NCP] and respiration [R] as determined by oxygen fluxes in the water column, providing information on the balance of autotrophy and heterotrophy within the Bay. Rates of NCP and gross community production [GCP] were typically shown to be appreciably higher near surface, despite the regular presence of subsurface biomass maxima. Characteristically, NCP was a significant fraction of GCP in the surface waters, but declined sharply with depth, and in most cases the community compensation depth [where NCP=0] was <10 m. Autotrophic communities, where organic matter is produced in excess of respiratory demand, were therefore typically confined to the upper 10 m of the water column, and often excluded the bulk of the phytoplankton community, where light limitation is considered to lead to heterotrophic community metabolism. Little consumption of oxygen was observed in the bottom mixed layer of the water column. With increasingly stratified conditions a seasonal decline in oxygen was achieved in near bottom waters through sub-seasonal events of hypoxia and ultimately anoxia linked to periodic deposition of senescent phytoplankton blooms as indicated by spikes in bottom chlorophyll a concentrations. A seasonal shift in phytoplankton composition during the upwelling season from diatom to dinoflagellate dominance was demonstrated with regular development of nearshore blooms termed red tides. Our estimates of NCP and R within these blooms
are among the highest values recorded. Ratios of R to GCP were particularly high [0.6–0.73] and are considered a function of the inherently high cellular respiration rates of dinoflagellates. Night time R in surface waters under these bloom conditions far exceeded oxygen replenishment via air-water exchange leading overnight to conditions of anoxia. Under these conditions oxygen may be stripped from the entire water column of shallow nearshore environments. We conclude increasing relevance of biological as opposed to hydrophysical drivers of low oxygen at the episodic scale.

Dissolved organic matter cycling in the coastal upwelling system off central Peru during an “El Niño” year

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Dissolved organic matter (DOM) represents one of the largest active pools of organic carbon in the global carbon cycle. The Humboldt Current Upwelling System off Peru is among the most productive ecosystems in the world ocean, with high rates of primary production and an intense oxygen minimum zone (OMZ). One of the major perturbations of this system is associated to El Niño-Southern Oscillation, especially to its warm phase “El Niño” (EN), which reduces primary production and affects water mass distribution. We characterized the composition of solid-phase extractable DOM (SPE-DOM) in the Coastal Upwelling System off Central Peru and the processes that affect it during 2015, an “El Niño” year. Seasonal sampling (April, August and December) was carried out off Central Peru (12°S), one of the main upwelling cells characterized by high organic matter production and a well-developed OMZ. The DOM molecular composition was obtained via 15T Fourier transform ion cyclotron resonance mass spectrometry. Solid-phase extractable dissolved organic carbon (SPEDOC) concentrations showed significant differences (p<0.05) between the water masses present off central Peru, they also showed significant positive correlations (p<0.05) with temperature (r=0.73), salinity (0.67) and chlorophyll-a (r=0.43). In order to explore if changes in SPE-DOC were behaving linearly with water mass mixing, we developed a conservative mixing model. Our model revealed a non-conservative behavior of SPE-DOC and allowed us to identify two distinct group of samples where SPE-DOC had been gained/lost respectively, and one group of samples inside the conservative mixing range. Environmental parameters as depth, dissolved oxygen and silicate concentrations showed significant differences between the groups that gained/lost SPE-DOC, showing evidence of processes associated to production and degradation of SPE-DOC. The comparison of the DOM molecular composition of the groups that gained/lost SPE-DOC with the samples in the conservative mixing range did not yield significant results when compared to a random dataset, only 7% of the total number of identified molecular formulae showed significant differences between the groups of samples. Nevertheless, these small number of molecular formulae showed hints of processes link to DOM production and degradation (i.e. photodegradation). Our study suggests that 1) even in low productivity conditions like EN, there are processes that add/remove SPE-DOC, and 2) changes in the DOM molecular composition during EN conditions are minimum and not significant, and therefore do not reflect changes in bulk DOM concentrations.
Distributions and emissions of dissolved methane in coastal upwelling region off Peru

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Methane (CH₄) is the most abundant hydrocarbon in the atmosphere and plays an important role in regulating the Earth's radiation balance and atmospheric chemistry in the troposphere. Coastal upwelling regions such as the eastern boundary upwelling systems and the Arabian Sea have been identified as sites of enhanced CH₄ concentrations and emissions to the atmosphere. The coastal upwelling area off Peru is one of the most biologically productive regions of the world's ocean connected to a large and persistent oxygen minimum zone (OMZ), but it is comparatively undersampled and poorly understood in the context of trace gas cycling so far. From 2012 to 2017 we collected fifty-two depth profiles of dissolved CH₄ during three cruises (M91, SO243, and M138) to the eastern tropical South Pacific Ocean off Peru. In this study, we present the inter-annual variations of the CH₄ distributions in the water column off Peru, estimate the air-sea exchange from the upwelling region and decipher the influence of both the OMZ as well as the eddy structures on the CH₄ pathways off Peru.

Pathways and variability of N₂O emissions in the Pacific Ocean

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N₂O is a potent greenhouse gas and a major sink for stratospheric ozone. About a third of atmospheric N₂O originates in the ocean, with the Pacific accounting for as much as half of all oceanic N₂O emissions. However, little is known about the variability of this flux. Part of the challenge lies in the difficulty of disentangling the multiple, and sometimes simultaneous pathways that produce and consume N₂O in the ocean interior, and the circulation features responsible for its outgassing. Ocean biogeochemical models can shed light on these processes; however they typically rely on crude parameterizations of N₂O production, and are too coarse to represent important scales for N₂O cycling and transport. In contrast, we build a process-based model that represents known pathways of N transformation that are relevant to N₂O cycling, using environmental dependencies that reflect microbial physiology. We optimize the model in a 1D advection-diffusion framework by using recent tracer and rate measurements. This optimized solution is incorporated into an eddyresolving, Pacific-wide ocean circulation model with enhanced resolution over eastern boundary upwelling regions, driven by atmospheric reanalysis. This model allows us to parse the contribution of different N-cycle pathways to oceanic N₂O production and outgassing, and to investigate their temporal variability, for example as driven by the El Niño-Southern Oscillation.
Insights of the dynamics in the East Pacific upwelling system from a nested 1/20° ocean circulation model

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The oxygen budget within the oxygen minimum zone (OMZ) is generally a complex and not yet fully understood interplay between different processes of oxygen supply and consumption. Modelling studies indicate that a deficient circulation is at the core of the problem rather than an admittedly poor quantitative understanding of biogeochemical cycle. Here we use the new high-resolution nest configuration VIKING20X to examine dynamics in the upwelling system and adjacent regions in the tropical east south Pacific. The horizontal resolution of 5km or less together with the temporal resolution of daily hydrographic parameter fields give a good representation of the boundary current system as well as mesoscale eddy features. Focussing on the physical aspects we will investigate formation processes and development as well as life-time and spreading paths of mode water eddies contributing significantly to property exchange (heat, salt and biogeochemical parameters) from the upwelling system to the ocean interior.

Dissolved oxygen dynamics in coastal upwelling systems: insights from idealized submesoscale physical-biogeochemical modelling

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Coastal and shelf regions are particularly vulnerable to deoxygenation due to the highly productive upper ocean ecosystem and to physical transport bringing low oxygen levels from subsurface open ocean waters. Here we use a coupled physical (ROMS-CROCO)-biogeochemical (Oxygen-Phytoplankton-Zooplankton) model of an idealized coastal upwelling system of the Iberian Peninsula forced by upwelling favourable wind stress to determine the controlling factors of dissolved oxygen variability. It causes the surfacing of cold, nutrient-rich waters promoting phytoplankton growth and oxygen production by photosynthesis. An unstable front generates a field of mesoscale and submesoscale turbulence that controls the stirring of the oxygen field and redistributes dissolved oxygen across the shelf. A bi-modal pattern emerges with oxygenated waters inshore and depleted waters offshore. Oxygen enrichment of the surface coastal upwelling is highly sensitive to wind regime and phytoplankton growth rate. Our model results suggest that sustained upwelling lowers the enrichment rate due to continuous low oxygen injection from below; conversely, a wind relaxation period following intense upwelling increases the enrichment rate due to the cessation of low oxygen input, allowing photosynthesis to replenish the oxygen levels. Changes in phytoplankton conditions substantially reduce the rates of oxygen enrichment due
to strong non-linear interactions between biological and physical factors. Future work will investigate the importance of current-wind interaction for the dissolved oxygen dynamics and will aim at disentangling those complex processes driving oxygen concentrations variability in a more permanent and less oxygenated upwelling system.

**Demonstrating the value of enhanced multidisciplinary sustained observations for understanding variability in the oxycline and its impacts on the EBUS ecosystems**

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Providing critical ocean information to satisfy societies changing socio-economic needs requires a coordinated implementation of multi-disciplinary ocean observing activities. For the past 12 months, building on the Framework for Ocean Observing (FOO), we perform technological readiness level (TRL) assessments for observing the oxycline in highly productive and economically important Eastern Boundary Upwelling systems (EBUS). The upper oxycline being the transition between high and low oxygenated waters is of fundamental importance for the ecosystem structure. The ‘Variability in the Oxycline and its ImpaCts on the Ecosystem (VOICE)’ initiative demonstrates how societal motivations drive the need for enhanced and optimized integration of physical, biogeochemical and biological components of regional ocean observing and modelling. VOICE outlines a roadmap towards an observation-model synthesis for a comprehensive observing of oxycline dependent processes. Local, regional and global effects, such as deoxygenation trends, prompt for a better observing of the oxycline. VOICE determines its observing design based on scientific and monitoring activities in selected EBUS regions: the Humboldt Current System, West Africa (Canary and Benguela Current Systems), Northern Indian Ocean, and the California Current System. To facilitate the process of readiness level assessment, regional champions appointed by VOICE collect information from all relevant stakeholders in their region. Identifying local societal benefits and scientific applications, determines the drivers for enhancing and optimizing the design of the regional observing systems. Analysis of existing observing and data management capabilities with respect to the corresponding requirements for Essential Ocean
Variables (EOVs) and key ocean phenomena forms the basis for a comprehensive analysis of gaps in the observing system. VOICE distinguishes between gaps that are correctable through adaptation of existing platform/sensor sampling schemes or data processing chain, and critical gaps which require initiation of new observing elements and schemes. The readiness level assessment will thus point at system bottlenecks which prevent ocean observations from delivering information products for the societal benefits and applications identified by the users of the observing system. The ultimate goal of VOICE is to provide a globally-applicable blueprint of a multi-disciplinary sustained OMZ observing system, outlining a minimum and optimized set of observational and modelling requirements for a fit-for-purpose system, capable of informing the society about the variability in the oxycline and its impacts on the ecosystem. In this presentation we provide an overview of the TRL assessment in all VOICE regions and propose an initial gap-analysis and strategy for increasing the readiness levels in the regions.

POSTER PRESENTATIONS

(35) Dynamical characterization of a low oxygen submesoscale coherent vortex in the Eastern North Atlantic Ocean

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A submesoscale coherent vortex (SCV) with a low oxygen core is characterized from underwater glider and mooring observations from the eastern tropical North Atlantic, north of the Cape Verde Islands. The eddy crossed the mooring with its center and a 1 month time series of the SCV’s hydrographic and upper 100 m currents structure was obtained. About 45 days after, and 100 km west, the SCV frontal zone was surveyed in high temporal and spatial resolution using an underwater glider. Satellite altimetry showed the SCV was formed about 7 months before at the Mauritanian coast. The SCV was located at 80–100 m depth, its diameter was 100 km and its maximum swirl velocity 0.4 m/s. A Burger number of 0.2 and a vortex Rossby number of 0.15 indicate a flat lens in geostrophic balance. Mooring and glider data show in general comparable dynamical and thermohaline structures, the glider in high spatial resolution, the mooring in high temporal resolution. Surface maps of chlorophyll concentration suggest high productivity inside and around the SCV. The low potential vorticity (PV) core of the SCV is surrounded by filamentary structures, sloping down at different angles from the mixed layer base and with typical widths of 10–20 km and a vertical extent of 50–100 m.
(36) The impact of meso-scale eddies on oxygen variability in the Benguela upwelling system

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Coastal upwelling systems, such as the Benguela upwelling system (BUS), are highly biologically productive regions that host extended oxygen minimum zones (OMZs) as consequence of strong subsurface oxygen consumption. OMZs are of particular interest for marine biogeochemistry because these are the places where bioavailable nitrogen is removed from the marine environment. Size and evolution of OMZs thus play an important role for global ecosystem structure, nutrient cycling and the marine carbon storage. As for all Eastern Boundary Upwelling Systems oxygen distribution and variability in BUS are shaped by complex interplay of regional and large-scale ocean circulation and biogeochemistry. Long-term trends in oxygen are likely to be controlled by large-scale circulation, i.e. transport of nutrients, oxygen, and organic matter into BUS, and atmospheric boundary conditions, i.e. wind and temperature trends affecting upwelling dynamics and gas-exchange. The extent of the OMZ and higher frequency dynamics of oxygen are on the other hand expected to be altered by small-scale features such as meso-scale eddies, filaments, or local fronts. These hydrodynamical features are, in general, not captured by global ocean biogeochemistry models. Due to their computationally expensive set-ups with a global extent and due to high process resolution including a large number of transported state variables these models tend to be affordable only at coarse horizontal and vertical resolution. However, by omitting the representation of small-scale features global ocean biogeochemistry models often overestimate the size of OMZs. Here, we investigate the role of the temporal evolution of meso-scale eddy activities on shaping the oxygen distributions in BUS using the global ocean biogeochemistry model MPIOM/HAMOCC in eddy-resolving horizontal resolution. We conduct a transient simulation over the 20th century driven by reanalysis data (ERA20C, ERAinterim). This way we capture a wide (spatio-temporal) range of hydro-dynamical features and include local and remote responses of ocean biogeochemistry consistently. Meso-scale eddy activity enhances locally cross shelf exchanges of all biogeochemical tracers. It affects as well the water mass composition in BUS which has an impact on oxygen distribution and variability. We find a good representation of the oxygen mean state with an OMZ limited to the shelf area (< 300 m) as has been observed. Low water mass ages indicate eddy induced high ventilation rates within the upper 400 m of the water column outside shelf areas.
Mechanisms of future equatorial upwelling change: CMIP5 inter-model analysis

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Equatorial upwelling play an important role in oxygen via advection of oxygen and transport of nutrient to the euphotic zone used by biological production. Previous studies showed that climate models project the weakening of equatorial upwelling in the Pacific and Atlantic Oceans, and the main suggested responsible mechanisms are Ekman pumping near surface and equatorial undercurrent (EUC) change at depth. The latter may be associated with flattening of the zonal slope of EUC. Both changes are presumably caused by weakening of the trade wind. However, how much of upwelling reduction was not explained by each mechanism quantitatively. Therefore, in order to understand better the mechanisms of upwelling change, we analyze output data from 24 CMIP5 models in the equatorial Pacific and Atlantic until 2100 under RCP8.5. In order to obtain better physical explanation, we divide total upwelling into isopycnal upwelling (vertical velocity component of current velocity parallel to isopycnal surfaces) and diapycnal upwelling (difference between total and isopycnal upwelling). The total upwelling decreases in the equatorial Pacific and western Atlantic about 50-200m depth until 2100. The maximum decrease in the Pacific (it is located in the eastern Pacific) is about 30% of its climatology, and it is three times larger than that in the Atlantic. Three-fourths of total upwelling reduction in the eastern equatorial Pacific at 100m depth, where there is a boundary of euphotic zone which is important for biological production, is explained by the isopycnal upwelling change. Further division indicate that 71% (47%) of isopycnal upwelling change there is caused by the zonal isopycnal gradient change (zonal velocity change). Thus, about a half of equatorial upwelling reduction in the eastern Pacific is induced by the EUC flattening. It is shown that weakening of trade wind can explain 95% of EUC flattening without enhanced stratification. In the Atlantic, however, the mechanism is unclear because contributions of isopycnal and diapycnal upwelling differ among models and they are not statistically significant in contrast to the Pacific. Notes that zonal wind stress change and stratification are not independent in the Atlantic, whereas they are almost independent in the Pacific. It is thus possible that the mechanisms of upwelling change are different between Pacific and Atlantic.

Oxygen and nitrate variability in the shallow oxygen minimum zone off Mauritania

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Upwelling systems play a key role in the global carbon and nitrogen cycles and are of local relevance due to their high productivity and fish resources. To capture and understand the high variability of physical and biogeochemical parameters found in
these regions novel measurement technics have to be combined in an interdisciplinary manner. Here we use high-resolution glider-based physical-biogeochemical observations in combination with ship-based underwater vision profiler (UVP5), sensor and bottle data to investigate the drivers of oxygen and nitrate variability across the shelf break off Mauritania in June 2014. Distinct patches of oxygen anomalies were derived from the glider data, which strongly correlated with nitrate anomalies. High oxygen and low nitrate anomalies were clearly related to water mass variability and probably linked to ocean transport. Low oxygen and high nitrate patches co-occurred with enhanced turbidity signals close to the seabed, which suggests locally high microbial respiration of resuspended organic matter near the sea floor. This interpretation is supported by high particle abundance observed by the UVP5 and enhanced particle-based oxygen respiration rate estimates close to the seabed. Discrete in-situ measurements of nutrients, dissolved organic carbon and amino acids were used to further relate the observed oxygen and nitrate anomalies to local and large scale remineralization processes. Our observations highlight the complex interplay of remote and local physical-biogeochemical drivers of oxygen and nitrate variability off Mauritania, which cannot be captured by classical shipboard observations alone. By applying adaptive sampling strategies, combining high-resolution in-situ data with satellite data in near realtime, interdisciplinary data can be sampled in regions of interest. Such a data set allows decomposing physical, biogeochemical and biological drivers in highly variable upwelling systems.
Physiological Effects of Oxygen & Interactions with Multiple Stressors

Topic abstract

Oxygen availability has been a driving force for marine life over geological timescales, and today we can observe how its variability creates heterogeneity in space and time. For most organisms, oxygen is essential for survival, but for some it is toxic. In OMZ regions, oxygen becomes limiting and therefore structures the marine ecosystem strongly. For example, some protists thrive under anoxia and employ anaerobic mechanisms, whereas other protists and many metazoans might avoid low oxygen regions. Some zooplankton and nektont organisms migrate into and out of hypoxic or anoxic parts of the water column while other planktonic and benthic organisms can survive prolonged hypoxia. These capabilities are underlain by physiological adaptations, and ultimately act to structure species distributions. Hypoxia tolerance also strongly depends on temperature, environmental carbon dioxide levels and possibly other abiotic stressors, and changes in these factors can have ecosystem-wide effects. We invite contributions that deal with the physiological effects of oxygen - including interactions with temperature, carbonate system parameters and other stressors - on individual performance of benthic and pelagic protists and metazoans from the gene to population level. Issues of interest for this session include (i) mechanisms by which organisms adapt or acclimate to variations in oxygen levels at the cellular to organism level, (ii) how this leads to differences in physiological capacity (iii) impacts on the functional and behavioral attributes of marine organisms, and (iv) how the features can be parameterized for biogeochemical model development.

Conveners
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KEYNOTE SPEAKERS

05.09. WEDNESDAY | 11:15
Microbial biota in anaerobic and microaerobic habitats

Tom Fenchel // tfenchel@bio.ku.dk

Anaerobic zones occur in stratified water columns and almost universally in aquatic sediments at various depths. Anaerobic zones are covered by zones characterized by more or less steep oxygen gradients. These habitats harbor characteristic biota of unicellular organisms with zonation patterns determined by oxygen tension. The presentation will especially emphasize eukaryotic microbes in microaerobic and anaerobic habitats with respect to physiological adaptations and constraints and to zonation patterns exemplifying both sediments and the stratified water column.
**Tom Fenchel** | Professor Tom Michael Fenchel is a Danish marine ecologist and Emeritus Professor at the University of Copenhagen. He integrated physical, mathematical and biological concepts to develop our understanding of marine ecological processes. Tom was instrumental in the discovery and description of the microbial loop and developed ‘Fenchel’s law’, which states that the maximum reproductive rate of organisms decreases with body size. His work focused on the role of bacteria and protists in marine biogeochemistry, spanning from their motility and chemosensory behaviour in response to different environmental cues - including oxygen, the adaptation and activity of facultative and obligate anaerobes, and the evolution of microbial life without oxygen. In 1986 he received the ECI Prize of ecology and the Huntsmann Medal for Excellence in Oceanography and in 2006 he was awarded the A.C. Redfield Lifetime Achievement Award by the American Society of Limnology and Oceanography. He is member of the Royal Danish Academy of Sciences and Letters, the Norwegian Academy of Science and Letters, the Royal Society London, the American National Academy of Sciences and the Academia Europaea.

05.09. WEDNESDAY | 11:50

**Critical oxygen levels of marine animals and the consequences of ocean deoxygenation and warming**

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Oxygen supply to the sites of cellular respiration requires a partial pressure (PO2) gradient from the environment to the mitochondria to drive diffusion. In surface waters of the ocean, as in air, the PO2 drops from 21 kPa in ambient water to less than 1 kPa at the mitochondria. In some marine environments, such as mesopelagic oxygen minimum zones (OMZ), the PO2 in the ambient water is less than 0.5 kPa. Thus, the PO2 gradient driving oxygen utilization is a mere fraction of that required for aerobic metabolism in terrestrial, and most marine, environments. While animal diversity and abundance are reduced in the OMZ core, life does thrive there. Here we review hypoxia tolerance (critical oxygen partial pressures, Pcrit) in marine animals and show that hypoxia tolerance varies widely across species. This variation is unrelated to metabolic rate, phylogeny, body mass or temperature due to the fact that O2 demand and environmental hypoxia are compensated for by evolved physiological adjustments that enable effective O2 extraction, transport, and utilization. Temperature is the primary driver of intraspecific variation in Pcrit due to effects on oxygen demand. However, because temperature increases O2 supply, the average temperature sensitivity of Pcrit is less than that for metabolic rate. Despite substantial physiological adaptation and diversity, distributions of most species...
appear to be constrained by oxygen supply relative to demand. We demonstrate that changes in oxygen of only a few micromolar, which may occur over very short vertical and horizontal distances, are important in structuring some mesopelagic communities, even though these ecosystems contain species with the greatest hypoxia tolerance (lowest $P_{\text{crit}}$s) of any animals measured to date. Ocean deoxygenation will reduce environmental oxygen supply while global warming will increase metabolic demand, reducing the metabolically available habitat and dramatically restructuring mesopelagic communities.

**Brad Seibel** | Brad Seibel is Professor of Biological Oceanography working at the University of South Florida’s College of Marine Science. His research employs a unique suite of field and laboratory techniques and approaches to assess the ecological consequences of climate change, including ocean acidification, deoxygenation and warming, and the role of animal energetics in ecosystem dynamics. He takes a broad comparative approach to determine the constraints on evolution and ecology. Physiological mechanism provides a foundation upon which ecosystem responses to climate change and the consequences for biogeochemical cycles can be understood. He studies organisms across size, depth, latitudinal and phylogenetic lines, from microzooplankton to macronekton, ctenophores to fishes, from the poles to the equator and from the abyssal plains to the ocean surface. He strives to integrate across levels of organization, from mitochondria to ecosystems. Most recently he has sought to reveal how physiological hypoxia tolerance determines the vertical and horizontal distributions of organisms in oxygen minimum zones. He holds a PhD in Ecology, Evolution and Marine Biology and a BSc in Biological Sciences from the University of California, Santa Barbara. He completed Postdoctoral Fellowships at the University of Miami’s Rosenstiel School of Marine and Atmospheric Science and at the Monterey Bay Aquarium Research Institute.

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**05.09. WEDNESDAY | 12:25**

**It’s not just oxygen: understanding and managing a multiple stressor world**

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Deoxygenation does not occur in isolation. Anthropogenic nutrient enrichment, acidification, fisheries, rising temperatures, and other consequences of human activities can all influence the process of deoxygenation and alter physiological and ecological consequences of oxygen decline. The effects of multiple stressors can depend on the timing and order of exposures as well as severity; interactive effects can occur at levels of organization ranging from physiology to landscapes. The difficulty of clearly predicting combined effects of multiple stressors complicates our ability to project futures under a variety of scenarios, and to develop and implement effective management strategies. This talk will focus on recent and new ideas on the general issue of multiple stressors, and especially the combined effects of oxygen...
and other stressors in coastal systems and semi-enclosed seas. Proximity to large human populations results in these systems being altered by activities within their local watershed, airshed and waters. In addition, they are strongly affected by global consequences of increased greenhouse gas emissions, and are warming and becoming more acidic as well as more oxygen-depleted as a result. Although the large temporal and spatial variation in physical characteristics of these systems may have already selected for species with wide physiological tolerances, both experiments and models show that the combined effects of multiple stressors can strongly affect both individual organisms and food webs. Rising temperatures, deoxygenation and acidification are especially tightly linked; warming and nutrient enrichment increase respiration, which depletes oxygen and releases CO₂. Some stressors, such as increased temperatures, can make animals more sensitive to low oxygen, while others such as high mortality rates due to fisheries, may mask oxygen effects. Development of a framework for understanding effects of multiple stressors will require us to consider processes across life stages, generations and landscapes, as well as how behavioral responses to hypoxia can determine exposure to other stressors.

**Denise Breitburg** | Dr. Denise Breitburg is a Senior Scientist at the Smithsonian Environmental Research Center. Her research focuses on the effects of low oxygen on organisms ranging from fish to jellyfish and oysters, including effects on food webs, fisheries, and disease. She has also worked on the issue of multiple stressors in marine systems for over 20 years and has led or participated in several large, collaborative programs linking land use, nutrients and upper trophic level organisms in coastal systems. Her recent research explores the combined effects of hypoxia and acidification in temperate estuaries and tropical mangrove systems. Denise is co-chair of GO2NE – the IOC-UNESCO Global Ocean Oxygen Network, and led the working group’s recent Science review on the problem of ocean deoxygenation in the open ocean and coastal waters. She has also served on the governing boards of the Association for the Sciences of Limnology and Oceanography (ASLO) and the Coastal and Estuarine Research Federation (CERF). Denise holds a PhD in Marine Ecology and Ichthyology from the University of California, Santa Barbara, as well as a BSc in Biology from Arizona State University.
In situ respiration rates of meso- and bathypelagic animals

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In order to understand the effects of deoxygenating oceans on their inhabitants, we need accurate assessments of the animals’ oxygen consumption rates and their ability to regulate their metabolism under the conditions where they normally live. While an abundance of metabolic rate data for many mesoand bathypelagic species is available in the literature, these determinations were made primarily by taking animals that were captured by net, extracted from the depth/pressures that they normally experience, and then incubated at atmospheric pressure in the lab. More recent collections often utilized submersibles and more gentle collection techniques, thus reducing the trauma of collection; but the incubations are still primarily made after forced decompression, under laboratory conditions quite different from the animals’ natural environment. An exception to these methods was a short-lived, in situ midwater respiration system developed at Harbor Branch Oceanographic Institution (HBOI) in the late 1980s, where initial experiments showed evidence of significantly higher in situ respiration rates 2 to 5 times higher in two ctenophores species, a trachymedusa and a pelagic holothurian than those obtained in the laboratory. Unfortunately, that system was compromised before further experiments could be conducted. In an effort to determine if removing deep-sea animals from their natural environment affects their respiration rates, MBARI developed an ROV-deployed, in situ Midwater Respirometry System (MRS) similar to that of the original HBOI system. Newer and more stable electronics and optical sensors, as well as quartz-walled chambers and circulating, flushing and injection pumps have been incorporated into the MBARI MRS. The result is a very stable system that allows us to manipulate conditions within the chambers, as needed, for a particular experiment. The MRS enables us to collect animals at depth and then deploy the MRS module on a mooring in the midwater for 24 to 48 hours at the approximate depth of collection, while continuous oxygen measurements are made. We will present the results of over 10 years of MRS-derived respiration rates for a variety of midwater and bathypelagic fish, jellies, cephalopods, worms and crustaceans collected between 200 to 3000 m in depth. The in situ rates will then be compared to parallel rates determined in our shipboard and shore-based labs, as well as those found in the literature.

Oxygen dependence of visual function and ecology in marine larvae

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Vision is an essential and metabolically demanding (oxygen intensive) process for both vertebrates and invertebrates; in the marine environment this is true for active arthropods, cephalopods, and fish that possess complex eyes and ‘fast vision’
(high temporal resolution). Oxygen loss in the ocean, termed ocean deoxygenation, is occurring as a result of ocean warming effects on solubility and stratification, intensified upwelling, and increasing eutrophication. Additionally, both light and oxygen concentration exhibit strong gradients with depth in the ocean, particularly on highly productive margins with eastern boundary currents where the upwelling of low-oxygen water creates these steep gradients at shallow depths. This research examines the consequences of oxygen loss for visual function in larvae of different representative taxa and visual groups (e.g. crustaceans and cephalopods, compound eyes and simple eyes) that rely on vision for survival in their early life stages. Hypotheses that oxygen stress changes the physiological capability of the eye to respond to light and that the response is species-dependent are tested using electrophysiology experiments. Results show a marked effect of oxygen on the visual response to light stimuli, with visual decline of 10% of maximum response occurring even at 95 μmol/L oxygen concentration (6.6 kPa) in some species; oxygen values much higher than traditional physiological critical limits and definitions of hypoxia. Declines of visual function in invertebrates occur more strongly at high light intensities, indicating light intensity can become an additional stressor for upward-migrating species in habitat compression. The combined distribution of oxygen concentration and light levels in the water column that organisms are exposed to can be perceived as a luminoxyscape. Physiological limits of oxygen and light sensitivity for these species are compared with environmental data and used to calculate a species-specific ‘critical luminoxyscape’ where there are sufficient light and oxygen conditions that enable normal vision. Using data from hydrographic profiles obtained during quarterly cruises by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program since 1984, changes in the available critical luminoxyscape over time for these species are discussed and visual decline from oxygen and light stress is demonstrated to be an additional explanation for habitat compression from ocean deoxygenation.

**Variation in growth, morphology and reproduction of the bearded goby (**Sufflogobius bibarbaratus**) in varying oxygen environments of northern Benguela**

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This paper examines variations in gender-specific body growth, morphology and reproduction of the bearded goby (**Sufflogobius bibarbaratus**) across the Namibian shelf. The results indicate a spatial variation in the size composition, condition factor and maturation of gobies across the shelf area. Low oxygen (<0.5 ml O₂/L) did not hinder reproduction in the bearded goby and off Walvis Bay, maturing and mature
females and males were found mostly at the outer shelf edge (150–200 m depth). The histological analysis of gonads validates the macroscopic scale applied for assessing maturity, and the mean number of maturing oocytes was from 690 to 1060 per gram body weight. Males were smallest in the central area (where oxygen levels are known to be lowest), and relative condition increased latitudinally from north to south. The bearded goby displays clear sexual size dimorphism (males larger than females), and there is evidence that supports previous findings suggesting that males display alternative reproductive tactics. Assumed territorial males were older than assumed sneaker males, and all morphological measurements, except eye diameter, were larger (absolutely and relatively) in territorial males compared to sneakers. The morphologic measurements of sneakers did not differ from those of females suggesting female mimicry by sneakers. The role of unclassified males was less clear. The findings are discussed in view of environmental variation and behavioural ecology.

Winning ways with hydrogen sulphide on the Namibian shelf

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The ancient shelf upwelling system of the northern Benguela off Namibia has long operated under hypoxic pressure, likely close to biological tipping points, balancing always the abundance of particulate food against oxygen limitation and hydrogen sulphide toxification. The shelf sediments off Namibia are some of the most unusual and extreme marine habitats, containing high hydrogen sulphide concentrations. Surface productivity provides benthic life with so much carbon that benthic processes must rely on innovative mechanisms to cope with perennial anoxia and toxic hydrogen sulphide. Bottom dwelling communities are forced to adapt lifestyles to deal physically, physiologically and behaviourally with these stressful conditions. The upside of hydrogen sulphide is that it fuels extensive mats of large sulphide-oxidizing bacteria on the seabed, which create detoxified habitat niches and food for the animals living there, whilst the threat of hypoxic stress exacerbated by hydrogen sulphide in the water column is largely overcome by microbes that detoxify sulphide, allowing animals in the upper water layers to thrive. The bearded goby Sufflogobius bibarbatus is a cornerstone species that successfully couples the stressful benthic environment with the pelagic. Whilst community-scale benthic studies have not yet been characterized, these have the potential to uncover biotic adaptations to toxic sulphide with novel industrial, biomedical, biomaterial, or other applications.

Combined effects of warming and acidification on hypoxia tolerance of northern shrimp, Pandalus borealis

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Northern shrimp (Pandalus borealis) of the Estuary and Gulf of St. Lawrence (EGSL) typically inhabit waters deeper than 175 m and face chronic hypoxia (dissolved oxygen [DO] levels of 18–40% sat.). Hypoxia is typically accompanied by high PCO$_2$ values and low pH. For instance, the pH of the deep waters of the EGSL are currently below 7.75. However, most studies of hypoxia tolerance have been
performed at current surface pH values. This is the case for P. borealis: published values of O2crit, a measure of hypoxia tolerance, show that the species is fairly hypoxia tolerant at uncontrolled (~8) pH: 9 and 16% sat. at 5 °C and 14 and 22% sat. at 8 °C, in males and females, respectively. With global warming, the deep waters of the GSL are expected to become ~ 2–4 °C warmer by the end of the century. Hypoxia and acidification are expected to get worse and shrimp may face DO levels 4% sat. lower and pH of 7.55, or worse. Metabolic rate is expected to rise with increasing temperature. This increased oxygen requirement should reduce hypoxia tolerance. But the effect of pH on hypoxia tolerance is unknown for this species. The main objective of this study is to determine the impact of temperature and pH on standard and maximum metabolic rate and on hypoxia tolerance of female P. borealis. Female shrimp were exposed to 12 combinations of temperature (3, 6, 9, 12 °C) and pH (8, 7.75, 7.55) for a minimum of 30 days and tested in individual intermittent-flow respirometers. There was no effect of pH on SMR and MMR, and both increased significantly with temperature. Hypoxia tolerance decreased with increasing temperature, as expected. Interestingly, hypoxia tolerance was lower at the most severe pH level (7.55), but only at 3 and 6 °C. These results suggest that future combinations of temperature, DO and pH will result in habitat loss for this species in the EGSL.

Understanding physiological mechanisms of Chilean scallop to the multiple-stressor scenario of upwelling by using an experimental integrative approach

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Environmental variability of coastal areas in many cases overcomes forthcoming climatic projections. Studies simulating future environmental conditions conclude that higher temperatures and decreasing pH and oxygen levels have negative impacts on the physiology and life-history traits of marine biota. Nevertheless, a constantly growing number of studies notify neutral or positive responses of marine species to future climatic conditions. These studies reveal the existence of biological mechanisms, and provide significant information, of how coastal species are successfully able to cope with their environment. The northern Chilean coast has one of the most intense upwelling centers of the Humboldt Current System (Punta Lengua de Vaca, 30°18'S), whose activity (wind-activation and relaxation) modifies largely the pH, dissolved oxygen and temperature conditions of nearby coastal areas. This environmental scenario impacts over the most important scallop (Argopecten purpuratus) culture industry of Chile, located at Tongoy Bay (30°15'S). Previous studies that addressed how A. purpuratus would response to future predicted changes in temperature, pH and oxygen have evidenced certain tolerance to these changes. These studies suggest that
*A. purpuratus* is adapted to a great range of environmental changes as consequence of the exposure to upwelling conditions. However, to understand how this species will respond to future conditions, it is required to untangle the biological mechanisms, as well as, the tolerance ranges to average and extreme conditions that upwelling imposes. This study, contributes with information about the biological mechanisms that this species displays to cope with upwelling conditions by using an integrative approach (field and laboratory experiments). Biological and biochemical mechanisms were studied by measuring metabolic, growth, calcification responses, as well as, the expression of multiple stress proteins. The results of this study would allow a better prediction of the sensibility of *A. purpuratus* to future global change.

**Is oxygen limitation the cause for summer heat wave mortality in a coastal keystone predator?**

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The Baltic Sea is characterized by low salinity and pronounced fluctuations in pCO$_2$, pO$_2$ and temperature. On-line monitoring of pCO$_2$ in 2014 in Kiel Fjord demonstrated occurrence of peak values of $>2,000$ μatm in summer and autumn and average values $>700$ μatm due to extensive wind driven upwelling of hypoxic hypercapnic water masses. We assessed the impacts of elevated temperature (ambient temperature, ambient +3°C) and pCO$_2$ (800, 1,500, 2,400 μatm) on a keystone species, the sea star *Asterias rubens*, in a fully crossed long term experiment (N=5 replicate tanks each, 1 year duration 2013-2014). During spring and early summer (February – June), high temperature animals ingested significantly more food and spawned significantly earlier than ambient acclimated animals. Elevated pCO$_2$ led to comparatively minor reductions in food intake and scope for growth during that period. During summer (June – August), elevated temperature $>25$°C caused negative energy budgets and $>95$% mortality in the warm acclimated groups, while mortality was low in the ambient temperature groups. Short-term heat tolerance experiments indicate that heat stress leads to reductions in coelomic fluid pO$_2$ and, eventually, accumulation of anaerobic endproducts. Sublethal heat stress induced reductions in feeding rates can also be related to oxygen limitation. Time series analysis indicates that 3 out of the last 15 years were characterized by heat waves of similar magnitude, indicating that future warming will constitute a strong selective pressure for sea stars in the Baltic Sea. Our results indicate that *A. rubens* may benefit from increased temperature during colder months, yet dramatically suffer during summer heat waves in warm years. Surprisingly, upwelling of hypoxic water masses from below the pycnocline is beneficial during summer heatwaves. Meaningful experimental approaches to assess species vulnerability to climate change need to encompass all seasons and realistic abiotic stressor levels.
Intraspecific diversity and the selection of correlated sensitivities to multiple global change factors

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Population responses to global change are driven by multiple factors interacting with each other and with intraspecific diversity. Correlations between responses to different drivers can alter selective outcomes dramatically. In three near-natural experiments, we explored response correlations of genetically different full-sibling families of seaweed germlings towards four global change drivers: elevated CO2 (ocean acidification, OA), ocean warming (OW), combined OA and warming (OAW), nutrient enrichment and hypoxic upwelling. Among families, sensitivities towards OA and OW as well as towards OAW and nutrient enrichment correlated positively whereas sensitivities towards OAW and hypoxia anti-correlated. This indicates a trade-off between OAW and hypoxia acclimation and may further imply that fast adaptation to one or two global change factors could be nullified by an associated increase in sensitivity towards a further stressor. We conclude that response correlations have a huge high potential to boost or hinder acclimation and adaptation to multifactorial global change scenarios.

The effects of hypoxia and ocean acidification on grazing interactions within giant kelp forests

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Climate change is impacting marine ecosystems worldwide through a suite of associated stressors, including ocean acidification, warming, and hypoxia. However, our current understanding of the effects of climate change are primarily confined to single species, single stressor studies. To gain a broader understanding of its impacts at the community level, it is critical to examine interactions between species under multiple stressors. To address this, we examined the effects of ocean acidification and hypoxia within giant kelp forest grazing communities of the California Current, systems that are characterized by rich diversity, economic value, and the natural co-occurrence of low pH, low oxygen waters associated with upwelling. We measured grazing on cultured juvenile giant kelp, an important foundation species, by four species of invertebrate grazers under the two stressors in laboratory factorial experiments. We ran four-day experiments and found that species differed in their grazing impacts, with the brown turban snail (Chlorostoma brunnea) consuming the most kelp, followed by the kelp isopod (Idotea resecata), kelp curler amphipod (Peramphithoe humeralis), and the purple urchin (Strongylocentrotus purpuratus). Overall, hypoxia negatively impacted grazing more than acidification across all four species, suggesting that hypoxia can drive changes in feeding behavior even over short timeframes. In follow up studies to confirm the dominant effect of hypoxia over ocean acidification, we ran a second set of four-day factorial experiments with a lower pH level. Once again, we found that hypoxia negatively impacts grazing across
the four species, while acidification has no effect compared to control conditions. In systems where stressors co-occur naturally, it is important and relevant to examine the impacts of multiple stressors, and equally relevant to examine the relative role of individual stressors in driving physiological and behavioral changes to predict thresholds and plan mitigation strategies. This study provides key insights into the impacts of multiple stressors associated with global change through the lens of species interactions, which will shed light on how kelp forest communities might function in the future.

**Variable yet predominantly additive effects of concurrent hypoxia and elevated pCO₂ on marine biota**

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O₂ depletion in marine ecosystems often occurs concomitantly with elevated pCO₂. On a global scale, this coupling is attributed to the concurrent processes of ocean acidification and reduced O₂ solubility as a by-product of rising ocean temperatures and enhanced stratification of the deep-sea. On a more local-scale, however, this inherent link is driven mostly by metabolic processes; where biological respiration outweighs primary productivity to consume O₂ and produce CO₂. Here we used a meta-analytical approach to assess the impacts of hypoxia and elevated pCO₂ on biological responses of marine biota. We further test the relative responses of biota obtained in the analysis against the Respiration Index (RI) as a potential predictor of biological responses for a wide range of pO₂ and pCO₂ conditions. Analysis of the dataset, comprised of 363 experimental comparisons, revealed predominantly additive effects (71.9%-additive, 19.0%-synergistic, 9.1%-antagonistic) of hypoxia and elevated pCO₂ on marine taxa. Results of our RI analysis support previous criticisms of its defined thresholds for limits of marine life. Even so, we demonstrate that the RI may hold power as a valid predictor of biological responses to hypoxia and elevated pCO₂. Our findings demonstrate heterogeneity of responses among taxa but highlight the importance of assessing the concurrent impacts hypoxia and elevated pCO₂ on marine organisms.

**Ocean deoxygenation overrules ocean warming and acidification impacts in marine biota**

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Man-induced global climate changes are leading to severe modifications on the ocean’s physicochemistry, with far-reaching consequences for marine life. While CO₂ emissions are warming and acidifying seawater masses, oxygen content is
diminishing due to decreased oxygen-solubility, increased stratification, augmented microbial respiration, and other abiotic/biotic processes. Following well-established theoretical model predictions, we performed hierarchical mixed-model meta-analyses testing the effects of climate change-related stressors (ocean acidification, warming, both aforesaid stressors combined, and hypoxia) across different biological responses, taxonomic groups, ontogenic life stages and climate regions (i.e. moderators). Overall, and within tested moderators, hypoxia affected marine life to a starkly greater extent than the other stressors. Thus, decreased mean oxygen content, and consequent expansion/forming of oceanic hypoxic areas, are likely to become a primary deterrent for life in future oceans.

**Marine invertebrate responses to temperature-related stressors and their interactions**

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As the global climate adjusts to anthropogenic high levels of CO₂, marine organisms have to cope with multiple changing environmental stressors that influence their performance. Marine metazoan hard limits to temperature and chronic anoxia have long been known. However, interactions between stressors, such as synergies between temperature and both low oxygen levels and acidification, have emerged relatively recently as concordant across many experiments and organisms. Understanding interactions is critical because stressors rarely occur singly. Multiple temperature-related stressors (TRS) have been implicated at most, if not all, past extinction crises, although their geographical distributions may be relevant to their impact. We present a meta-analysis of experiments involving multiple TRS and their interactions. Results have implications for the interpretation of patterns in fossils in regard to ancient impacts of TRS. We show interactions to be wider than previously reported within TRS, and to vary by response type and organism ontogenetic stage. Forecasting the effects of TRS on marine organisms by modelling single stressors, such as temperature, is unlikely to reveal more than a low estimate of the severity of response. Geographical context is also likely to be important, although general trends are evident. Cross-checking biological responses between fossil and current evidence is recommended as best practice.
Impacts on Fisheries / Socioeconomics

Topic abstract

Declining oxygen in the world's oceans is expected to have a significant impact on fisheries as well as other socioeconomic activities over the 21st century. In fact, change may already be detectable in terms of reduced biomass production, loss or diminution of species, losses of shellfish beds and coral reefs, and changes in fish stock locations as species are forced to flee low oxygen water masses, for example. This session will explore the effects of spreading deoxygenation on fisheries, tourism, coastal communities, and other aspects of societal well-being. Papers are welcome on topics ranging from fisheries assessments, to economic, ecological-economic, and social-ecological-systems analyses.

Conveners
Karin Limburg // SUNY College of Environmental Science and Forestry, USA
Martin Quaas // Kiel University, Germany

KEYNOTE SPEAKERS
06.09. THURSDAY | 09:00
Deoxygenation effects on fisheries: a mosaic of effects and responses

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Dimitri Gutiérrez // Marine Institute of Peru, Peru
Denise Breitburg // Smithsonian Environmental Research Center, USA
Daniel Conley // Lund University, Sweden
J. Kevin Craig // NMFS/SFSC-NOAA, USA
Halley E. Froehlich // Conservation Aquaculture Research Team, USA
R. Jeyabaskaran // Fishery Environment and Management Division, Central Marine Fisheries Research Institute, India
V. Kripa // Fishery Environment and Management Division, Central Marine Fisheries Research Institute, India
Baye Cheikh Mbaye // Maurice Lamontagne Institute, Canada
K.S. Mohamed // Fishery Environment and Management Division, Central Marine Fisheries Research Institute, India
Shelton Padua // Fishery Environment and Management Division, Central Marine Fisheries Research Institute, India
D. Prema // Fishery Environment and Management Division, Central Marine Fisheries Research Institute, India

Fisheries (harvest) are an ecosystem service that provide employment and nutrition in the global food system. Worldwide production of wild fisheries has leveled off, while demand continues to increase. Over harvesting switches fisheries from an ecosystem service to a stressor. Deoxygenation is anticipated to expand over the next decades, and can affect fisheries through negative effects on growth, survival, and reproduction, and effects on movement that, in turn, affects the availability and location of the harvestable biomass. Quantifying the effects of deoxygenation
on fisheries is challenging because of the effects of other stressors (e.g., warming, acidification) that partially covary with oxygen and because the dynamics of oxygen and fisheries are highly site-dependent. We review existing studies on the effects of deoxygenation on fisheries. In statistical (correlation-based) analyses spanning multiple coastal hypoxia ecosystems, stock biomass and landings were positively related to nitrogen loadings but it was difficult to isolate a direct hypoxia effect. However, the analysis suggested that trophic efficiency (landings per unit nitrogen loadings) was low in systems with extensive hypoxia. Eight case studies show the various ways deoxygenation can affect fisheries: Atlantic croaker and shrimp in the Gulf of Mexico, Dungeness crab in Hood Canal (Puget Sound), cod in the Baltic Sea, anchovy and other species in the Peruvian EEZ, Indian Oil Sardine in the southwest coast of India, white grouper in coastal west Africa, and billfishes in the eastern tropical Pacific. Case studies include low oxygen effects on the population itself through reduced recruitment and population abundance, and examples of spatial distribution effects resulting in changes in the dynamics of the fishing vessels. Modeling analyses demonstrate that, in those situations when hypoxia alone may have small to moderate population-level effects, the effects become amplified when hypoxia is combined with other stressors. A prevalent effect of deoxygenation documented in the case studies was changes in fishing locations in response to fine-scale distributional changes of the fish that then affect the catchability and bioeconomics of fishing. Further refining the role of deoxygenation on fisheries will increase the effectiveness of management by enabling proper interpretation of population fluctuations and spatial dynamics, more accurate view of the vulnerability of fish to harvest (e.g., catchabilities), and the derivation of robust population indices used in stock assessments. There is little room for management mis-calculations; too many people depend on effective management of fisheries to ensure sustainable harvests and healthy ecosystems.

Kenneth Rose | Dr. Rose’s research centers on using mathematical and computer simulation modeling to predict and better understand fish population and food web dynamics in estuaries, lakes, reservoirs, and oceans. Dr. Rose is presently the France-Merrick Chair in Sustained Ecosystem Restoration at Horn Point Laboratory. Prior to that, he was a Professor at the Department of Oceanography and Coastal Sciences, and Associate Dean in the College of the Coast and Environment, at Louisiana State University. He started his career as a consultant in Washington, D.C. and then as a research staff member at Oak Ridge National Laboratory. Dr. Rose has served on multiple editorial boards, and was recently awarded the Award of Excellence (for lifetime achievement) from the American Fisheries Society. He has been a member of multiple steering and advisory committees providing scientific guidance and oversight, including several National Academy of Sciences’ committees, the US GLOBEC program, and the US Army Corps of Engineers. Dr. Rose has been involved with a wide range of fisheries management issues and contentious environmental issues that often involve fish; these highlight the sometimes tricky arena for scientists where science meets policy and decision-making. He received his BSc degree in biology and mathematics from the University at Albany, and his graduate degrees in fisheries from the University of Washington.
Effect of deoxygenation on fish biology and fisheries in an enclosed brackish marine ecosystem

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Increased deoxygenation has affected worldwide the biology and behavior of fish and invertebrates, and the structure and functioning of marine ecosystems. Hypoxia can affect organisms through several direct and indirect mechanisms, which are not mutually exclusive and whose effects may sum up to lead to the observed changes. The species that are directly affected by deoxygenation are often highly important commercial species with large consequences on the fisheries relying on these resources. The effects of low-oxygen conditions on the fishery can span from lower quantity and quality of the catches as well as increased fishing efforts and changes in exploitation areas and gears. In some areas, such as the brackish Baltic Sea, deoxygenation has also coincided with an increased difficulty to determine fish age using otoliths, hampering the reliability of stock assessment estimates that are used as base for management advice. This has made the Baltic cod fishery losing its quality certification and eco-labelling with potential repercussions on the industrial revenues. In this talk, an overview of the effects of increased hypoxia on exploited fish species and the industry will be provided with focus on the Baltic Sea.

Michele Casini | Dr. Michele Casini is a marine and fisheries ecologist working at the Swedish University of Agricultural Sciences, SLU (Sweden). He is currently Professor in Marine ecology and fisheries management at SLU’s Department of Aquatic Resources. His research activities are mainly focused on fish ecology, population dynamics, trophic interactions and ecosystem functioning, at both temporal and spatial scales. In general, his research has overall addressed the issue of integrating information on hydro-climate, human-related aspects (such as fishery and eutrophication) and species interactions to foster an ecosystem-based management of the natural resources, using the brackish Baltic Sea as model system. His research has generated a great deal of interest, and has been cited by, among others, the New Scientist and BBC News. Dr. Casini has been Chair and member of several Working Groups within the International Council for the Exploration of the Sea (ICES) and collaborated with the European Commission and European Parliament for the implementation of an ecosystem-based fisheries management. He also collaborates with third-world countries, especially in Africa, in fisheries management and biological conservation. He received his BSc degree in Natural Sciences from the University of Bologna (Italy), and his graduate degrees in Marine Ecology from the University of Gothenburg (Sweden).
Fish, ocean oxygen depletion and the food security of current and future generations

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It turns out that the ocean carries a heavy burden of climate change by absorbing more than 30% of the carbon produced on land. While this is a great service in the first instance it results in physical and chemical changes that are already changing the biophysics of the ocean, triggering acidification and de-oxygenation. Here, I will explore the potential food security and economic consequences of increasing depletion of ocean oxygen via its impacts on fish populations. This analysis is needed because it has been predicted that oxygen levels in the world’s oceans have already declined by 2% on average in the last 50 years, with the fall in the Pacific Ocean much higher than the average. This decline is predicted to accelerate into the future if we fail to take action to reduce CO₂ emissions. In conducting our analysis, we will develop a number of scenarios and use economic indicators such as catch, revenues and profits to explore how and to what extent de-oxygenation would likely threaten the food security (defined broadly) of both current and future generations of people through its impact on fish stocks.

Rashid Sumaila | Dr. Rashid Sumaila is Professor and Director of the Fisheries Economics Research Unit & the Ocean Canada Partnership at the University of British Columbia. He specializes in bioeconomics, marine ecosystem valuation and the analysis of global issues such as fisheries subsidies, illegal fishing, climate change and oil spills. Sumaila has authored over 225 journal articles; including in Science, Nature and the Journal of Environmental Economics and Management. He is winner of the 2017 Volvo Environment Prize, the 2017 Benchley Oceans Award in Science, the 2016 UBC Killam Research Prize, and the 2013 American Fisheries Society Excellence in Public Outreach Award, the 2009 Stanford Leopold Leadership Fellowship and the 2008 Pew Marine Fellowship. Sumaila was named a Hokkaido University Ambassador in 2016. He has given talks at the UN Rio+20, the WTO, the White House, the Canadian Parliament, the African Union, the British House of Lords and the St James Palace on the invitation of Prince Charles. His research has generated a great deal of interest, and has been cited by, among others, The Economist, The Boston Globe, New York Times, the Globe and Mail, the Wall Street Journal and the Vancouver Sun.
ORAL PRESENTATIONS

Economic repercussions of tipping points in the Humboldt upwelling system

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Although the Eastern boundary upwelling ecosystems (EBUS) comprise less than 2% of the ocean area, they contribute more than 20% of the world's marine capture. With catches about currently 8 million and a decadal-scale variation ranging from 2.5 to 13 million tonnes per year, the catches from the Humboldt upwelling system (HUS) are by far the largest of all EBUS. The anchoveta fishery of Peru is the most important fishery of the HUS, and the largest fishery worldwide in terms of biomass output. Globally, it is the most important producer of fishmeal, with a share of roughly one third in global production. While the world price of fishmeal negatively correlated with Peruvian anchoveta catches before 2000, the price has steadily increased independent of Peruvian catches during the past decade, due largely to the growing demand of fishmeal in aquaculture production. In this paper, we first review the empirical evidence that identifies an effect of changes in Peruvian fish catches on world market prices of fishmeal and fish oil. We set up a stylized bioeconomic model that links catches in the Peruvian anchoveta fishery on the one side to biophysical conditions in the HUS and on the other side to aquaculture and reduction fisheries around the globe to explore the down-stream effects of changes in the HUS. We conclude that a regime shift in the HUS towards oxygen depletion can impair food security in developing countries. An increased world-market price for fishmeal decreases the supply of local markets with small pelagic fish available for human consumption, and increases fishing effort, thus aggravating the problems of overfishing in the long term.

Valuing ecosystem services at risk from deoxygenation of oceans, estuaries, and coastal seas

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“Ecosystem services” is a construct to motivate people and institutions to preserve and steward ecosystems. As such, the concept has been much discussed, but has been difficult to integrate into mainstream policies, except for aspects that are
readily monetized, such as income from harvest. This has been particularly true for services that are not readily apparent to the average person. Here we address a problem – ocean deoxygenation – increasing in scope and severity, but mostly invisible to the public. We consider aquatic ecosystem services that have, or will be, placed into jeopardy from oxygen loss. We take a case study approach, focusing on a number of well-known hypoxic regions (Baltic Sea, California OMZ, Gulf of Mexico, Gulf of St. Lawrence, and Western Long Island Sound near New York City), as well as the emerging issue of coral reef deoxygenation events. We provide preliminary assessments, and also discuss how to communicate this information to policymakers as well as to the general public.

**Ecological-economic sustainability of the Baltic cod fisheries under global change**

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Human-induced climate change such as ocean warming and acidification, threatens marine ecosystems and associated fisheries. In the western Baltic cod stock socio-ecological links are particularly important, with many relying on Atlantic cod for their livelihoods. A series of recent experiments revealed that cod populations are negatively affected by climate change, but an ecological-economic assessment of the combined effects, and advice on optimal adaptive management are still missing. We use experimental and time-series data to upscale physiological processes to the population level by incorporating these effects into the stock-recruitment model. Using an ecological-economic optimization approach, we assess the effect of increasing CO₂ and temperature levels on ecological (stock size), economic (profits), consumer-related (harvest) and social (fishing effort) indicators, ranging from present day conditions up to future climate change scenarios. Ocean warming has an overall negative effect on cod recruitment in the Baltic. Optimal management would react by lowering fishing mortality with increasing temperature, to create a buffer against climate change impacts. The negative effects cannot be fully compensated, but even at 3°C warming above the 2014 level, a reduced but viable fishery would be possible. However, when accounting for combined effects of ocean warming and acidification, even optimal fisheries management cannot adapt to changes beyond a warming of +1.5° above the current level. Our results highlight the need for multi-factorial climate change research, in order to provide the best available, most realistic, and precautionary advice for conservation of exploited species as well as their connected socio-economic systems.
Coastal Systems: From Understanding to Management

Topic abstract

In the coastal ocean, encompassing the river-estuary-sea continuum, low-oxygen zones have spread exponentially since the 1960s and have been reported for hundreds of systems worldwide. This primarily results from the proliferation of eutrophication as a consequence of the increased river exports of nitrogen, phosphorus and carbon during the last decades. In some regions, the oxygen levels are so low that living organisms and biogeochemistry are altered, leading, in some cases, to mass mortality events. In extreme cases, anoxia occurs with the production of hydrogen sulphide which is toxic to multicellular organisms. In addition to deoxygenation, the coastal zone faces many other stressors like warming, acidification, and fishing. These stressors in combination with deoxygenation will affect coastal ecosystems in ways that are not well understood with potential consequences that are currently ignored in environmental and resource management. The session aims to overview recent developments and understanding, by inviting observational, experimental and modelling studies of the deoxygenation process in the coastal zone. Themes of particular interest include:

• Observing oxygen: development of new sensors for the coastal zone (e.g. improvement of detection limits, spatial and temporal resolution, observation from space of anoxic events), establishment of an observing system for the coastal zone (e.g. alarm system, variables that need to be monitored conjointly with oxygen)
• Mapping oxygen: data availabilities for the global coastal zone, coastal climatologies, new methodologies
• Assessing the consequences on biogeochemical cycling of oxygen deficiency: impact on the cycling of major elements, production of greenhouse gases (e.g. CH₄, N₂O), nitrogen fixation, development of feedback loops (e.g. release of sediment phosphorus)
• Assessing the consequences of oxygen deficiency on individual organisms: multi-stressor impacts, development of particular species (e.g. invasive species, cable bacteria), trait selection
• Assessing the consequences of oxygen deficiency at the scale of the ecosystem: from individuals to ecosystem and fisheries: how to scale up?
• Modelling oxygen: processes and scales of importance, coupling between systems (e.g. development of an approach offering a seamless coupling between the river-estuary-sea continuum, coupled ocean-atmosphere models, benthic-pelagic coupled models), models addressing the impact of blue growth activities (e.g. aquaculture development)
• Predicting oxygen: predictive capabilities, forecasting oxygen in operational oceanography, modelling the risk, ensemble approaches, scenarios of changes
• Recovering from oxygen deficiency in a globally changing environment: management strategies that succeeded or failed to recover from oxygen deficiency, combination of different stressors (e.g. warming, acidification, fishing)

• Communication to stakeholders: information needed (e.g. saliency, robustness, richness), cost-benefit analysis, best practices of interactions

**Conveners**
Marilaure Grégoire // University of Liège, Belgium
Katja Fennel // Dalhousie University, Canada
Minhan Dai // Xiamen University, China
Renato Quiñones // University of Concepción, Chile

**KEYNOTE SPEAKERS**

**06.09. THURSDAY | 11:15**

**Greening of the land and the coastal ocean**

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Increasing human population. Increasing need for food, fiber and fuel. Increasing use of fossil fuel. Increasing generation of reactive-Nitrogen into airscapes, landscapes, and seascapes. Increasing incidences of coastal ocean oxygen-depleted waters (or hypoxia), especially since the 1950s. Increases in coastal areas of oxygen depletion parallel large-scale landscape changes, including deforestation, expansion of agricultural lands, more intense fertilizer use, cropping choices including corn for corn-based ethanol, loss of wetlands and riverine buffer zones, changes in cropland drainage, especially subsurface tile drains, and hydrologic controls restricting the floodplain removal of nutrients (i.e., levees or impervious surfaces). This trend for well-developed countries and developing countries is especially evident in agriculture landscapes and highly populated coastal urban centers. Physical/biological dynamics generate varying levels of dissolved oxygen concentrations that affect living resources in multiple ways. The assemblages of organisms in estuaries and coastal waters are exposed to deoxygenated waters in ecosystems ranging from mostly permanent hypoxia, seasonally but annually persistent hypoxia, intermittent deoxygenation where physical forces disrupt longer periods of seasonal deoxygenation, and during diel cycles in areas with subaquatic vegetation. Oxygen deficiency creates unsuitable feeding habitat for demersal organisms, including the commercially important penaeid shrimps, crabs, lobsters, cod, red snapper, and other prized fish. Consider that cod eggs sink to their preferred density/depth within macroalgal beds affected by low oxygen, and where they now die and do not contribute to future recruitment, and that a 20,000 km² swath of severely low oxygen waters in the northern Gulf of Mexico occurs at the same time brown shrimp need to migrate from estuaries to deeper waters and greater secondary production. Hypoxia restoration requires the reduction of the high nutrient loads to coastal waters, which are primarily the result of expanded agribusiness (artificial fertilizers), intensified animal husbandry, insufficiently treated wastewater, and unnecessary consumption of fossil fuels. The societal shifts to a less consumptive life style are not always politically palatable, but some governmental units have come
together and implemented multi-faceted plans that partially reduced nutrient loading. Ecosystem recovery may take years to decades following long-term exposure to long-lasting hypoxia, and a serious commitment by individuals, societies and governments will be needed to improve coastal water quality.

Nancy Rabalais | Nancy N. Rabalais is a Professor and the Shell Endowed Chair in the Department of Oceanography and Coastal Sciences at Louisiana State University. Her research interests include the dynamics of hypoxic environments, interactions of large rivers with the coastal ocean, estuarine and coastal eutrophication, benthic ecology, fate and effects of contaminants, and science policy. She is an author of 3 books, 34 book chapters, and over 125 peer-reviewed publications. Dr. Rabalais is active in state, national and international working groups, panels, and advisory boards. She currently serves on the University-National Oceanographic Laboratories Fleet Improvement Committee and Board of Directors of the Gulf of Mexico Coastal Ocean Observing System. She has served on eight National Research Committees for the National Academies and is a past member and chair of the Ocean Studies Board. Dr. Rabalais has received numerous awards for her work on eutrophication and coastal hypoxia. She is an American Association for the Advancement of Science Fellow, an American Geophysical Union Fellow, an Aldo Leopold Leadership Program Fellow, and a National Associate of the National Academies of Science. She was awarded the Clarke Prize of the National Water Resources Institute, the Ruth Patrick Award of the American Society of Limnology and Oceanography, the B. K. Ketchum award from Woods Hole Oceanographic Institution, the Blasker Award for Environmental Science and Engineering, shared with R. E. Turner, a Rachel Carson Lectureship for the American Geophysical Union, the Benchley award, the Heinz award, and in 2012 was named a MacArthur Fellow.

06.09. THURSDAY | 11:50

**Coupled physical-biogeochemical study of eutrophication / hypoxia in the Pearl River estuary off Hong Kong**

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The coastal waters around Hong Kong are affected by persistent and increasing eutrophication. This deteriorating situation may increase the frequency of HABs, expand the area of hypoxic zones and lead to other ecosystem disruptions and worse of all, offset the environmental improvements achieved through the costly Harbour Area Treatment Scheme over the last decade. Eutrophication/hypoxia in Hong Kong waters is primarily caused by the ecosystem’s responses to the increasing nutrient discharge from the Pearl River and local sewage effluent. Highly variable oceanic currents transport the nutrients in the interactive river-estuary-shelf (RES) waters around Hong Kong, which undergo complex coupled physical-
biogeochemical processes and modulate eutrophication/hypoxia. To date, these key processes have not been investigated in a comprehensive manner in the RES waters, and they remain largely unresolved in similar ecosystems elsewhere in the world. Understanding the full spectrum of intrinsic coupled physical and biogeochemical processes in eutrophication is crucial to predicting and mitigating the impacts of eutrophication, and it remains a huge scientific challenge regionally and globally. By conducting an interdisciplinary study, we investigate the coupled physical-biological-chemical processes in this interactive RES system, and diagnose the eutrophication/hypoxia in the study region. We conducted interdisciplinary mapping and time-series measurements, and based on them, developed a novel coupled physical-biogeochemical modelling system under a grand OCEAN_HK project to determine: sources and sinks of nutrients, their biogeochemical controls, ecosystem dynamics, and physical controls on the eutrophication/hypoxia in the RES waters.

Jianping Gan  |  Dr. Jianping Gan graduated from the Department of Atmosphere and Ocean Sciences, McGill University (Canada) in 1995. He is a Chair Professor in the Department of Ocean Science and Associate Dean of Fok Ying Tung Graduate School, the Hong Kong University of Science and Technology (HKUST). He joined HKUST in 2003 after 15-years of research in Canada and United States. He is a physical oceanographer conducting hard-core research in ocean circulation, marine ecosystem dynamics and numerical ocean modeling. In the last 30 years of his career, he has made various contributions in these fields. Prof. Gan has contributed to geophysical fluid dynamics of ocean circulation and interdisciplinary numerical ocean modeling study. In particular, he has developed the knowledge-based numerical modeling of ocean circulation and of associated physical dynamics in the China Seas and in other parts of the world's oceans. He has also developed the first hard-core interdisciplinary study in coupled physical-biogeochemical dynamics, both in numerical modeling, field measurement and process study in Hong Kong. Prof. Gan has participated in several grand research projects as a PI, such as Coastal Ocean Advances in Shelf Transports (COAST, USA), the National Basic Research Project (973 Project, China) on Carbon Cycle in China Seas (Mainland China) and an on-going Theme-based Research Scheme (Hong Kong, China). He actively served in international and domestic communities. He was elected as a founding President of the Ocean Section and a council member in the Asia Oceania Geosciences Society (AOGS).

06.09. THURSDAY | 12:25
The Baltic Sea: From Understanding to Management

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Excessive nutrient inputs over the last century have altered the subtle balance between oxygen supply and oxygen consumption and changed the Baltic Sea from a state with hypoxia confined to the deepest bottom waters to widespread hypoxia in most bottom waters. The Baltic Sea is naturally susceptible to hypoxia because...
the pronounced vertical stratification in the water column prevents the resupply of oxygen below the permanent halocline, and the salt water inputs from the adjacent North Sea through shallow sills influences both horizontal and vertical water exchange. Analysis of the extensive data available from different countries, their monitoring program and research cruises, has allowed for the computation of basin-wide trends of oxygen conditions over more than a century. The low oxygen zone has increased by a factor of 10 over the last 115 years and has grown from about 5,000 km² around 1900 to more than 60,000 km² in recent years. Anthropogenic nutrient inputs are the primary cause of the hypoxia, however, global warming has exacerbated low oxygen conditions. In the estuarine and coastal systems of the Baltic hypoxia is much more variable and strongly dependent on processes controlling vertical mixing. The low oxygen conditions have altered many biogeochemical cycles (P, N, Fe, Mn, S, etc.) and influenced many processes including the nutrients limiting phytoplankton production, altering microbial communities and changing the burial of elements in sediments. In addition, the enhanced accumulation of organic-rich sediments with hypoxia, e.g. the legacy of eutrophication, has increased benthic oxygen demand. Although reductions in nutrient loads have reduced overall eutrophication, especially local conditions, a response is not yet evident in the dynamics of hypoxia. The time lag in responses to current efforts to reduce nutrients is slow, which also challenges management efforts to reduce eutrophication. Additional efforts to achieve nutrient reductions from catchments will be necessary to improve oxygen conditions in the Baltic Sea.

Daniel Conley | Professor Conley completed a PhD in Chemical Oceanography from the University of Michigan in 1987 and was an Assistant Research Professor at Horn Point Laboratory at the University of Maryland Center for Environmental Studies, USA. He moved to the National Environmental Research Institute, Denmark in 1995 where he worked on the marine monitoring program and then to Lund University, Sweden where he held a Marie Curie Chair from 2007-2009. Conley is a Pew Fellow for Marine Conservation, a Wallenberg Scholar and a member of the Royal Swedish Academy of Sciences. He is currently a Professor in Biogeochemistry in the Department of Geology at Lund University, Sweden.

His research focuses on the perturbation of nutrient cycles by human activities and the responses of marine ecosystems to changes in human impact and climate. He is engaged in research on the spread of dead zones in estuaries and coasts, and the impact of low oxygen upon biogeochemical cycles. In addition, he carries out research on the global biogeochemical silica cycle and has shown that the Si cycle is dominated by biological processes along the land-sea continuum. Finally, his recent research has suggested that the first biological impacts on the global Si cycle were likely by prokaryotes in deep time during the Archean with further decreases in oceanic dissolved Si with the evolution of widespread, large-scale skeletal biosilification.
ORAL PRESENTATIONS

**Chesapeake Bay hypoxia: relative impacts of nitrogen entering from the land, the atmosphere, and the coastal ocean**

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Very few studies of estuarine hypoxia have simultaneously examined the impacts of nutrients from the land, the atmosphere, and from the coastal ocean. However, all three nutrient sources can be important to estuarine oxygen dynamics, and can have important ramifications for managers, since in general inputs from the atmosphere and coastal ocean are more difficult to control at the local level. In this study, the three-dimensional Estuarine-Carbon-Biogeochemistry model embedded in the Regional Ocean Modeling System is linked to a management-based watershed model, and is used to examine the relative impacts on Chesapeake Bay hypoxia resulting from nitrogen entering from rivers, the atmosphere and the coastal ocean. Model sensitivity experiments highlight that dissolved inorganic nitrogen (DIN) inputs from the atmosphere have roughly the same impact on hypoxia as the same gram for gram change in riverine DIN loading. DIN inputs at depth from the shelf have a similar overall impact on hypoxia as those from the atmosphere (~0.2 mg L⁻¹), however the mechanisms driving these impacts are distinct. While atmospheric DIN impacts hypoxia primarily via the decomposition of autochthonous organic matter, coastal DIN impacts oxygen concentrations primarily via the decomposition of allochthonous organic matter entering the Bay from the continental shelf. The impacts of coastal and atmospheric DIN on estuarine hypoxia are greatest in the summer, and occur farther downstream (lower mesohaline) in wet years than in dry years (upper mesohaline). Integrated analyses of the relative contributions of all three DIN sources to summer bottom oxygen concentrations indicate that impacts of atmospheric deposition are largest in shallow near-shore regions, riverine DIN has dominant impacts in the largest tributaries and the oligohaline Bay, while coastal DIN fluxes are most influential in the polyhaline region. However, during the winter when estuarine circulation is strong and shelf DIN concentrations are relatively high, coastal DIN impacts bottom oxygen throughout the Bay. Overall, this research describes an integrated modeling approach for the Chesapeake riverine-estuarine-sea continuum that quantifies the impacts on hypoxia of multiple nutrient sources.

**Quantifying the relative contributions of riverine versus oceanic nutrient sources to coastal hypoxia**

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The coastal ocean is increasingly affected by eutrophication, i.e., the supply of excess nutrients with subsequent enhancement of productivity and potentially harmful occurrences of toxic algal blooms and hypoxia or anoxia. Hypoxia occurs when dissolved oxygen concentrations drop below 2 mg/L. Because some
systems are naturally prone to hypoxia, a quantification of the relative influence of anthropogenic versus oceanic nutrient sources is important. Here we use coupled physical-biogeochemical models combined with an element tracing technique to assess the impact of different nutrient sources and provide quantitative information on their influence on the individual biogeochemical processes. The technique is applied to two coastal systems that experience severe seasonal hypoxia on large spatial scales (~15,000 km²): the northern Gulf of Mexico (NGoM) and the East China Sea (ECS). The NGoM is an open shelf system with the North American coast in the north and an open connection to the oligotrophic open Gulf in the south. The ECS connects the shallow Yellow Sea in the northwest with the Pacific Ocean in the southeast, and is influenced by the northward Taiwan Warm Current. The NGoM and ECS are both strongly influenced by large amounts of riverine freshwater and nutrients from the Mississippi/Atchafalaya River System and the Changjiang River, respectively. In the NGoM, seasonal stratification due to high freshwater discharge, which limits the exchange between surface and bottom waters, and high sediment oxygen consumption resulting from enhanced productivity generate seasonal hypoxia in the bottom boundary layer. Here, hypoxia is driven primarily by anthropogenic inputs. In the ECS, hypoxia occurs in a thicker layer below the pycnocline, where water-column respiration is an important oxygen sink. In this system, the Changjiang River is among several nutrient sources supporting productivity and oxygen consumption; nutrients of oceanic origin are thought to be a significant driver of oxygen depletion in the ECS. Our analyses of the NGoM and the ECS – two dynamically very different coastal systems – illustrate the value of combining physical-biogeochemical models and element tracing techniques to improve our understanding of hypoxia in coastal systems.

Oscillations of oxygen in the hypoxic transition zone of the Eastern Gotland Basin (Baltic Sea) – causes and consequences on benthic biogeochemical fluxes

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Depending on time scales, magnitude and persistency, fluctuating oxygen (O₂) levels at the boundaries of oxygen deficient areas strongly affect benthic element cycling and redox-sensitive mobilization of nutrients and trace metals. Via feedback loops, this contributes to maintain or even amplify low oxygen levels. Beside biological consumption, bottom water availability of O₂ in such transition zones depends on physical transport and atmospheric forcing, which render them particularly susceptible to environmental change. We present time series of bottom water O₂ concentrations measured in water depths of 90 and 120 m in the Eastern Gotland Basin (central Baltic Sea) in conjunction with hydro-dynamical and atmospheric parameters. The depth range of 80 to 125 m referred to as Hypoxic Transition Zone (HTZ) separates the oxic surface layer (0 to ~ 80 m) from the almost persistently anoxic and sulfidic deep basin. Although slightly dampened with increasing water depth, O₂
variability in the HTZ was pronounced on temporal scales of days to weeks. During summer, O\textsubscript{2} concentrations at 90 m water depth were typically close to anoxia with periodic excursions of up to 30 μM. In the autumn to spring period O\textsubscript{2} levels fluctuated around ~20 μM. High levels of up to 170 μM were episodically recorded during storm events. The HTZ makes an important contribution to the internal nutrient loading in the central Baltic Sea, releasing 70% of P (76 kt yr\textsuperscript{-1}) and 75% of DIN (200 kt yr\textsuperscript{-1}) despite covering only 51% of area (Noffke et al. 2016), impeding the recovery of the Baltic Proper from eutrophication. However, this estimate of the annual nutrient load is based on sparse in situ flux measurements mostly taken during the summer season and does not consider the impact of O\textsubscript{2} dynamics on nutrient release.

**Upscaling the impact of coastal hypoxia from species to ecosystem function. The case of bioturbation in the Black Sea**

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The Black Sea is an almost enclosed Sea that combines naturally-induced permanent anoxia in its deep part with anthropogenically-induced hypoxia on the bottom of its north-western shelf. Shelf hypoxic events occur during the stratification period in regions with high accumulation of organic matter and low ventilation rates. These events started in the 70-80s when eutrophication developed with potential consequences on ecosystem functioning and biogeochemical cycling that we hardly know. Ocean numerical models provide a wealth of information on environmental conditions with always more details and accuracy but still the scaling up of hypoxic impact at organisms scale to managerial scale is challenging for ecosystem modelers.

We use a trait-based approach for linking the functions of the Black Sea’s shelf macrobenthos with the environmental conditions provided by in-situ data and a 3D ocean numerical model. The ocean model is the BiogeochemicAl Model for Hypoxic and Benthic Influenced areas (BAMHBI) developed for the Black Sea. BAMHBI solves biogeochemical processes over the whole water column coupling the pelagic and benthic compartments. The model is used in an operational context in the frame of the Copernicus Marine Environment and Monitoring Service (CMEMS) for providing near real time predictions and reanalysis of the Black Sea biogeochemistry. It has been validated according to the skills assessment plan established in CMEMS using historical and BGC-ARGO data sets. Macrobenthos samples have been collected during several field campaigns organized in May 2016 and September 2017 in the frame of the FNRS BENTHOX project and the EMBLAS UN expeditions. Species are identified and their bioturbation traits (i.e. sediment reworking, mobility) determined using databases. Statistical analyses (e.g. RLQ approach) are used to select the environmental variables that best explain the variability of the trait. Variables specifically linked with the characterization of the hypoxic events are tested (e.g. severity of hypoxia, averaged/minimum oxygen concentration, age of water). From this information, a Trait Distribution Model (TDM) is developed to link the trait and its “niche” and to
Co-existence of nitrogen oxidation and reduction in oxygenated estuaries

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Estuaries received eroded sediments from catchment with heavy anthropogenic nutrient and organic loadings serving as a bioreactor favoring intensive cycling of elements, such as nitrogen and organics. Increasing evidences showed the importance of active particle mediated aerobic-anaerobic metabolisms in estuary and coastal waters, however, little is known about the production of N₂O, a strong greenhouse gas, in such environment due to technological difficulty. By using multiple isotope labeling technique, we investigated potential nitrogen transformation pathways contributing to N₂O production in two estuaries in Southeast of China along a wide DO gradient. We found nitrogen oxidation and reduction processes co-existed and both actively contributed to N₂O production. Particle mediated aerobic-anaerobic metabolisms accounted for such co-existence. Moreover, the bulk production N₂O and the fractional contribution of reduction pathway to N₂O were negatively correlated with DO and nutrient concentrations. Our results demonstrated that eutrophication and deoxygenation synergistically promote N₂O production in turbid and eutrophic estuarine systems that might induce enhancing feedback to global warming.

Controls on coastal hypoxia: A global synthesis

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Aquatic environments experiencing low-oxygen conditions have been described as hypoxic, suboxic or anoxic zones, oxygen minimum zones, and, in the popular media, the misnomer “dead zones.” This review aims to elucidate important aspects underlying oxygen depletion in diverse coastal systems, and provides a synthesis of general relationships between hypoxia and its controlling factors. After presenting a generic overview of the first-order processes, we review system-specific characteristics for selected estuaries where adjacent human settlements contribute to high nutrient loads, river-dominated shelves that receive large inputs of freshwater and anthropogenic nutrients, and upwelling regions where supply of nutrient-rich, low-oxygen waters generates oxygen minimum zones without direct anthropogenic influence. We propose a non-dimensional number that relates the hypoxia timescale and water residence time to guide the cross-system comparison. Our analysis reveals the basic principles underlying hypoxia generation in coastal systems and provides a framework for discussing future changes.
Oxygen concentrations from water column to seabed – integrating observations and modelling to support assessments of status and predict change

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Shelf seas and their coastal areas are highly dynamic environments subject to many natural processes and anthropogenic pressures. They exhibit large spatial and seasonal gradients in pelagic and benthic oxygen concentrations both naturally with depth, temperature, hydrography, stratification and sediment type and in response to a range of pressures including anthropogenic nutrient inputs, trawling and climate change. Dissolved oxygen concentration is used as a measure of ecosystem health for formal eutrophication assessments under agreements and directives such as OSPAR, MSFD and WFD. It is also a fundamental control on other carbon and nutrient processes within the pelagic and benthic systems. Understanding the key processes controlling shelf sea oxygen concentrations is essential if we are to take appropriate management action and adapt to future changes. In this contribution, we will present a synthesis of work carried out over the last two decades. The extent and magnitude of oxygen depletion in the water column in seasonally stratified UK shelf seas has been determined using high frequency in situ observations from moorings (surface and bottom) and gliders. These observations demonstrated that low values can occur, and are a normal feature of such shelf seas. The penetration of oxygen into the seabed and its coupling to seasonal water column conditions is also spatially variable. Microelectrode insertion into sediment cores was used extensively in different parts of the UK shelf sea to record oxygen profiles in surficial sediments. The level to which free oxygen is present is driven primarily by sediment characteristics, such as particle size and organic matter content, their combined impact on permeability and hence pore-water exchange with the overlying water. In turn, it determines zonation and rates and pathways of redox sensitive elemental cycles and carbon mineralisation. While oxygenation of the seabed is not formally used as an indicator in assessments, it has high relevance for present and future seabed function. Furthermore, ecosystem models which couple the water column and seabed components were used to predict horizontal and vertical oxygen distributions under various scenarios of present day and climate change conditions. In addition, recent oxygen mass-balance model developments have been made which provide robust estimates of net community production in shelf seas. Challenges of representing oxygen distributions accurately throughout the water column and into the bed will be discussed in the context of spatial variability, seasonality, climate change and associated model process parameterisation and outputs.
On the eutrophication, hypoxia and ocean acidification in the coastal ocean

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Many studies have shown that coastal hypoxia is primarily associated with autochthonous organic carbon (Auto-OC) production, stimulated by coastal eutrophication resulting from excessive terrestrial nutrient runoff. Nutrients stimulate algal blooms in coastal surface waters. Sinking and remineralization of algal biomass drive dissolved oxygen (DO) consumption below the pycnocline. Therefore, Auto-OC is believed to be the predominant oxygen sink. Other studies, however, have suggested that Auto-OC may support only a fraction of DO consumption in the hypoxic zone. The relative contributions from eutrophication-induced autochthonous and terrestrially sourced allochthonous organic matter in causing coastal hypoxia are, however, still the subject of considerable debate despite decades of research. Another emerging but less studied environmental problem associated with entrophication is the enhanced ocean acidification (OA) in the coastal ocean, which often occurs accompanied by hypoxia. This enhanced acidification is typically induced by two processes. One is the in situ decomposition of the settled organic matter, which produces CO$_2$ and decreases pH. The other is the decrease of the buffering capacity of the water, which further decrease pH. This study examines major drivers of hypoxia and OA in both the East China Sea off the Changjiang estuary and in the lower Pearl River estuary off Hong Kong. Also examined is the interplays between eutrophication, hypoxia, and ocean acidification in these two highly impacted systems. My presentation highlights that both the hydrodynamic and biogeochemistry should be taken into consideration and multidisciplinary research approach is essential in order to diagnose individual processes in complex coastal environment.

The future of coastal hypoxia under scenarios of river management

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River systems worldwide are increasingly influenced by flood control measures and river diversion operations. Yet, surprisingly little is known about the effects of river management on coastal hydrodynamics, nutrient transport pathways, and hypoxia. Freshwater diversions on the Lower Mississippi River play a central role in the proposed 50-billion, 50-year strategy for restoring the Louisiana’s coast. Under the proposed 2017 Coastal Master Plan, four large-scale river diversion projects are being considered that would divert a third of the Lower Mississippi River into deltaic Louisiana estuaries. The effects of existing and proposed river diversions on nutrient transport pathways and hypoxia were investigated using a high-resolution, three-dimensional, coupled hydrodynamic-biogeochemical model (FVCOM-LATEX). The numerical model domain covers most of the Alabama-Mississippi-Louisiana-Texas continental shelf and includes high resolution (on the order of 20 meters) nested grids in Barataria and Breton Sound estuaries. The model was driven by tidal and subtidal forcing at the open Gulf of Mexico boundary, freshwater and nutrient loads from rivers and river diversions, and surface wind stress. A number of different diversion
scenarios were assessed, including a concurrent operation of six river diversions with a combined flow of 6,500 cubic meters per second. Numerical modeling results indicate that, depending on the scenario considered, the proposed large-scale river diversions would have the potential to strongly influence hydrodynamics and estuarine-shelf exchanges, which in turn could profoundly affect nutrient transport pathways and hypoxia in the northern Gulf of Mexico.

**Climate change is projected to exacerbate impacts of coastal eutrophication in the northern Gulf of Mexico**

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The northern Gulf of Mexico receives excessive nutrient inputs from the Mississippi-Atchafalaya River Basin that promote high phytoplankton production and high respiration rates due to algal decomposition. Every summer, respiration, in combination with vertical stratification, results in hypoxia, high dissolved inorganic carbon concentrations and low pH in bottom waters. By the end of the century, rising temperatures, higher freshwater inputs from the Mississippi-Atchafalaya River Basin, and a drastic increase in atmospheric CO2 are expected to further intensify eutrophication-induced hypoxia and acidification. Using a high-resolution, regional biogeochemical model, we simulate the dynamics of oxygen and inorganic carbon in the Northern Gulf of Mexico under present and end-of-the-century climate conditions. Results indicate a modest spatial expansion of the hypoxic zone in the future, but more severe hypoxia with greater exposure to prolonged hypoxic conditions, primarily due to lower oxygen solubility and increased stratification. Simultaneously, pH will decrease across the shelf to a minimum of 7.39 in hypoxic waters, primarily controlled by future atmospheric and offshore CO2 levels. The lower buffering capacity in acidified waters will exacerbate the effect of respiration on pH. The magnitude of the changes in hypoxia and eutrophication-induced acidification varies significantly from year to year. The largest response to future conditions occurs in years with high freshwater discharge and upwelling-favorable wind.

**Future climate change exacerbates hypoxia in Chesapeake Bay due to warming temperatures**

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Hypoxia is a potent stressor on living resources in waters adjacent to populated coastal areas due to excessive nutrient inputs, and may be further impacted by global climate change. The Chesapeake Bay, the largest estuary in the continental United States located in the Mid-Atlantic region of the east coast, undergoes hypoxic conditions annually and is also experiencing increases in sea level, temperature, and precipitation. Coastal managers rely on numerical models to assess the magnitude of nutrient reductions needed to increase oxygen concentrations to desired levels in...
the Bay, and also utilize the results of climate scenarios to better gauge the resiliency of planned management actions in the face of uncertain future conditions. Here we used a 3-D hydrodynamic-biogeochemical model of the Chesapeake Bay linked with a regulatory watershed model to simulate the impacts of climate change on hypoxia along the river-estuary-sea continuum. We examined three major anticipated effects driven by a mid-century (2050) future climate change scenario: increasing levels of riverine nutrient inputs and freshwater flow due to increased precipitation, increased water temperatures, and sea level rise. Of these factors, increased temperatures were found to exert the greatest control on changes in the extent and duration of hypoxia throughout the Bay, with a +1.75°C temperature change causing an increase in the cumulative hypoxic volume for low oxygen waters (DO < 5 mg L\(^{-1}\)) of ~15% (219 km\(^3\) days\(^{-1}\)), and an increase in the cumulative hypoxic volume of anoxic waters (DO < 0.2 mg L\(^{-1}\)) of ~30% (13 km\(^3\) days\(^{-1}\)). These increases are due to both an earlier onset and a greater spatial extent of low oxygen conditions. Impacts of temperature on hypoxia result from a combination of increased biological rates (production, respiration, remineralization, grazing) and decreased solubility. Multiple sensitivity experiments demonstrate that solubility drives approximately 85% of the decrease in dissolved oxygen concentrations averaged annually throughout the water column. However in areas and times with the most severe hypoxia, changes in solubility and biological oxygen demand account for approximately equal percentages of the decreased dissolved oxygen concentrations. Ultimately, this study demonstrates that increasing temperatures due to climate change have the potential to limit the effectiveness of nutrient management actions designed to reduce hypoxia, a goal explicitly tied to numerous ecological management objectives within the Chesapeake Bay.

Benthic community resilience in a harsh place: hypoxia and tsunami perturbations in the coast of the southern Humboldt Current System

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In the last 10 years the coast of south-central Chile was strongly perturbed by two events of different origin on a scale of tens to hundreds of kilometers. The first, which occurred in January 2008, was a natural hypoxic event associated with the coastward intrusion of upwelled water low in dissolved oxygen, which produced massive mortality of benthic and planktonic organisms in Coliumo Bay. The second was the world’s sixth strongest earthquake on record (8.8 Mw) and subsequent tsunami that occurred on February 27, 2010, heavily impacting Coliumo and Concepción Bays which are located 25 and 30 km south of the epicenter, respectively. These events provided a unique opportunity to study the dynamics and resilience of benthic communities after major perturbations. Here we analyze the effect that both major perturbations had on the megafaunal community of Coliumo Bay, evaluating its stability and resilience over the following seven years. Either by natural or anthropogenic sources, the benthic environments of both bays are subjected to forcing factors, which modify the oxygenation of the deeper layers of the water column. Quarterly oceanographic
surveys were conducted at Coliumo Bay from 2007 to 2017. The megafauna community was sampled using a modified Agassiz trawl. Vertical profiles for salinity, temperature and dissolved oxygen were taken at the sampling sites with a CTD-O. Within approximately three months after the hypoxic event the megafaunal community of Coliumo Bay had returned to conditions similar to those existing prior to the hypoxic event, suggesting a rapid recovery. After the tsunami the megafaunal community (both in density and biomass) shifted inter-annually through different structures, with an apparent directionality. Oceanographic and biological seasonality at Coliumo Bay showed a strong cyclical influence on this inter-annual community response. A spatial homogenization of the community over time (i.e. diversity recovery) took place, probably promoted by ecological functionality of scavenger species and by the proportional increase of non-dominant species. In this community recovery, bottom dissolved oxygen and bathymetry also played a crucial role in the spatial structure. Seven years after the tsunami total density and total community biomass were still considerably below those described for unperturbed conditions (i.e. before 2008), mainly associated with the decrease in density and biomass of dominant species. A comparison of the effects that the tsunami and hypoxic conditions produced on the structure of the benthic communities of Coliumo and Concepción Bay is also reported. Funding: PIMEX PROGRAM (U.R. 23801.567.552), INCAR (FONDAP-CONICYT 15110027)

Seasonal and annual variability of coastal sulphur plumes and forcing processes in the Benguela upwelling system

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We investigated the seasonal and annual variability of surface sulphur plumes in the Namibia Benguela upwelling system because of their significant impacts on the marine ecosystem, fishing industry, aquaculture farming and tourism due to their toxic properties. We identified the sulphur plumes in ocean colour satellite data for the 2002-2012 time period using the differences in the spectral properties of Namibian Benguela optical water types. The sulphur events have a strong seasonal cycle with pronounced main and off-seasons forced by local and remote-driven processes. The main peak season is in late austral summer and early austral autumn at the beginning of the annual upwelling cycle caused by increasing equatorwards alongshore trade winds. The sulphur plumes activity is high between February and April during the seasonal oxygen minimum associated with the seasonal reduction of cross-shore ventilation of the bottom waters, the seasonal southernmost position of the Angola Benguela Frontal Zone, the seasonal maximum of water mass fractions of South Atlantic and Angola Gyre Central Waters as well as the seasonal arrival of the downwelling coastal trapped waves. The off-season is in austral spring and early austral summer during increased upwelling intensity and enhanced oxygen supply. The annual variability of sulphur events is characterized by very high activities in years 2004, 2005 and 2010 interrupted by periods of lower activity in years 2002 to 2003, 2006 to 2009 and 2011 to 2012. This result can be explained by the relative contribution or adding effects of local (wind) and remote-driven forces (from the equatorial area). The probability for the occurrence of sulphur plumes is enhanced in years with a lower annual mean of upwelling intensity, decreased oxygen supply.
associated with decreased lateral ventilation of bottom waters, more southern position of the Angola Benguela Frontal Zone, increased mass fraction of South Atlantic Central Water and stronger downwelling coastal waves (Ohde and Dadou, 2018, PLoS ONE 13 (2): e0192140. https://doi.org/10.1371/journal.pone.0192140)

**Linking shelf/break processes to coastal hypoxia in the upwelling core of the central California Current System**

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Coastal upwelling supports highly productive ecosystems in eastern boundary currents that provide ecologically and economically important habitats, e.g., off the west coast of North America. However, upwelling of nutrient-rich deep waters poses ecosystem risks as well as benefits, as cold upwelled waters are increasingly enriched in CO2 and depleted in oxygen. Because the mechanisms responsible for changing oxygen levels within the California Current System (CCS) are not fully understood, our ability to characterize the duration and extent of exposure to hypoxia is limited, thus preventing proper assessment of habitat vulnerability, and how management tools can be applied to address local impacts of globally driven changes. Oxygen levels in coastal upwelling regions vary owing to influx of oxygen-poor undercurrent waters, local drawdown of oxygen through net respiration, local oxygen replenishment through net production and/or vertical mixing of oxygenated surface waters. Recent observations of oxygen levels in coastal waters of the CCS have revealed a complex pattern of variability in space and time, controlled by the interaction of multiple processes. Observations document (i) a shoaling hypoxic boundary in the southern CCS; (ii) a decline of oxygen in both the northern and southern CCS; and (iii) an increased frequency of hypoxic events off the Pacific Northwest and Southern California. Similar trends are expected for the central CCS (the region between 36°N and 42°N). However, there has been comparatively limited research on dissolved oxygen in the central CCS, despite being the location of maximum upwelling wind stress over the CCS, and despite the well-recognized productivity of the greater Gulf of Farallones (from Monterey Bay to Bodega Bay) – a “hot spot” for its biological resources, as recognized by three National Marine Sanctuaries. Further insight to this variability has emerged from associated studies of ocean acidification, given the close coupling between low oxygen, low pH and low aragonite saturation state in these productive coastal waters. Here we present new information acquired from near-bottom moored sensors, deployed at a few different locations over the shelf from 2013 to 2018. These continuous time-series measurements of temperature, salinity, and dissolved oxygen provide new insight and allow us to describe the seasonal cycle in dissolved oxygen and short-term events. Our aim is to develop an understanding of spatio-temporal patterns and to quantify the multiple mechanisms that can account for hypoxic events in the central CCS by relating temperature, salinity and oxygen variability to forcing mechanisms and source water types.
Influence of hypoxic upwelled waters on the distribution of trace metals in the surficial sediments of the Cochin estuary

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Coastal and estuarine hydrography along with trace metal (Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, and Zn) distribution in sediments were studied in the Cochin estuary (southwest coast of India) during pre-upwelling (April 2016) and upwelling (July 2016) periods. Oxygenated, high saline and low nutrient coastal waters were found (30kms) in the estuary during the pre-upwelling period where coastal upwelling in the Arabian Sea brought cold, high saline, nutrient-rich low oxygen waters intruded 20 km in the estuary. The concentrations and distributions of trace metals and organic matter in the sediments are found to be high during pre-upwelling and it is very low during upwelling periods. Marginal variation in Mn and Fe and comparatively low values of Cu, Cd, Zn, Pb and almost same values of Co, Cr, Ni were found during upwelling period than the pre-upwelling period. The mobilization of sediment bound metals during hypoxia/anoxia is high, nevertheless, the results highlight particular problems for management in areas where hypoxia might occur. The release of metals exacerbating already high loads or resulting in adverse effects on biological life are possible or even highly probable.

Human regulation of fresh-salt water budget and hypoxia in semi enclosed seas

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Dissolved oxygen concentrations in natural water bodies are governed by the balance between oxygen production, consumption, and exchange with the atmosphere. The occurrence of coastal hypoxia/anoxia can be natural, human influenced, or result from the interaction between natural and anthropogenically induced processes. Naturally occurring hypoxia/anoxia is found: in bottom waters of silled basins and fjords with restricted circulation. This study originated from the need to manage the extension of the anoxic water layers, from deeper to shallower environments, aiming to control the consequences in environments with great economic and ecological values. Two Greek coastal basins, the anoxic Aitoliko lagoon and the hypoxic Amvrakikos Gulf were used as case studies as both are systems where fresh water discharges are human controlled, and this is directly correlated with the development of hypoxic/anoxic conditions in their bottom layers. The deep basin of Aitoliko (~27.5m) is connected with the adjacent Messolonghi lagoon (~2m deep) through shallow and narrow openings (mean depth ~1.2m). The interaction between the two lagoons is interrupted by the fresh water that inflows into Aitoliko lagoon by the function of a pumping station, near the connecting sill. The Amvrakikos Gulf is an enclosed basin as its only link to the open Ionian Sea is a narrow strait. It receives fresh water from two Rivers, Arachthos and Louros. The rivers’ discharges are controlled by Hellenic Electricity Company, disturbing the seasonal density variations in the water column of Amvrakikos Gulf. Samplings were conducted on seasonal basis at an extensive sampling net in both basins. Continuous profiles of temperature, salinity
and dissolved oxygen were measured in situ. Water column stability was estimated and seasonal changes were brought out. An attempt to understand the influence of the human controlled fresh water discharges on density profiles and consequently on the seasonal changes on the water column stability was made, for both basins.

**POSTER PRESENTATIONS**

**(39) Dynamics of ammonium in the Pearl River Estuary under summer hypoxic conditions**

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We examine ammonium dynamics in the Pearl River Estuary (PRE), a highly eutrophic system where extensive hypoxia is emerging in its lower estuary in the summer time. A total of 312 water samples for ammonium were collected from the PRE in July 2017 when an extensive area in the lower PRE was under hypoxic conditions. Ammonium was measured on board by using the indophenol blue colorimetric method at uM level concentrations or by using a more sensitive fluorescence method with preconcentration was at nM concentration levels. Ammonium concentration ranged from 37 uM in the upper estuary down to 100nM~2 uM in the lower estuary, and to 35 nM~300 nM in the offshore area. Our data showed that ammonium was overall non-conservative during the estuarine mixing showing rapid removal in the upper estuary due probably to nitrification but significant additions in the lower estuary around Shenzhen, Hong Kong and Macau due likely to the sewage discharge. Such ammonium additions were also obvious in the subsurface and bottom waters where we found consistently high concentrations of total suspend matter suggesting that degradation of organic particles is a major source of ammonium therein. We adopted a multiple end-members model to further characterize the ammonium dynamics in different regimes of the lower estuary. Ammonium was slightly removed in the surface layer (0.8±0.3 umol/kg) where nitrate was much more profoundly removed (28±5 umol/kg), indicating that nitrate was the major nitrogen species fueled the phytoplankton bloom. Ammonium was slightly added in the hypoxic bottom water (<0.5 umol/kg) where nitrate was much more significantly regenerated (15±5 umol/kg). This inferred that nitrification contributed to the oxygen consumption in the hypoxic zone. However, the ratio between oxygen consumption vs inorganic nitrogen production amounted to 25±5.1, which was much higher than the Redfield stoichiometry, indicating nitrogen losses relative to the oxygen consumption, the exact reason of which remains however unknown. We contend that ammonia dynamics in the hypoxic zone is much more complex than what was previously thought.
(40) Using observations from gliders to understand oxygen dynamics in shelf seas

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The decline in global ocean dissolved oxygen (DO) concentrations, particularly in shelf seas, has led to an immediate need to better understand the multitude of processes that control the DO distribution. Recent model studies using regional-scale, coupled physical-ecosystem models estimate that large regions of the Northwest European Continental shelf seas (325,000 to 400,000 km²) have the potential to become deficient in DO during the latter stages of seasonal stratification. Here we use glider measurements of turbulence and DO to estimate vertical DO fluxes across the thermocline between the well oxygenated surface mixed layer (SML) and dark bottom mixed layer (BML) over 40 days during the spring bloom and summer stratified period in the central Celtic Sea. Rates of respiration in the BML and the diapycnal flux of DO across the thermocline were quantified. The change in oxygen over time and consideration of vertical flux allowed for the estimation of oxygen consumption in the BML, which agreed well with direct observations of respiration. The vertical DO flux was twice as high in summer relative to spring due to a strong vertical DO gradient. Enhanced mixing during the spring tide increased the vertical DO flux by 9-fold. Diapycnal mixing replenished up to 18% of the DO consumed in the BML during the stratified period, with a significant proportion of this being due to the spring tide. Without the diapycnal flux of DO, the BML DO would reach levels approaching ecological risk, this result has important consequences for marine ecosystem health in shelf seas since the observed ventilation mechanism of diapycnal mixing likely elevates oxygen levels relative to what would otherwise be considered. In order to correctly predict oxygen levels in shelf seas, the internal mixing needs to be quantified accurately.

(41) Short-term ecosystem alterations produced by a strong natural hypoxia event in a shallow bay of the southern Humboldt Current System

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In January 2008 there was an intensive and extensive upwelling event in the southern Humboldt Current System. This caused an intrusion of equatorial subsurface water into the coastal zone, generating severe hypoxic conditions (≤ 0.5 ml O₂ l⁻¹) on a time scale of hours-days. A massive mortality and the beaching of pelagic and benthic organisms, including fishes, megafauna and zooplankton occurred in Coliumo Bay, a shallow bay located in the southern Humboldt Current System (HCS). During the hypoxic event, in the pelagic environment Redox, pH, nitrate, phosphate, silicate and chlorophyll-a values were the lowest, while nitrate and the phaeopigment values were the highest. Nanoand microphytoplankton were at their lowest abundances. Macrozooplankton had the greatest abundance during hypoxia, dominated mainly
by crustacean eggs, fish eggs and amphipods. During the initial stranding 26 fish species were identified: 23 teleosts, 1 myxiniform and 2 elasmobranchs. Most beached specimens were juveniles. Haematological and histological evidence indicate that the severe hypoxia which lasted for at least 48 hours was the most plausible cause of fish mortality. For the entire megafauna benthic community, including fishes, we found that (i) strong changes in total density, total biomass, and diversity occurred immediately after the hypoxic event, negatively affecting crustaceans and fishes, while gastropods were favoured, and (ii) initial changes were reverted over a period of three months. The hypoxia event generated a strong short-term alteration of all biotic and abiotic components of the pelagic system in Coliumo Bay and the neighboring coastal zone. These negative effects associated with strong natural hypoxia events could have important consequences for the productivity and ecosystem functioning of the coastal zone of the HCS if, as suggested by several models, winds favorable to upwelling should increase due to climate change. The effects of severe natural hypoxic events in this coastal zone can be dramatic, especially for pelagic and benthic species not adapted to endure conditions of low dissolved oxygen.

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(42) Heat waves and hypoxic upwelling events: relevance for coastal benthic communities and the possibilities for mitigation

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Globally, climate change influences marine ecosystems. Superimposed on these mean changes are extreme events such as heat waves, freshening events or wind-driven upwelling, causing deoxygenation of surface waters. Both, mean changes and extremes will certainly stress marine species and ecosystems. Marginal, often shallow, seas are particularly affected by environmental variability of various drivers, at various scales. While a vast majority of literature now focuses on the significance of extreme events and environmental variability in the context of climate change research, experimental evidence is still lacking. In the framework of this project, we aim on elucidating the interplay between marine heat waves and hypoxic upwelling events on Western Baltic Sea marine benthic communities. The occurrence of heat waves and upwelling events will be modelled for the Kiel Fjord area and trends of changing frequencies and amplitudes will be clarified. In the following, the effect of modelled characteristics of heat waves followed by upwelling events will be experimentally investigated on two typical Baltic Sea benthic communities: a seagrass and a secondary hard-bottom community. This will allow more realistic conclusions on the effect of ongoing climate change, including extreme events, on important benthic communities, and on the interplay between multiple relevant stressors. Modelling on past and current events as well as the applied experimental work will form the basis for designing guidelines for the management of local ecosystems. Through the interaction of scientists, local industry (aquaculture and fishery) and tourism, the needs for possible forecasts of these extreme events will be evaluated as well as the potential for an extreme event warning system (EEWS). This EEWS, along with mitigation guidelines, can, thus, be used to reduce additional anthropogenic stress on local ecosystems during extreme events.
Ocean Deoxygenation – How the Past can Inform the Future

Topic abstract

Anthropogenic warming is expected to drive oxygen out of the ocean, as seawater temperature will rise and the upper ocean will become more stratified. Widespread deoxygenation will have an impact on marine habitats as well as major biogeochemical cycles, with O₂ being a key factor controlling the cycling of carbon, nitrogen, phosphorous, and redox sensitive elements. While recent observations appear to confirm this prediction, the changes have so far remained subtle and may at least partly be the result of natural decadal variability. Beyond the instrumental record, paleoceanographic reconstructions extend much further back in time, and can provide an independent perspective on changes in oxygen concentrations and their drivers, such as ocean circulation and export production changes. We welcome contributions addressing past changes in ocean oxygenation (global, regional, local) since the Cretaceous. This includes assessments of associated consequences on nutrient cycling, such as nitrogen and trace metal inventories, as derived from model simulations and/or sedimentary reconstructions.

Conveners
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Babette A.A. Hoogakker // The Lyell Centre, Heriot Watt University, UK
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KEYNOTE SPEAKER

07.09. FRIDAY | 09:00
Past variability and recent trends of subsurface ocean oxygenation in the Eastern Tropical South Pacific: insights from proxy records

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The Eastern Tropical South Pacific (ETSP) oxygen minimum zone (OMZ) is one of the largest regional OMZs in the global ocean. At multidecadal to millennial scales, the intensity and extension of this OMZ is modulated by changes of the Walker circulation, which control the thermocline depth –and thus productivity and respiration– in the ETSP, as well as the subsurface ventilation associated to the equatorial currents. Further south, the OMZ is also influenced by the meridional shifts of the subtropical front and by the intensity of the South Pacific Subtropical High (SPSH), which control the ventilation at higher latitudes and the alongshore wind forcing, respectively. Here we review a number of sedimentary proxy records that have been studied to reconstruct past variations of this OMZ under climate variability, in order to gain insights of the OMZ response to past global warm periods and this its potential
sensitivity to current and future global warming. After the Last Glacial Maximum, a rapid deoxygenation process took place following the Southern Hemisphere signature of the deglaciation warming, leaving a distinct imprint in d15N sediment records along the Peru-Chile margin, up to maximal values during Heinrich Stadial 1. Thereafter, an average positive trend of oxygenation characterized the late deglaciation, overimposed with millennial fluctuations. A weaker OMZ during the warm mid-Holocene, as inferred by multiple proxies in the Peruvian slope, has been attributed to the intensification of the eastward subsurface equatorial currents and the poleward undercurrent, ultimately as a consequence of a much stronger Walker circulation. For the late Holocene, proxy records of oxygenation and productivity have evidenced significant shifts at multi-centennial time-scales, associated to global ‘cold’ and ‘warm’ climatic periods. Thus, for the Little Ice Age (LIA, 1400-1850 AD), proxy records off Peru and Northern Chile indicate an increased oxygenation in the water column and lower export production, under both weak Walker circulation and SPSH conditions. By contrast, for the late Medieval Climatic Anomaly (MCA, 1100 – 1350 AD) and after the LIA, the records report an increase in subsurface deoxygenation and a higher export production, while the Walker circulation and SPSH intensified. For the twentieth century, in the subtropical region, several shelf/slope records suggest an increased subsurface and bottom oxygenation with lower export production. At lower latitudes, a slight oxygenation is noticeable for the last half century that seems decoupled from increased export production. It needs to be elucidated in what extent the recent oxygenation trend could be explained by enhanced advection of the more oxygenated subsurface equatorial waters, lower productivity and respiration, increased northward advection of oxygen-rich subsurface and intermediate waters from the south and/or other mechanisms.

Dimitri Gutiérrez | Dr. Dimitri Gutiérrez is the Director of Research in Oceanography and Climate Change of the Peruvian Marine Research Institute (IMARPE). He received his PhD degree in oceanography at the University of Concepción, Chile, in 2000. As a biological oceanographer, his research has been focused on benthic responses to natural and human-induced hypoxia, effects of climate variability on the marine productivity and subsurface oxygenation in the coastal South Eastern Pacific involving paleoproxies and in situ data analyses, and recent spatial and temporal changes of the Peruvian upwelling as related to global trends. Currently Dr. Gutierrez is also involved in developing adaptation projects for the impact of climate change on Peruvian fisheries and marine coastal ecosystems and participates in the IOC-UNESCO Global Ocean Oxygen Network (GO2NE).
Large changes in ocean oxygenation during the last ice age: observations, mechanisms and ecosystem responses to change

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The controls on dissolved oxygen are complex, involving oxygen saturation concentrations, ocean circulation, air-sea gas exchange and the rate of organic matter respiration. Marine sediment records of oxygenation during the last ice age provide a means to gauge the relative importances of these mechanisms, as well as the response of the marine ecosystem, under climate forcings that are comparable in magnitude to the expected future changes. During the peak of the last ice age - the last glacial maximum - observations show that, despite greater oxygen solubility caused by lower ocean temperatures, the oxygen concentrations throughout the deep ocean were generally lower. This implies that greater oxygen utilization overwhelmed the solubility changes, which could have been due to more sluggish ocean circulation, more restricted air-sea exchange, and/or a more rapid sinking flux of organic matter to depth. Radiocarbon measurements from the last glacial maximum have previously been interpreted as showing more sluggish circulation, but model simulations show that the measured radiocarbon values can instead be explained by a change in ocean circulation patterns, which would not necessarily change oxygen concentrations. On the other hand, model simulations show that a significant decrease in the preformed oxygen content of Antarctic bottom waters could have occurred under glacial conditions, due to blocking of air-sea exchange by very extensive sea ice cover. In addition, a greater flux of organic matter to the deep sea may have contributed to the low deep ocean oxygen concentrations, due to an increased supply of iron and nitrogen to the surface, and/or ecosystem changes that increased the export fraction, transfer efficiency, or both. Relatively abrupt changes in the Atlantic Meridional Overturning Circulation that punctuated the glacial period and deglaciation were accompanied by dramatic changes in oxygen concentrations, particularly at intermediate-depths of the northern Indian and Pacific oceans. Qualitatively, these abrupt changes are well captured by models, but it is not clear if the models correctly simulate the magnitude of changes, owing to a paucity of quantitative observational constraints. Microscopic fossil assemblages, including fish debris, show large responses to changes in dissolved oxygen concentrations, pointing to an unrealized potential for sediment records to inform the sensitivity of marine ecosystems to changes in oxygenation.

Eric Galbraith | Eric Galbraith is an ICREA Research Professor, based at the Universitat Autònoma de Barcelona. He completed his PhD in oceanography at the University of British Columbia in 2006, worked as a Research Associate at Princeton University in the US, and also as a Professor at McGill University in Canada. His research is broadly interdisciplinary, and is generally concerned with using numerical models and data analysis to better understand the interactions between climate change, human activities and the marine ecosystem. He has worked on both past and anticipated climate changes and their links with ocean
biogeochemistry, as well general principles of air-sea exchange, nutrient cycling and ecosystem stoichiometry. One favourite topic of his work has been natural changes in dissolved oxygen on ice age timescales, and related links with the nitrogen cycle. His current research project, BIGSEA, focuses on developing a better understanding of linkages between fisheries, climate change and marine biogeochemistry.

### 07.09. FRIDAY | 10:10

**Looking back into the future with a geochemical oxygenation proxy (I/Ca)**

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Forecasting trends in deoxygenation is evolving to become a major task for research communities focusing on the ocean-climate system. Geological records provide great opportunities to investigate environmental perturbations occurred in the past, in order to improve constraints on the rate and magnitude of modern climate change impacts. It is beneficial to examine events across different time scales, particularly for gauging the sensitivity of various controls on ocean oxygenation. Proxy approaches are key to unveiling past ocean conditions, however, oxygenation reconstructions have their unique challenges. This talk will review results of a carbonate-based proxy iodine to calcium ratios (I/Ca). I advocate that well-established approaches in paleoceanographic studies (e.g. temperature and pH) may require adaptations to best serve the deoxygenation community.

**Zunli Lu** | Since 2011, Zunli Lu has been an Associate Professor for the Department of Earth Sciences of Syracuse University, where he currently serves as Director of Graduate Studies. Zunli started his research studying halogen and I-129 Systematics in the gas hydrate fields, looking at the implications for the transport of iodine and methane in active margins, at the Department of Earth Sciences, University of Rochester, where he completed his PhD in 2008. He then joined the Ocean Biogeochemistry Group at the Department of Earth Sciences of the University of Oxford, where he studied the potential of ikaïtes in marine sediments as a paleo-environmental temperature proxy. Dr. Lu has been awarded several grants covering multiple disciplines (RAPID: Developing sensitivity tests for detecting water chemistry changes associated with shale bed methane production in the Appalachian Basin; and a recent NSF collaborative NSF grant: Refining foraminiferal I/Ca as a paleoceanographic oxygenation proxy for the glacial Atlantic Ocean’). His multi-disciplinarity is also reflected in his publication record. Zunli has pioneered the development and application of iodine in foraminifera as a sea water redox proxy, confirming the earliest appearance of dissolved oxygen in the ocean’s surface waters, and discovering oxygen depleted subsurface waters in the Southern Ocean during the last glacial period.
ORAL PRESENTATIONS

Variability of dissolved oxygen over the last millennium and the 21st century in an Earth System Model

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Oceanic dissolved oxygen has been observed to decrease over the past decades. Yet, the exact mechanisms leading to these changes and the relative role of natural and forced variability are not completely understood. Similarly, the time of emergence (ToE) of anthropogenic O2 trends from the “noise” caused by chaotic internal variability as well as naturally-forced variations, e.g., in response to volcanic eruptions and solar irradiance changes, awaits further investigations. We analyze results from a simulation from 850 AD to 2100 forced by solar irradiance changes, explosive volcanic eruptions and anthropogenic greenhouse gases and of a corresponding control simulation performed with the NCAR-CESM climate model. Results from the preindustrial period are used to define the natural variability (internal and external forcing) of the climate system and to compute ToE for oxygen and temperature as well as for apparent oxygen utilization and the O2 solubility component. In contrast to earlier work on ToE, we consider both forced and internal variability of the pre-anthropogenic period as contributing to the background noise. We find that the global mean oxygen concentration in the ocean is decreasing under anthropogenic forcing and becomes smaller than the pre-industrial range as early as around 1900 AD. Focusing on the thermocline, where oxygen concentrations are particularly relevant for biological processes, the simulated oxygen decrease is detectable before the increase in ocean temperature in some regions such as the North Pacific and the Southern Ocean and as indicated by an earlier time of emergence of the anthropogenic signal of O2 than of temperature. Physical and biogeochemical processes, influence dissolved O2. The role of these processes, their magnitude and timescales of simulated responses in marine O2 will be discussed in the context of ToE of anthropogenic signals.

Reconstruction of paleo-redox conditions in particle rain vs. diffusion dominated settings in Pacific oxygen minimum zones

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The extent and intensity of oxygen miminum zones (OMZs) along productive continental margins are tightly coupled to changes in ocean ventilation and biogeochemical feedbacks. The reconstruction of spatial and temporal changes of these parameters is crucial to understand the mechanisms driving marine redox conditions in the past. The application of redox-sensitive proxies like molybdenum
(Mo) and its isotopes can unravel valuable information archived in the sedimentary record. However, the mechanisms by which Mo is delivered to and sequestered by sediments in OMZs are still poorly constrained. In this study, we compare Mo concentrations and isotope compositions of modern shallow maine sediments as well as paleorecords covering the last 10,000 years from the OMZs in the Gulf of California and the Peruvian Margin [1]. The investigated sites differ in sedimentation rate, export production and ocean circulation. Shallow sediments from the Gulf of California OMZ have δ$^{98}$Mo signatures ranging from +1.64 to +2.13 ‰ and Mo concentrations between 3 and 17 μg g$^{-1}$. The paleorecord has δ$^{98}$Mo signatures ranging from 1.66 to 1.92 ‰ and Mo concentrations between 5 and 10 μg g$^{-1}$. In contrast, shallow sediments from the Peruvian OMZ are isotopically lighter (+1.16 to +1.55 ‰) with higher Mo concentrations (11 to 101 μg g$^{-1}$) [1]. Similarly, the paleorecord reveals a large range in δ$^{98}$Mo signatures (+1.23 to +1.79 ‰) and Mo concentrations (13 to 98 μg g$^{-1}$). The differences between the two settings can be explained by unique transport mechanisms of Mo to the sediments. The OMZ off Peru is characterized by high organic carbon rain rates and intense water column denitrification. The sedimentary Mo inventory is consequently dominated by particulate supply via Fe-oxides [1] and organic matter. In contrast, the OMZ in the Gulf of California is characterized by a lower organic carbon rain rate and denitrification does not occur in the bottom waters. The Mo flux is dominated by diffusion into the sediments. These findings demonstrate the importance of particulate vs. diffusive Mo delivery in controlling the Mo isotope composition of sediments with important implications for the reconstruction of paleo-redox conditions in the eastern equatorial Pacific.

References: [1] Scholz et al. (2017) GCA 213, 400-417

I/Ca ratios of carbonates as proxy for changes of deoxygenation in the past: A Nano-SIMS study on benthic foraminifera for better mechanistic understanding, evaluation and application

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Oceanic oxygen decline due to anthropogenic climate change is a matter of growing concern. A quantitative oxygen proxy is highly desirable in order to identify and monitor recent dynamics as well as to reconstruct pre-Anthropocene changes in amplitude and extension of oxygen depletion. Geochemical proxies like foraminiferal I/Ca ratios seem to be promising redox proxies. Nevertheless, recent studies on microanalyses of benthic foraminiferal I/Ca ratios at the Peruvian Oxygen Minimum Zone (OMZ) measured with Secondary-Ion-Mass-Spectrometry (SIMS) revealed a possible association of iodine with organic accumulations within the test. Furthermore, it appeared that oxidative cleaning even removed organics from within the massive centre of the foraminiferal test walls. Here we present a new study on the microdistribution of nitrogen, sulphur and iodine within the test-walls of Uvigerina striata from the Peruvian OMZ measured with Nano-SIMS. Uncleaned specimens were compared with specimens which have been treated with an oxidative cleaning procedure. Both nitrogen and sulphur which are used as tracer for organics show
a patchy distribution within the test walls of the uncleaned specimens and a strong association with the iodine distribution. All three elements, sulphur, nitrogen and iodine are strongly depleted in the cleaned specimens, even within the massive parts of the test walls which lack test pores. These results indicate that the organic parts of the test walls are located inside a microporous framework within the foraminifer calcite which has yet been overseen. This has to be considered in the interpretation of geochemical proxies on foraminifer calcite, especially for microanalytical methods.

Decadal to millennial-scale changes in oxygen minimum zone intensity, export production and fish fluctuations in the Humboldt Current System

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The Humboldt Current System (HCS) off Peru yields about 10% of the global fish catch, producing more fish per unit area than any other region in the world ocean. The current high productivity is fuelled by the upwelling of cold, nutrient-rich water from the oxygen minimum zone (OMZ). However, the potential impacts of climate change on upwelling dynamics and fish productivity as well as the response of fish populations to the expected future expansion of the OMZ are uncertain, but may have large impacts on local economies and foreign aquaculture feeds. To unravel the response of these fish populations to past climate changes, we here present reconstructions of their variability for several time windows during the last 130 000 years using fish scales and vertebrae deposited in multiple laminated sediments off Peru. Specifically, we discuss the role of temporal changes in the intensity of the OMZ and productivity on fish population fluctuations, since both oxygen and productivity seem to be the major drivers during the fishery period. During the Holocene, characterized by high productivity and a relatively strong and temporal variable OMZ, we observe high abundance of anchovy, sardine, jack mackerel, chub mackerel, saury, hake and mesopelagic fishes, suggesting that the oceanographic conditions were favorable for fish productivity. The deglaciation, characterized by a strong OMZ and a relatively low productivity, was more favorable for anchovy and mesopelagic fishes, while sardine abundance was very low. During the glacial periods, characterized by a weak OMZ and low productivity, the fish productivity in general was low, the oceanic species were particularly reduced. Finally, during the last interglacial (MIS 5e) characterized by a strong OMZ, high productivity and enhanced water column stratification, anchovy biomass was extremely low. Our results indicate that anchovy and sardine, and other fishes, are strongly linked to changes in productivity at multiple timescales and that changes in water column oxygenation seems to be an important factor regulating sardine abundance off Peru. The results support the idea that the warming climate observed during the last decades is favorable for anchovy, since the shallowoxygenated habitat, promoted by the strong OMZ and upwelling, concentrates the anchovy prey near the surface, which enhances anchovy foraging, promotes a massive anchovy biomass and gives the
Decadal to multidecadal changes in marine subsurface oxygenation off central Peru since the XIX century

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Permanent oxygen deficiency in intermediate-depth waters is an important feature of the ocean. These water volumes are known as oxygen minimum zones (OMZ) and exhibit a high sensitivity to climate variability providing feedbacks on climate drivers. Over the last decade, several studies have reported global ocean deoxygenation trends since the 1960s and a consequent OMZ expansion. However, paleoceanographic reconstructions of subsurface waters from Eastern Boundary Upwelling Ecosystems (e.g. California, Concepción) show a centennial OMZ weakening over the XX century, instead of an OMZ strengthening as observed for the last decades. This pattern has been associated to several climate variabilities, but the mechanisms behind the subsurface (de)oxygenation trends in these areas are still not well understood. At the South East Pacific, the upper Peruvian continental margin is characterized by a shallow and intense OMZ which has been preserved since the ending of the Little Ice Age period. In this study, we aim to reconstruct the (multi)decadal oxygenation variability off central Peru to identify the influence of both large-scale and local factors, differentiate between trends and multidecadal variability, and the potential underlying mechanisms governing in the East Pacific. We combined a multiproxy approach based on multiple paleoceanographic records for the last ~180 years and instrumental records of subsurface oxygen content since the 1960s. Finely laminated sediments were retrieved in the upper margin off Callao (180 m) and Pisco (~300 m). We analyzed benthic foraminiferal assemblages and compared them with records of redox-sensitive metals (Mo, Re, U) and TOC, biogenic silica and δ15N. Foraminiferal assemblages from sulfidic, postoxic and mixed conditions were identified in the record with different trends, mostly showing more permanent sedimentary postoxia. We identified three major multidecadal periods: i) the mid to late nineteenth century, characterized by a strong OMZ and reducing sedimentary conditions, in parallel with enhanced siliceous productivity; ii) the late nineteenth century to mid-twentieth century, with a relaxing trend of OMZ and redox conditions, superimposed to a slight multidecadal variability; and iii) the late twentieth century until the early 2000’s, when despite the high variability, there was a slight oxygenation trend over the upper Peruvian margin. The general OMZ relaxation trend until 1960s is similar to those in other upwelling areas. However only Peru maintains the oxygenation in the last decades in intermediate waters, meanwhile the shelf showed reducing conditions. We suggest that subsurface ventilation and local productivity are the main controlling factors generating this scenario.
Multidecadal changes of OMZ intensity over the Peruvian upper-slope inferred by pore density in benthic foraminfer *Bolivina seminuda* since XIXth century

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The abrupt change to a regime of high productivity with nutrient-rich and low-oxygen concentration waters on the Eastern Tropical Pacific since the end of the Little Ice Age (LIA) promoted the development of an intense Oxygen Minimum Zone (OMZ) that allows the preservation of carbonates at the seafloor. Calcareous benthic foraminifera dominates foraminiferal faunas in most OMZ realms and exhibits some morphological attributes which have only been reported for this type of settings. Among these, the presence of pores on their shells has been attributed to an environmental response. More recently, some studies have proposed that pore density in epifaunal taxa is closely linked to the bottom water oxygenation and infaunal taxa could be reflecting reducing conditions in the sediment. Therefore, we present pore density results of *Bolivina seminuda* Cushman 1911 in a sediment core collected on the Peruvian upper-slope to reconstruct the past variability of bottom oxygenation since the beginning of XIXth century. For this purpose, up to 10 specimens of the shallow infaunal species *B. seminuda* were picked from the 125 μm fraction at different depths along the core B1404-11 (off Pisco, 302 m depth, April 2014). The whole shell of the specimen was photographed in a scanning electron microscopy (SEM) at different magnifications. Pores were counted manually using the software ImageJ and based on two methodologies. The pore density was expressed as #pores μm⁻². In addition, rose Bengal-stained specimens of *B. seminuda*, previously sorted from different depths, were used for a calibration with bottom nitrate concentrations collected during R.V. Meteor cruise M92 in January 2013. Sediment accumulation rates were assessed through downcore profiles of ²¹⁰Pb and ²⁴¹Am and allowed us to develop a chronology for the upper 30 cm. Pore density in *B. seminuda* displayed a slight positive trend since the end of the LIA to the end of XIXth century, supporting some previous studies regarding reducing bottom-water conditions in this period. From here, a muti-decadal scale variability is observed towards the current period. Moreover, pore density exhibited a drop for the last decades, suggesting the increase of nitrate availability and therefore, a reduction in the intensity of the OMZ in this region of the Eastern Tropical Pacific.
Benthic foraminiferal Mn/Ca evidence for bottom water deoxygenation in the Baltic Sea over the past 7,500 years

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Deoxygenation is recognized with growing concern in the modern Baltic Sea and results in increasing areas of hypoxia ([O$_2$]<1.4 ml/l). The Baltic Sea has been highly prone to deoxygenation during the Holocene. Our goal is to study how the extent and severity of hypoxia in the region have varied over the Holocene from 7.5 ka BP to present: to achieve this, we use high accumulation rate sediment cores retrieved during IODP Exp. 347 (Baltic Sea Paleoenvironment) spanning the past 8 ka BP. We apply benthic foraminiferal geochemistry and faunal assemblage data to reconstruct past marine conditions (e.g. oxygenation, temperature, salinity). We analyse the trace elemental composition (Mg/Ca, Mn/Ca Ba/Ca, Sr/Ca, U/Ca) and stable carbon and oxygen isotopes of the low-oxygen tolerant foraminifera species *Elphidium selseyense* and *Elphidium clavatum* from two Baltic Sea sites: the Little Belt, Danish Straits (Site M0059) and the Landsort Deep, the deepest basin of the Baltic Sea (Site M0063). For trace element analysis, we use laser ablation (LA-)ICP-MS to avoid the influence of surface diagenetic coatings on these foraminifera. In particular, Mn is a redox-sensitive element, and it has an increased concentration in bottom waters and sedimentary pore waters under hypoxic conditions which may result in increasing Mn incorporation into foraminiferal carbonate. Site M0059 Mg/Ca and Mn/Ca results show a general decrease from 7.5 ka to present. These proxies may suggest high temperature and low bottom oxygen conditions at Site M0059 ~7 ka BP and between 4.5 and 3.5 ka BP. Ba/Ca and oxygen stable isotopes have potential to be used as a multiproxy approach for salinity reconstruction, potentially indicating increasing bottom water salinity from 7.5 to 3 ka BP in the Little Belt. Initial trace element results from the Landsort Deep show that some samples have much higher Mn/Ca ratios compared to those in Site M0059, potentially indicating low oxygen conditions in this area. By combining geochemical results with foraminiferal assemblage data, we quantify and discuss the hypoxia and ecosystem changes at these two sites in the Baltic Sea over the past ~7.5 ka BP.

Spread of ocean anoxia and sluggish overturning circulation in a warmer-than-today world: does the geological record support this scenario?

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During the past 125 million years, the Earth experienced a series of major global warming episodes, including the Early Aptian Selli-Event (OAE1a) the Cenomanian-
Turonian Boundary Event (OAE2), the Paleocene-Eocene Thermal Maximum and the Miocene Climate Optimum (MCO). All these episodes were associated with fundamental disturbances of the global carbon cycle, expressed as prominent excursions in marine and terrestrial carbon isotope records. Characteristic features are (1) an initial negative carbon isotope excursion, which last several 100,000 years and is related to the injection of d13C depleted carbon into the atmospheric and marine reservoirs followed by a massive and relatively rapid increase in d13C to a plateau, that can last as long as 3.2 million years during the middle Miocene Monterey Event (~16.7 to ~13.5 Ma). The positive excursions and ensuing plateaus suggest large-scale burial of d13C depleted organic carbon associated with the development of widespread anoxia in the Cretaceous Ocean. We present high resolution carbon and oxygen isotope records across the Cretaceous OAE1a, and OAE2 which show that the positive excursions and plateau phases of the d13C records are punctuated by transient cooling events. These cooling events were paced by changes in orbital eccentricity and obliquity of the Earth’s axis and were associated with re-oxygenation events of the ocean floor during Cretaceous OAEs. Processes that controlled this unexpected dynamic behavior of climate and ocean oxygenation following important episodes of greenhouse gas release into the atmosphere include increased drawdown of atmospheric CO2 by enhanced carbon sequestration through feedback loops in marine nutrient cycles and a more vigorous than expected thermohaline circulation in a warmer ocean.

**Climate-carbon cycle dynamics on a warmer-than-modern Miocene Earth**

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The late Miocene (~11.6 to 5.3 million years ago) represents a geologically recent interval of relative global warmth that was marked by profound environmental change in both terrestrial and marine ecosystems. This period offers the opportunity to assess the sensitivity of the Earth’s climate to changing boundary conditions, such as ice volume and radiative forcing, on a warmer-than-modern Earth. However, the uncertainty of the CO2 forcing during the Miocene remains a major challenge for understanding the dynamics of warmer climate states. In particular it is difficult to reconcile late Miocene warmth with current reconstructions of atmospheric pCO2 levels close to pre-industrial values. This apparent decoupling between climate warmth and atmospheric pCO2 has prompted intense debate about the role of pCO2 as driver of climate variations under different background states. Our high-resolution benthic isotope record in combination with paired mixed layer isotope and Mg/Ca-derived temperature data from the subtropical northwest Pacific Ocean reveals that climate cooling and intensification of the southeast Asian winter monsoon from ~7 Ma until ~5.5 Ma were synchronous with decreasing pCO2 within a global context of steepening meridional thermal gradients. The climate shift occurred at the end
of the most important global δ¹³C decrease of the Cenozoic, suggesting that changes in the carbon cycle involving the terrestrial and deep ocean carbon reservoirs were instrumental in driving climate change. Our results further show that intensified monsoonal wind forcing of upper ocean circulation enhanced productivity, thus strengthening the Pacific Ocean's biological pump and increasing global carbon sequestration efficiency. We speculate that this late Miocene climate shift was associated with a relatively small decline in pCO₂ and that climate sensitivity was amplified by a conjunction of positive feedbacks.

The initiation and establishment of the Western Indian Ocean oxygen minimum zone during the Early to Middle Miocene

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Presently, productivity and oxygenation of the Arabian Sea are governed by the upwelling generated along the Oman Margin. Upwelling in this area is strongly related to the modern monsoonal regime and tectonic configuration of the region, which was established during the Early and Middle Miocene (~23.0 to 11.7 Ma). Recent new records from the north Western Indian Ocean (Maldives) and revisitation of older Ocean Drilling Project sites (Omanian Margin, Owen Ridge) have established the upwelling initiation at ~12.8 Ma, concordant with the initiation of the modern-day South Asian Monsoon system. Recently published record from the Maldives revels initial pulses of decrease in Mn occurred during the Early Miocene, which may indicate initial pulses of upwelling and OMZ expansion at that time. Prior studies have suggested that the early Oxygen Minimum Zone (OMZ) was apparently much larger and more extensive than the modern one. However, several uncertainties persisted regarding initiation of the OMZ, coupling of the OMZ and the upwelling, as well as the evolution of the oxygen state in the OMZ. In this study, a detailed reexamination of the initiation of the Western Indian Ocean OMZ using records from the Early to Late Miocene from Owen Ridge (15 Ma to 8 Ma). Systemic analysis of sedimentary facies, nannofossil assemblages, as well as trace element and organic geochemical proxies was carried out to ascertain the evolution of the OMZ. As of the base of the Serravallian a decreasing trend of Mn content is established, reaching minimum values around ~12.8 Ma, coinciding with the initiation of the modern South Asian Monsoon system and concordant with a marked increase in the abundance siliceous fossils has is recorded in the Arabian Sea (ODP site 722). Our study, in light of recently published data, indicates that the formation of the Western Indian Ocean Oxygen Minimum was in fact the culmination of a process that already initiated during the Early Miocene and achieved an apex in the Late Miocene.
Oscillations in Cretaceous ocean productivity and deoxygenation induced by redox-dependent nutrient cycling

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Deoxygenation and productivity of the Late Cretaceous ocean were studied using the UVic earth system model. Simulations were performed at 4 different atmospheric pCO$_2$ values (500 ppm, 1200 ppm, 1800 ppm, 2200 ppm) using a state-of-the-art reconstruction of paleogeography and ocean basin configuration. Consistent with the proxy record, the model predicts low oxygen conditions for the proto North Atlantic and Tethys while most of the Pacific is well ventilated. This pattern is maintained over the entire pCO$_2$ range applied in the modeling when the standing stock of nutrients is conserved. The mean oxygenation state of the Cretaceous ocean responds only weakly to pCO$_2$ and surface temperature change because an increase in overturning circulation under high pCO$_2$ compensates for the coeval decrease in oxygen solubility. A box model was set up to study the effects of changing nutrient inventories on deoxygenation. The Cretaceous ocean was represented by 36 boxes and the water fluxes between these boxes were defined using output of the UVic model. The turnover of dissolved oxygen, sulfide, nitrate, ammonium, phosphate, ferrous and ferric iron was simulated considering redox-dependent fluxes across the sediment/water interface and a range of abiotic and biotic redox reactions in the water column. Two classes of phytoplankton (nitrogen-fixing and non-fixing) and three potentially limiting nutrients (reactive nitrogen, phosphate, iron) were considered. Surprisingly, many of the simulations did not converge into a steady state but showed persistent oscillations in deoxygenation and ocean productivity with cycle lengths ranging from 20 kyr to 100 kyr. These cycles were generated in the North Atlantic where dissolved iron accumulated in intermediate and deep waters due to intense deoxygenation and denitrification. This anoxic ocean basin served as dissolved iron source for adjacent basins. Global ocean productivity increased until the benthic iron release in the North Atlantic was diminished by sulfate reduction and pyrite formation. The resulting productivity decrease in adjacent iron-limited basins induced a rise in lateral dissolved oxygen supply to the North Atlantic that reduced the rates of pyrite formation and induced a recovery of the dissolved iron level. The cycle started again when the export production in the North Atlantic promoted sufficient pyrite precipitation to limit benthic iron release. The simulations show that periodic changes on orbital time-scales observed in the geological record are not necessarily related to orbital forcing but may be induced by the internal non-linear dynamics of the marine biogeochemical system.
Impact of Cenomanian-Turonian Anoxic Events on ocean oxygenation: High-resolution records from the Atlantic Tarfaya-Laayoune Basin, SW Morocco

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Major perturbations of the global carbon cycle are globally imprinted as prominent carbon isotope excursions (CIEs) in Mesozoic sedimentary successions. These CIEs have been linked to the widespread enhancement of primary productivity in ocean basins, which strongly impacted the oxygenation of subsurface water masses. We investigate changes in redox-conditions in a 265 m continuous succession of hemipelagic deposits spanning the Cenomanian to early Turonian, which was recently drilled in the Tarfaya Basin (SW Morocco). X-ray fluorescence core scanner derived logarithmic ratios are integrated with stable isotope data on bulk and organic material and discrete geochemical analysis to establish a robust chronology and to document the detailed evolution of sub-surface oxygenation across the Oceanic Anoxic Event 2 (OAE2), one of the largest CIEs, and across its precursor, the mid-Cenomanian Event (MCE). Enhanced upwelling, inducing deteriorating redox-conditions in the Tarfaya Basin, started in the early Cenomanian and was in part associated with eustatic sea level changes occurring on orbital and tectonic timescales. We speculate that oxygen depletion controlled by increased productivity during the Cenomanian CIEs allowed leakage of the limiting nutrient phosphorus from the sediments, as recorded by sudden increases in $\text{C}_{\text{org}}/\text{P}_{\text{react}}$ and $\text{N}_{\text{total}}/\text{P}_{\text{react}}$, which further enhanced primary productivity during the later phases of OAE2. Increased carbon burial controlled by this feedback loop caused atmospheric CO$_2$-drawdown resulting in prominent cooling episodes (i.e., the Plenus Cold Event during OAE2) that influenced the latitudinal distribution pattern of marine organisms. The major decrease in subsurface water oxygenation also caused prominent global extinctions of thermocline dwelling foraminifera during OAE2, which serve as useful biostratigraphic correlation tools. Evaluating the scale of environmental changes during Mesozoic CIEs is relevant to better understand the processes associated with the burial of excess anthropogenic CO$_2$, demonstrating that extreme climate change can impact marine biota on a global scale.

Constraining global (de)oxygenation during Phanerozoic climate events

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Recent observations of the modern ocean show that the ocean is experiencing progressive deoxygenation. While it is likely that ancient climate events experienced similar variations, our current proxies lack the resolution to definitively fingerprint non-sulfidic, low oxygen bottom waters. Throughout the Phanerozoic there are numerous climatic perturbations with associated extinction events that are associated with carbon cycle perturbations. Carbon isotopes can be driven by multiple parameters, including but not limited to, enhanced organic carbon burial. Redox
conditions and sedimentation rates are important factors controlling the magnitude of organic carbon burial. Therein, it is important to constrain ancient non-sulfidic, low oxygen environments which is required to better understand Earth system biogeochemical feedbacks. We will present new data from the modern and ancient record using a new metal isotope system, thallium (Tl), to better constrain the global marine record of the earliest deoxygenation. The modern ocean mass balance of Tl isotopes suggest that the two dominant sinks are (1) adsorption onto manganese (Mn) oxides and (2) low-temperature oceanic crust alteration, while all the sources of Tl are isotopically indistinguishable. For short-term (million years or less) climate events it is likely that the primary control on seawater Tl isotopes is the burial magnitude of Mn oxides. Importantly, Mn oxide burial requires free oxygen at or near the sediment-water interface. Sediments deposited in reducing conditions have been shown to record the oxic seawater Tl isotope value, which respond to ancient variations in global burial of Mn oxides. Thus we can track initial changes in oceanic oxygen conditions. Initial thallium isotope perturbation during Phanerozoic climate events coincide with with many of the onset of extinction events and volcanism and proceed carbon isotope excursions.

Exploring the links between flood cyclicity and the OMZ development on the Nile deep-sea fan during the African Humid Period

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Suboxic to anoxic conditions were existing in large parts of the Mediterranean basin during the deposition of Sapropel S1 (ca. 12 to 6 ka BP). If the general mechanism for the development of a basin-wide paleo-OMZ have been intensively investigated, the relationships between flood seasonality and the strength and extend of the OMZ remain elusive. Here we propose to use a unique 5 m-thick sapropel S1 section of finely laminated sediments deposited in front of the Nile mouth (close to the Rosetta channel). The core was retrieved at 700 m water-depth and sedimentation rates computed for the sapropel are in the order of a few mm per year. The couplets of alternating darkand light-colored layers most likely represent seasonal deposits of Nile floods and marine hemipelagic sedimentation, respectively. This sequence therefore allows to explore the relationships between flood seasonality and oxygenation conditions in the water column and sediments. Using varve microfacies description and counting developed for lake sediments, we aim at reconstructing the changes in flood dynamics during the sapropel deposition. Micro-XRF scanning and element mapping will provide additional information about sedimentation and diagenetic processes associated with flood deposition and oxygenation conditions at a sub-annual resolution. We finally intend to compare this very proximal record (to the source of freshwater and sediments) to more distal S1 records in the Mediterranean and to terrestrial archives (speleothems and lake records) in order to infer overarching forcing mechanisms.
Nitrogen removal across glacial terminations in the Eastern Tropical South Pacific

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Our understanding of how marine microbial processes and nitrogen cycling will respond to future increases in atmospheric CO₂ and global temperature, as well as ocean acidification and deoxygenation, is very limited. This is largely due to a lack of proxies that can register ocean biogeochemical processes in sedimentary archives during past transitions to warmer climates. We present biomarker (anammox bacteria and phytoplankton) and stable isotope (bulk δ¹⁵N) records from sediments underlying the oxygen minimum zone of northern Chile (GeoB15016, 27°29.48′S, 71°07.58′W) that trace variations in microbial nitrogen removal across glacial terminations leading to Marine Isotope Stages 5 and 11. Our results demonstrate that increases in temperature and productivity during glacial terminations (and peak interglacial periods) were associated with enhanced oxygen depletion and nitrogen removal, as evidenced by parallel increases in anammox and denitrification signatures. Notably, whereas a decrease in denitrification and algal productivity was observed during the waning of interglacial temperatures, anammox biomarkers (and thus anammox activity) remained elevated for up to thousands of years thereafter. Our results indicate that heterotrophic denitrifying bacteria is stimulated by changes in organic carbon supply (i.e., enhanced upwelling and productivity), while chemoautotrophic anammox activity occurs as a “background” metabolism when denitrification is less intense. The observed temporal offset between these two bacterial processes indicates differences in their response to variations in ocean circulation, primary productivity and oxygen depletion across glacial-interglacial transitions in the OMZ of the ETSP. We discuss the implications of this offset in terms of past and future projections of ocean deoxygenation and nitrogen removal.
A quantitative nitrate reconstruction over the last 22,000 years in the intermediate Pacific based on the pore density of the denitrifying foraminifera *Bolivina spissa*

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Anthropogenic impacts are perturbing the global nitrogen cycle via warming effects and pollutant sources such as chemical fertilizers and burning of fossil fuels. Nitrate is one of the main limiting nutrients in the modern ocean and nitrate fertilization might contribute to the ongoing ocean deoxygenation. The quantitative reconstruction of past reactive nitrogen inventories is indispensable to facilitate future projections for biogeochemical cycling. Benthic foraminifera from oxygen depleted habitats are a rare example of eukaryotes with the ability to perform denitrification. The uptake of nitrate for denitrification is most probably facilitated through the pores within the foraminiferal shell and the pore density can be used as a quantitative proxy for past nitrate concentrations. Here we present the quantitative reconstruction of nitrate concentrations in intermediate water depths of the Peruvian oxygen minimum zone over the last deglaciation using the pore density of *Bolivina spissa*. Deglacial nitrate concentrations correlate significantly with the downcore stable carbon isotope (δ¹³C) record which indicates a strong coupling between the carbon and nitrogen cycles over the last deglaciation. The linear correlation between δ¹³C and nitrate availability remained stable over the last 22,000 years, facilitating the use of δ¹³C records as a quantitative nitrate proxy. The combination of the pore density record with δ¹³C records shows an elevated oceanic nitrate inventory of >10% during the Last Glacial Maximum as compared to the Holocene. Our novel proxy approach is consistent with a δ¹³C-based and δ¹⁵N-based 3D ocean biogeochemical model and previous box modeling. The modeling results also indicate that the correlation between δ¹³C and nitrate, probably facilitated by remineralization, did not differ significantly between the Last Glacial Maximum and the Pre-Industrial Holocene. The coupling of nitrate and δ¹³C thus provides sound estimates of the spatial nitrate distribution in the intermediate Pacific from the Last Glacial Maximum until the Holocene.

The natural variability of marine de-oxygenation in the Eastern-Tropical Pacific since the last Glacial Maximum

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Global warming and its effect on the stratification and oxygen solubility of the Ocean is leading to declines in the marine oxygen inventory, with potentially catastrophic consequences for ecosystem and habitat sustainability and marine productivity. Total oxygen inventory has already declined by 2% since 1960 and deoxygenation is...
predicted to accelerate over the rest of the century (Keeling et al. 2010). Decreased oxygenation in the ocean triggers the rapid expansion of Oxygen Minimum Zones (OMZs) with implications for marine N₂O production, fixed nitrogen budget and productivity (the biological CO₂ pump). The North Tropical Pacific accounts for up to 40% of the (existing and forecast) oxygen loss and hosts the largest oxygen minimum zone in the ocean. While decreased solubility, overturning circulation and physical mixing of the top layer of the water column are all observed consequences of global warming leading to ocean deoxygenation, multi-decadal variability such as PDO (Pacific Decadal Oscillation) has been identified in some of the Pacific and Atlantic oxygen records (Schmidtko et al., 2017). However, these instrumental records of marine oxygen and climatology are short, only dating back to the 60’s. One of the challenges in quantifying and predicting the global decline in oxygen level is our ability to constrain natural variability. Here we reconstruct the natural, multi-decadal to annual variability in deoxygenation in the Northern Tropical Pacific since the last Glacial Maximum. We present a continuous, 25,000 year long record of upwelling-induced biological productivity (biogenic silica and organic carbon) and water column deoxygenation (denitrification) in the Gulf of California at centennial timescales. Several 200-year long, annually-varved sections distributed from the Holocene to the last Glacial maximum were selected from this long record, and both denitrification and productivity were measured with annual resolution. Spectral and wavelet analyses of the annually resolved records reveal the permanence of ENSO and PDO-like (Pacific Decadal Oscillation) variabilities throughout the record. While we see only minor deviations in the length of the ENSO and PDO periodicities since the last glacial period, changes in the amplitudes of both ENSO and PDO are manifest. This study confirms the mechanistic link between the 2 types of climate variabilities in the Pacific and their suspected role in modulating oxygen levels in the region. Future changes in the amplitudes of the ENSO and PDO climatic cycles in response to global warming might hold the key to deoxygenation trends in the Tropical Pacific.

**Benthic pelagic coupling in the Peruvian upwelling system over the last 25 thousand years**

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Multiproxy paleoenvironmental reconstructions are crucial in order to improve our understanding of the nutrient rich, high productivity environments, such as the Peruvian upwelling system, in relation with the currently changing climate. In this study we present compilation of multiproxy results focusing on the relationship between benthic and pelagic environment in relation with a strong oxygen minimum zone (OMZ) over the last 25 thousand years. The sediment core M77/2- 52-2 was obtained from the northern part of the Peruvian continental slope from 1250 m
Multidecadal to millennial-scale changes in oxygen minimum zone intensity off Peru during the last 20 kyr: proxy – model comparison

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Oxygen minimum zones (OMZ) have expanded in all tropical oceans during the last decades resulting in habitat contraction and considerable changes in marine biogeochemistry. However, it is still an open question as to how the magnitude and temporal changes in oceanic dissolved oxygen of the last few decades compare to the natural variability on longer timescales and how local and remote mechanisms were driving OMZ changes in the past. We discuss climatic and biogeochemical processes as potential controls for the intensity and the spatial extent of the OMZ off Peru during the last 20 kyr. First, we use multiple sediment records along the Peruvian margin (from 3ºS to 17ºS) to reconstruct changes in OMZ intensity during the last 20 kyr. Analysis of a suite of proxies, including the presence of laminations, redox sensitive metals and δ¹⁵Ν measurements on organic matter, highlight changes in ocean oxygenation and are combined with proxy records for past variations in sea surface temperature and productivity. Second, we compare our records with results from transient global climate and biogeochemistry model simulations to identify mechanisms that have driven past oxygenation changes. Our results imply pronounced centennial to millennial-scale changes in subsurface oxygenation off Peru during the last 20 kyr, as well as increased centennial-scale variability during the last 3 kyr BP. Globally recognized cold climate periods such as the Last Glacial Maximum and the Little Ice Age were associated with a weak OMZ and low export production, while warm intervals such as the Last Deglaciation, part of the Medieval Climate Anomaly and the last 100 years are associated with a stronger OMZ and high export production. Contrary to previous assumptions and model projections for climate warming during the next few decades, we observe weak OMZ and colder conditions in the Eastern Tropical South Pacific (ETSP) during the overall warm Middle Holocene.
This was probably the result of a stronger Walker Circulation that intensified the ETSP cold water tongue and, via equatorial undercurrents, brought more oxygen to intermediate depths off Peru. Accordingly, a re-amplification in water column deoxygenation and denitrification during the Late Holocene could be the result of a slowdown of the equatorial Pacific Ocean circulation at mid-depths. Our model-data comparison, in combination with other paleoceanographic reconstructions, implies that oxygen variability in the ETSP-OMZ was mainly influenced by ocean circulation changes and to a lesser degree by changes in local upwelling and biological production.

POSTER PRESENTATIONS

(43) Unravelling the cause of OAE 1a (~120 Myr), one of the largest ocean deoxygenation events of the last 200 million years

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Oceanic Anoxic Event (OAE) 1a took place during the early Aptian (~120 Ma) and represents one of the largest disruptions in ocean oxygenation and biogeochemical cycles of the last 200 million years. So far it has been difficult to constrain the processes and mechanisms that drove this event, hindering a holistic understanding of the relative importance of external forcing and internal feedbacks during this perturbation. For the first time, we study changes in the global carbon cycle at the onset of OAE 1a combining proxy data and a global biogeochemical ocean model of intermediate complexity (cGENIE). In a series of experiments, cGENIE was forced to follow the atmospheric stable carbon isotope ($\delta^{13}$C) evolution obtained from proxy data throughout the onset of OAE 1a using a variety of timescale assumptions and CO$_2$ change scenarios. Depending on the scenario, the model calculates for each experiment the magnitude and $\delta^{13}$C signature of carbon inputs required to reproduce the recorded $\delta^{13}$C excursion. Our results suggest that the majority of the deoxygenation was driven by emissions from sedimentary organic carbon reservoirs and volcanic sources and not biogenic methane. Also low emission scenarios comply with proxy data constraints, highlighting the potentially crucial role of internal feedbacks in the extreme ocean deoxygenation during OAE 1a.
(44) Variations in intermediate water oxygen concentrations in the equatorial Pacific over the last 140,000 years

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Intermediate waters (500 - 2000 m) from the equatorial- to North Pacific are currently hypoxic (oxygen concentrations below 120 μmol/kg), while deeper waters are well oxygenated. For the last iceage, proxy records suggest that this trend was reversed, with well-oxygenated Pacific intermediate waters, and lower oxygenated deeper waters associated with an increased deep carbon reservoir. Here we assess changes in bottom water oxygen concentrations at an intermediate water depth from the eastern equatorial Pacific (site ODP 1242, 1360 m depth) over the last 140,000 years, to test whether intermediate water oxygen concentrations increased during glacial intervals (e.g. Marine Isotope Stages 2 and 4). We use the carbon isotope gradient between bottom water (recorded by epifaunal benthic foraminifera *Cibicidoides wuellerstorfi*) and pore water at the anoxic boundary (recorded by infaunal *Globobulimina spp.*) as a quantitatively proxy to reconstruct intermediate water oxygen concentrations at this site, following the approach of Hoogakker et al. (2015).

(45) About the beginning and end of OAEs: a story of biogeochemical feedbacks and organic matter burial

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Despite more than 40 years of research on oceanic anoxic events (OAEs), the specific mechanisms that initiated, maintained and terminated widespread ocean anoxia (and euxinia) are still disputed. One way to explain these extreme conditions is via increased oxygen demand in the water column resulting from enhanced productivity, itself fueled by increased nutrient availability for instance from the sediments as the burial efficiency of phosphorus declines when bottom waters become anoxic. Also for the recovery from OAEs the sediments may play a dominant role, here via globally increased organic matter (OM) burial, as it removes CO2 from the ocean/atmosphere system and drives oxygen accumulation in surface waters, eventually leading to the reoxygenation of the deeper ocean and a shut-down of the positive feedback of anoxia, P-regeneration and productivity. Although diagenetic processes and OM burial are considered of pivotal significance for OAEs the role they play has yet to be quantified using an explicit OM diagenesis model. The major hurdle is the high computational cost of simulating the essential redox reactions in marine sediments, which are critical to quantify the burial of OM and benthic recycling fluxes. In order to close this knowledge gap, we developed a mechanistic analytical early diagenetic model resolving OM cycling (OMENSED) and coupled it to a 3D Earth system model (cGENIE). Using this new model we investigate feedbacks between water column anoxia/euxinia and enhanced OM preservation using OAE2 as a case study. Our results imply that feedbacks between carbon, oxygen, phosphorus and sulfur cycles in the oceansediment system lead to significantly enhanced OM preservation during OAE2.
compared to background Cretaceous values. In addition, we show that the coupled model can reproduce geographical patterns of OM-rich black shales as observed in the geological record. Model simulations further illustrate that anoxia/euxinia develops from oxygen minimum zones in the photic zone and at the seafloor. Simulated sediment-water interface fluxes show enhanced P-regeneration from the sediments in response to seafloor anoxia which could further intensify marine productivity.

(46) Testing the suitability of Chilean and Peruvian margin core tops for bottom water oxygen reconstructions

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In tropical and subtropical oceans, models and empirical observations indicate an expansion of the “hypoxic oceanic areas”, namely Oxygen Minimum Zones (OMZ) and Anoxic Zones (AZ), under nowadays global warming conditions. Since the OMZs are located in eastern boundary upwelling areas, the Eastern Tropical and South East Pacific offer a natural laboratory to study the evolution of a OMZ and AZ. In order to reconstruct the past geometry of their respective OMZ and AZ, we aim to characterize the community structure and stable isotope composition (δ18O and δ13C) of benthic foraminifera (both Rose Bengal stained and non-stained) to generate new calibrations of geochemical (δ18O, δ13C) and biological proxies (transfer functions) to infer past environmental conditions (e.g. water density, nutrient and oxygen content) in the region. The data are complemented with measurements of seawater δ18O and δ13C. We analysed the uppermost centimetre of multicores, gravity and piston cores (n=84) collected from the steep Peru-Chile continental margin during several expeditions along a N-S transect between 12°-42°S, spanning latitudes of 71°-80°W and water depths of 24-4000 m. The sediments are bathed by the main water masses in the region, Subantarctic Surface Water, Equatorial Subsurface Water, Antarctic Intermediate Water, Equatorial Subsurface Water, Pacific Deep Water and
Circumpolar Deep Water; and are ideal for testing the suitability of Chilean and Peruvian margin core tops for bottom water oxygen reconstructions. Ages of samples are assessed using radiocarbon dating and benthic foraminiferal oxygen isotopes, only truly modern samples are considered in the calibrations.

(47) Rapid climate change and oceanic anoxia in the Cretaceous greenhouse

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Predicted increases in atmospheric carbon dioxide and global warming have many possible environmental consequences, including increasing ocean acidification, deoxygenation and the development of large harmful bacterial blooms. Notably, there are initial indications of increasing levels of anoxia in the oceans today. These environmental phenomena have been recorded during greenhouse climates in Earth's geological past and are often associated with mass extinction events. Therefore, the Earth’s geological record provides a powerful and important analogue to infer the ecological consequences of future climate scenarios. The Cretaceous greenhouse record includes Ocean Anoxic Event 2 (OAE-2) at the Cenomanian- Turonian boundary – the warmest interval in the last 100 million years – which is often seen as the archetypal marine deoxygenation event. Despite ~40 years of research, key questions remain concerning the role and extent of oceanic stratification, the importance of salinity stratification (i.e. fresh-water input), the implications of primary marine productivity and the effects of anoxia in controlling nutrient budgets, nitrogen fixation, and resulting ecosystem structure. Middle and high paleolatitude data are critical for deciphering inter–hemispheric climate synchronicity, but are notably scarce. The Cretaceous Western Interior Seaway (WIS) of North America, stretching from the Gulf of Mexico to the Arctic Ocean, provides a broad latitudinal range to investigate OAE-2. In addition, it has been postulated that anoxic trends within this semi-restricted epeiric seaway may be antiphase to that of the open ocean, and produces a unique setting to investigate the mechanisms behind anoxia. This project will utilise organic geochemistry as its main tool to assess levels of anoxia and wider changing environmental conditions during OAE-2 across the WIS latitudinal gradient. Molecular fossils (biomarkers) and stable isotopes will be used to study physical and biogeochemical evolution of the WIS during the mid-Cretaceous by reconstructing variations in water column oxygenation, stratification, sea surface temperatures, organic matter provenance and, in concert with paleontological data, planktonic ecology. The overarching goals are to test hypotheses regarding: a) the role of anoxia as a kill-mechanism in extinction events; b) the role of precipitation and salinity stratification as precursors for ocean deoxygenation; c) the role of productivity and changing ecology on ocean deoxygenation and black shale formation; d) the lag time between anoxic conditions, black shale deposition and carbon isotope excursions; and e) the occurrence of elevated SSTs at high latitudes, which might allow proxy and model data to better constrain latitudinal thermal gradients.
(48) A quantitative, late Pleistocene to Holocene bottom water oxygen record from the Peruvian oxygen minimum zone (OMZ) based on benthic foraminiferal assemblages

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Many paleo-proxy records from the mid-depth Eastern Pacific Ocean indicate an extension of oxygen-depleted conditions during the last deglaciation. The ensuing oxygen loss has not been quantified to date. Being one of the strongest and most pronounced OMZs in the world’s oceans, the Peruvian OMZ is a key area to monitor such changes in bottom-water oxygenation in relation to a changing climate. We investigated the extension of the OMZ through time and space using four sediment cores from intermediate depths (600 - 1250 m) at the northern part of the Peruvian OMZ between 3°S and 8°S. A multiple regression analysis was applied to a comprehensive dataset of living (Rose Bengal stained) calcareous benthic foraminiferal faunas from the Peruvian continental margin. The oxygen concentrations close to the sea bed (BWO) during sampling periods were used as dependant variable. The correlation was significant (R² = 0.87; p < 0.05) indicating that the prevailing oxygen concentrations are governing the foraminiferal assemblages. We applied the regression equation to four sediment cores from the lower OMZ and below, with emphasis on the late Holocene (LH), early Holocene (EH), Bølling Allerød (BA)/Antarctic Cold Reversal (ACR), Heinrich-Stadial 1 (HS1) and Last Glacial Maximum (LGM). The shallowest core (M77/2-47-2; 600 m) did not reveal major changes in BWO during the last deglaciation proposing that the OMZ has been relatively stable at these depths. The deeper cores on the other hand showed that BWO continuously decreased from ca. 50 μmol/kg to ca. 20 μmol/kg during the last deglaciation. This oxygen drawdown happened in particular during the BA/ACR. The oxygenation slightly increased during the Holocene.

(49) Oxygen minimum zone variations during the Holocene from transient model simulations

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Climate and marine biogeochemistry changes over the Holocene are investigated based on transient global climate and biogeochemistry model simulations over the last 9,500 yr. The simulations are forced by accelerated and non-accelerated orbital parameters, and atmospheric pCO₂, CH₄, and N₂O, respectively. The analysis focuses on key climatic parameters, the processes that determine the strength of the marine carbon pumps, and on the oxygen minimum zones (OMZs) in the world ocean. The most pronounced changes occur in the eastern equatorial Pacific (EEP) OMZ, where a substantial increase in volume of the OMZ in the EEP continuing into the late Holocene was found in the non-accelerated simulation. The concurrent increase of age of the water mass within the EEP OMZ suggests that this growth is driven by a slow down of the circulation in the interior of the deep Pacific. This results in large scale deoxygenation in the deeper Pacific and hence the source regions of the EEP
OMZ waters from mid-to-late Holocene. The simulated expansion of the OMZ in the late Holocene raises the question whether the currently observed deoxygenation is a continuation of the orbitally and greenhouse gas driven decline in oxygen, or a result of climate change from anthropogenic forcing as widely assumed. An additional explanation would be that the anthropogenic forcing amplifies the natural forcing.

(50) Changes in North Atlantic deep-water oxygenation across the Mid-Pleistocene Transition

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Deconvolution of the benthic $\delta^{18}O$ signal at Site 1123 into its temperature and seawater components suggests an abrupt increase in glacial ice volume occurred at 900 ka (MIS 24-22) during the MPT. At the same time, neodymium and carbon isotopic evidence suggests a major change occurred in deep-water circulation. Benthic $\delta^{13}C$ values are among the lowest at many sites during MIS 22-24, suggesting increased storage of carbon in the deep sea and lower values of glacial pCO$_2$. Remineralisation of carbon should have also affected Apparent Oxygen Utilization (AOU) of deep-water. Here we reconstruct nutrient regeneration and AOU across the MPT using a stoichiometric proxy for palaeooxygen (McCorkle and Emerson, 1988) based on the carbon isotope gradient between epifaunal $Cibicidoides$ $wuellerstorfi$ and infaunal $Globobulimina$ $affinis$ ($\Delta\delta^{13}C_{epi-infaunal}$), which has been recently calibrated by Hoogakker et al. (2015). We apply the method to Site U1385 (“Shackleton site”) and extend the Iberian Margin record back to ~1.44 Ma. The first sharp decreases in the $\Delta\delta^{13}C$ gradient, indicating times of reduced oxygenation, are observed immediately prior to Terminations 26/25 (~960 ka), 24/23 (~915 ka) and low $\Delta\delta^{13}C_{epi-infaunal}$ persisted throughout much of MIS 22 (~890-864 ka). The $\Delta\delta^{13}C_{epi-infaunal}$ values are less than those observed during some Heinrich events of the last glacial period (Hoogakker et al., 2015). We estimate that oxygen concentrations were nearly two thirds lower than today during maximum glaciations of MIS 26, 24 and 22, which equates to more than double pre-industrial AOU. These low-oxygen conditions may have contributed to increased extinction rates of benthic foraminifera observed in the Middle Pleistocene (Kender et al., 2016).

References:
(51) Role of biological pump in glacial-interglacial carbon and oxygen cycle: a model study

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The atmospheric CO$_2$ concentration during glacial periods is lower than interglacial periods by 80-100 ppm. Ocean has been implicated as key driver of glacial-interglacial CO$_2$ change. However, the mechanisms for oceanic carbon accumulation during glacial periods are still unclear. Enhanced biological pump due to iron fertilization and higher nutrient inventory via sea-level drop accumulate carbon and consume dissolved oxygen in the deep ocean. In this study, we investigated the role of enhanced biological pump in the glacial variations of atmospheric CO$_2$ and dissolved oxygen using AOGCM and ocean biogeochemical model. For the LGM simulation, iron fertilization and higher nutrient inventory via sea-level drop reduce atmospheric CO$_2$ by 20 ppm and 15 ppm, respectively. The total CO$_2$ reduction of 60 ppm (including physical and biogeochemical processes) is smaller than the glacial-interglacial CO$_2$ difference. Simulated oxygenation in upper ocean (~ 1 km) and deoxygenation in global deep ocean under LGM condition are consistent with proxy data (Jaccard and Galbraith, 2012). Enhanced biological pump due to iron fertilization reduces oxygen concentration by about 20 μmol/kg in the Southern Ocean and global deep water. However simulated oxygen reduction of 30 μmol/kg in the deep Southern Ocean is smaller than proxy-based reconstruction of oxygen reduction of 175 μmol/kg (Gottschalk et al., 2016). This is because enhanced mixing in the Southern Ocean supplies oxygen into the deep ocean. Our results suggest that a sluggish circulation in the Southern Ocean is necessary for reducing deep ocean oxygen, thus resulting in further carbon accumulation there.
Biogeochemical Cycles: Feedbacks and Interactions

Topic abstract

Oxygen concentrations in the ocean are decreasing with potential major consequences for marine life. In the open ocean, natural variability and global warming are key contributors to the expansion of oxygen deficient zones (ODZs). Coastal dead zones are mostly the direct result of increased anthropogenic inputs of nutrients. The nutrient inputs are fueling algal blooms that, upon their demise, drive an enhanced oxygen demand in bottom waters. In both the open and coastal ocean, variations in oxygen concentrations are known to induce major changes in the pathways of organic matter remineralization. For example, low oxygen is known to enhance nitrogen removal through denitrification and anammox, while phosphorus is typically recycled more efficiently. Iron release from sediments is characterized by a “window-of-opportunity” where oxygen concentrations are low but bottom waters are not yet sulfidic. Observations with new analytical techniques and modelling studies are revealing a role for previously overlooked processes and (potential) linkages and feedbacks between elemental cycles in low oxygen areas, such as cryptic sulfur cycling and anaerobic methane oxidation, which are directly or indirectly linked to the nitrogen cycle. In order to gain an integrated picture and make reliable projections of element cycles and their fluxes and interactions in ODZs of the future ocean, we require a mechanistic and quantitative process understanding of biogeochemical processes in low oxygen areas of the ocean. This session invites presentations from observational, experimental and modeling standpoints on the biogeochemistry of ODZs and areas suffering from coastal hypoxia. Contributions focusing on the cycling and/or interactions of carbon, nitrogen, phosphorus, iron and sulfur and the emerging research areas of methane and N₂O production and emission in ODZs are particularly welcome.

Conveners
Eric Achterberg // GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
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The Bay of Bengal (BoB) is a peculiar oxygen minimum zone (OMZ). With traditional oxygen sensing techniques, mid-level water oxygen concentrations are below detection, yet, geochemical analysis have provided little evidence for N\(_2\) production as might be expected in the absence of oxygen. New, ultra-high sensitivity STOX oxygen measurements show, in contrast, that low, sub-micron, levels of oxygen are a persistent feature of BoB OMZ waters. Molecular genetic analyses show that these waters contain a suite of anaerobic bacteria capable of producing N\(_2\) (both anammox bacteria and the denitrifiers), as well as nitrifying bacteria and archaea, as typical for OMZs. Thus, microbes capable of a completely coupled anaerobic/aerobic nitrogen cycle are present. Despite these microbial populations, our geochemical analyses confirm that rates of N\(_2\) production within the BoB OMZ are very low. Thus, extremely low-oxygen conditions, but with occasional anoxia allowing limited N\(_2\) production, seem to have been a long-term feature of the BoB OMZ. This persistence of low oxygen conditions is remarkable. Simple modeling shows that such a situation is extremely unstable without an active stabilizing mechanism. In this talk, we review our current understanding of BoB biogeochemistry and microbial ecology. We also propose biological feedback mechanisms, in the context of a simple box model, that may act to stabilize oxygen in the BoB to low sub-micromolar concentrations. Such feedback mechanisms could well operate elsewhere, but they cannot keep an OMZ from becoming anoxic if the carbon flux to OMZ waters is high enough.

**Donald Canfield** | Don Canfield received a Bachelor's Degree (magna cum laude) in chemistry from Miami University in Oxford, Ohio in 1979. From there he spent two years studying the biogeochemistry of Antarctic Dry Valley lakes, entering the PhD program in Geology at Yale University 1982, where he studied the early diagenesis of modern marine sediments with Bob Berner. In this work he was one of the first to explore and quantify the relationship between the iron and sulfur cycles in sediments. After his PhD, Canfield incorporated more microbiology into his work, exploring the chemical and microbiological dynamics of microbial mats with Dave Des Marais at NASA-Ames research center. After a short stay at Georgia Tech, Canfield worked 3 years at the Max Planck Institute for Marine Microbiology in Bremen, where he turned to exploring the systematics of sulfur isotope fractionation and the evolution of the sulfur through geologic time. From here, Canfield moved to his current home at the University of Southern Denmark, where he explores the physiology of modern organisms and their role in biogeochemical cycling, as a basis for understanding the
interplay between the evolution of life and the evolution of the Earth surface environment through time. Canfield in member of the National Academy of Sciences and a foreign member of the Royal Societies of Denmark and Sweden as well a fellow of the Geochemical Society, the American Association of Microbiology, AGU and AAAS. He has received the Vladimir Vernadsky Award from EGU and the Urey Prize from EAG.

07.09. FRIDAY | 11:50
A comparative study of coastal ocean hypoxia and acidification in two large river dominated systems (northern Gulf of Mexico and East China Sea)

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The northern Gulf of Mexico (nGOM) and the East China Sea (ECS) face similar physical drivers and anthropogenic stressors. Most importantly, both systems are strongly influenced by large rivers (the Mississippi and Changjiang) and intense eutrophication due to agriculture and population growth. Bottom water hypoxia and acidification appear to grow more severe in recent years in both systems despite the fact that riverine nutrient supply has been stabilized since the 1980’s in the nGOM, however, it is increasing in the ECS. In the surface water of the nGOM and ECS, the spatial distributions of O2 and pH are associated with the trajectory of the river plumes and in situ biological activity driven by riverine nutrients. In both plume regions the highest O2 and pH values and lowest pCO2 values were observed at intermediate salinities where light and nutrient were both favorable for phytoplankton production. In the bottom layer, low O2 and pH values were observed in hypoxic waters. The subsurface pH shows correlations with DIC and apparent oxygen utilization (AOU), suggesting that decomposition of organic matter was the dominant factor regulating pH variability. In addition to the low O2 and pH in the hypoxic bottom water, there was a layer of low O2 and pH at mid-water depth in the nGOM. T-S diagrams and numerical modeling suggest that this mid-water acidification and hypoxia was not caused by respiration of organic matter from local surface production, but was a result of intrusion of low O2 and pH water from a nearshore bottom layer. This extension of hypoxia and acidification from the nearshore bottom to the offshore mid-depth can form rapidly after a storm disruption and can then extend further to the bottom. This process might be a threat to marine organisms in offshore mid-water depths once thought to be unaffected by bottom hypoxia. Lateral transport also plays an important role in the formation of hypoxia and acidification in the ECS. We further reveal that the intensity and extensiveness of hypoxia and acidification events closely correlated to a climate change index in the ECS. We will discuss the common drivers and the differences between these two large-river dominated, eutrophic coastal systems with examples from recent and historical cruises.
Wei-Jun Cai | Wei-Jun Cai is Professor of Oceanography at the School of Marine and Policy of the University of Delaware, where he holds the title of Mary A.S. Lighthipe Chair of Earth, Ocean and Environment. He obtained his Ph.D. from the Scripps Institution of Oceanography, University of California in 1992 and, after a postdoctoral fellowship at the Woods Hole Oceanographic Institution, became a faculty member in the Department of Marine Sciences, University of Georgia (1994 - 2012). Cai is an expert in the marine carbon cycle and biogeochemistry. His research areas include, in early days, CaCO3 dissolution and sediment diagenesis in the sea floor using microelectrodes (O2, pH and pCO2) and, since 1998, air-sea exchange of CO2 and carbon cycling in estuarine and coastal oceans. Most recently, his research focuses on the responses of the coastal ocean carbon cycle and ecosystem to a changing terrestrial export of carbon and nutrients, interactions between coastal ocean acidification and eutrophication-hypoxia, mechanisms of coral calcification, and carbon cycle and acidification in the Arctic Ocean. Cai has collaborated extensively with colleagues in China and elsewhere. Cai has published 150 peer reviewed papers. In 2017, Cai was elected a Fellow of the American Geophysical Union (AGU) and Fellow of the Association for the Sciences of Limnology and Oceanography (ASLO).

07.09. FRIDAY | 12:25

Impacts of a changing global phosphorus cycle on coastal ocean deoxygenation

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Phosphorus (P) is an essential element for all life on Earth due to its presence in critical intracellular compounds such as adenosine triphosphate (ATP) and nucleic acids. Hence the global distribution of bioavailable P strongly controls the distribution of life. In the oceans, P is regarded as the ultimate limiting nutrient for phytoplankton production, thus changes in the supply of P from the continents on geological timescales influence marine productivity, with impacts on the biogeochemical cycles of carbon, nitrogen and oxygen. The global P cycle today is rapidly changing due to human activities, including the exploitation of mineral P reserves for fertilizer production and the subsequent dissipation of this P into the environment, the widespread damming of rivers, and the effects of climate change. All these factors may impact on the net flux of P from the continents to the oceans, as well as the forms in which P enters the oceans and the spatial distribution of P inputs. Coastal regions in particular have experienced direct eutrophication as a consequence of enhanced recent inputs of P, as well as nitrogen, leading to the expansion of hypoxic and anoxic zones in near-shore areas. This talk will focus on the cycling of P in coastal regions impacted by human activities, highlighting the current state of knowledge and the key focus areas for future research. Special attention will be given to feedbacks in the cycling of P between sediments and the water column, which introduce strong non-linearities in the relationship between external P loading and coastal hypoxia.
Understanding these feedbacks is critical to predicting – and managing – the future development of low-oxygen conditions in the coastal oceans.

**Tom Jilbert** | Tom Jilbert is Assistant Professor in Aquatic Biogeochemistry at the University of Helsinki, Finland. He graduated in Environmental Geoscience (BSc. Hons) from the University of Edinburgh, UK in 2003 and completed his PhD in Marine Geochemistry at the University of Utrecht (Netherlands) in 2008. Tom’s research interests in the marine realm include the coupled cycling of phosphorus, iron and carbon in eutrophied coastal systems, especially in the Baltic Sea. He is specialized in sediment biogeochemistry, with a focus on understanding short timescale feedbacks in elemental cycling in low-oxygen systems through the use of high-resolution geochemical analysis approaches such as MicroXRF and laser ablation ICP-MS. Tom was a postdoc within the groups of Caroline Slomp at Utrecht and Susanna Hietanen at Helsinki before being appointed to his current position at Helsinki in 2016. As well as ongoing work on the mechanisms of coastal hypoxia his current research activities include the study of eutrophied freshwater systems, with a focus on understanding the role of legacy phosphorus in determining the timescale of recovery from eutrophication.

### ORAL PRESENTATIONS

**Particle flux of sinking organic matter in the Peruvian oxygen minimum zone**

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Oxygen Minimum Zones (OMZs) may expand in the future as a result of the decline in oxygen concentrations in the ocean (e.g., Stramma et al. 2010). The downward flux of particulate organic matter (POM) from the euphotic zone via the biological carbon pump (BCP) is critical to transfer carbon to the ocean’s interior. Export efficiency and flux attenuation impact the vertical distribution of oxygen and nutrients in the ocean’s interior. Flux attenuation indicates the amount of sinking OM that is remineralized in the mesopelagic zone, contributing to oxygen demand within the OMZ. Particle export has been suggested to fuel nitrogen loss in the OMZ by supplying ammonium required by microbial anaerobic ammonium oxidation (Kalvelage et al. 2013). Observations suggest that the flux attenuation is lower in the OMZ compared with well-oxygenated waters at similar temperatures. However, the processes behind reduced POM flux attenuation in the OMZ remain unclear. Proposed mechanisms include reduction of aggregates fragmentation due to the absence of zooplankton within the OMZ, a higher refractory nature of sinking particles, preferential degradation of nitrogen-rich organic compounds, enhanced chemoautotrophy, and a decrease in heterotrophic activity due to oxygen limitation. Here, we investigate how oxygen deficit affect the...
magnitude and composition of the particle flux in the Eastern Tropical South Pacific (ETSP) OMZ off the coast of Peru. Sinking OM was collected in April and June 2017 using surface-tethered drifting sediment traps. The traps were deployed for four to seven days, at six to eight different depths between 50 and 600 m to estimate fluxes to and within the OMZ. Characterization of the sinking material includes total mass, particulate organic carbon/nitrogen/phosphorus, biogenic silica, and gel particles. We will evaluate the effect of oxygen deficit on sinking particles composition and flux attenuation in the OMZ of the ETSP.

**Sinking organic matter fluxes and remineralization attenuation in the Peruvian oxygen minimum zone**

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One of the impacts of climate change on the oceans is the reduction in dissolved oxygen concentrations in seawater (termed ‘deoxygenation’) as less oxygen dissolves in warmer waters and enhanced oceanic stratification reduces oxygen supply to the ocean interior. Expansion and intensification of the tropical oxygen minimum zones (OMZs) as a result of ocean deoxygenation in turn may affect the remineralization processes such as oxygen consumption rates and the biogeochemical cycling of carbon, nitrogen, and phosphorus. Important to the carbon, nitrogen, and phosphorus biogeochemical cycling is the attenuation of particulate organic matter (POM) fluxes with depth and within the core of OMZs. However, quantification of oxygen consumption rates in OMZs is difficult and knowledge of particle fluxes is currently lacking in the Peruvian OMZ. To gain better understanding of the remineralization processes in the Peruvian OMZ, we applied the tracer $^{234}$Th that allows a quantitative assessment of the POM fluxes and their roles in oxygen consumption. We will present profiles of total $^{234}$Th and dissolved $^{238}$U collected along four transects at 11ºS, 12ºS, 14ºS and 16ºS during two SFB 754 cruises M136 and M138 off the coast of Peru. Fluxes of organic carbon, nitrogen and phosphorus of large particulates (> 51 μm) will be determined using the $^{234}$Th fluxes and the ratios of particulate organic carbon, nitrogen and phosphorus to $^{234}$Th. We will access flux attenuation, and evaluate the contribution of sinking particles to organic matter supply and oxygen consumption.

**As good as it gets: fitting a global biogeochemical model to oxygen minimum zones**

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Global biogeochemical ocean models are now routinely used to estimate the potential increase of tropical and subtropical oxygen minimum zones (OMZs). However, to date many of these models do not accurately represent the current extent and
location of these. Beside the representation of physical processes, biogeochemical model parameters might be of importance for a model’s fit to observed OMZs. The manual calibration of a global biogeochemical model against observations is a time-consuming and rather subjective approach. Based upon a recently developed framework for automatic model calibration, here we investigate whether the degree of overlap between simulated and OMZs helps to constrain these models and results in a better fit to the extent and location of OMZs. The interplay between the different cost functions, parameter values and their identifiability is examined. We finally investigate how the parameters reflect upon model dynamics and biogeochemical fluxes, and discuss how model calibration can help to improve models used for projecting climate change and its effect on fisheries and climate gas emissions. Results from three different optimisations suggest that a good fit to observed OMZs is obtained with parameters that enhance fixed nitrogen cycling; this comes at the cost of too low nitrate concentrations and a too high global pelagic denitrification rate. A good fit to nutrient and oxygen concentrations is achieved with a different set of parameters, and a lower global fixed nitrogen turnover; this results in a worse fit to OMZs. Encouragingly, model calibration against OMZ location and extent helps to improve the model not only with respect to the OMZ criterion used in the optimization, but across a range of different criteria, which are of relevance for organisms of higher trophic levels. These results and the associated methodology may help to construct and set up global models that aim at simulating the transient response of the ocean to climate change, and thus the potential economic and ecological consequences.

Ocean phosphorus inventory and oceanic deoxygenation: large uncertainties in future projections on millennial timescales

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Observations indicate an expansion of oxygen minimum zones over the past 50 years, likely related to ongoing global deoxygenation. Here we analyze the processes and feedbacks, which contribute to global deoxygenation on millennial timescales using an Earth system model of intermediate complexity for a business-as-usual CO2 emission scenario. Particularly, we discuss how terrestrial weathering and redox processes in marine sediments in conjunction with marine feedbacks modulate marine inventories of P and O2. Higher availability of phosphorus, e.g. from intensified weathering, enhances biological production, remineralisation and oxygen consumption and promotes deoxygenation. Release of sedimentary phosphorus from anoxic sediments plays only a minor role in our simulations, indicating a weak oxygen-nutrient feedback. One reason for such a weak oxygen-nutrient feedback is the slow response of the nitrogen cycle to an increasing P inventory. Locally, nitrogen limitation in upwelling regions is intensified due to a strong oxygen-denitrification feedback. Globally, nitrogen fixation is not able to counteract the nitrogen loss due to denitrification in our model, which is in contrast to conclusions from palaeo-
reconstructions of large-scale deoxygenation events. Considerably large amounts of the added P (up to 90%) leave the ocean surface unused, increasing preformed P. Our model results further indicate a large spread in weathering and benthic fluxes of P, given a range of plausible parameterizations tested. In year 5000, phosphorus weathering anomalies range from 0.1 to 0.6 Tmol P/yr and benthic-release flux anomalies range from 0.0 to 0.2 Tmol P/yr. This results into a large range of possible future phosphorus inventories from 110 to 160% of the current value and suboxic volumes from 1 to 5% of the ocean volume. Uncertainties originate from differences in the parameterization of weathering and of benthic fluxes, in the representation of sediment P inventories, and in the representation of slope and shelves in the coarse model bathymetry of UVic. Applying a detailed sub-grid bathymetry leads to 5 times higher organic matter fluxes on the shelves than with a standard model bathymetry, which improves the fit to estimates based on observations.

**Benthic trace metal fluxes in the oxygen minimum zone off Peru**

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Iron and several other trace metals (e.g. cobalt, zinc, cadmium) are essential micronutrients, required for the growth of marine organisms. Their availability in the oceans can (co-)limit primary productivity and thus affect the cycling of macronutrients and the biological pump [e.g. 1]. Marine sediments in oxygen-deficient regions are proposed to be an important source or sink for these trace metals to the ocean. In the Peruvian oxygen minimum zone (OMZ), substantial fluxes of reduced iron across the sediment-bottom water interface have been documented [e.g. 2] and inferred for other trace metals such as cobalt [e.g. 3]. However, the key biogeochemical processes that control the sedimentary release or burial of trace metals are poorly constrained. We present iron and other trace metal data for in situ benthic chamber incubations, sediment pore waters, near-bottom water profiles and ex situ experiments from a transect across the Peruvian continental margin at 12 °S. During our sampling campaign (austral autumn 2017), the water column featured steep biogeochemical gradients. While the upper shelf was oxygenated, anoxic conditions prevailed on the deeper shelf and slope, with a nitrogenous OMZ core expanding from around 150 m to 400 m water depth. Close to the upper rim of the OMZ core, the highest in-situ benthic fluxes of iron and the steepest iron gradients in the bottom water were found. In some incubations and ex-situ experiments, the release of iron coincided with nitrate and nitrite depletion, suggesting that reductive processes in the nitrogen cycle exert an important control on the benthic iron release. The distribution of mat-forming sulfide-oxidizing bacteria on the seafloor also seems to affect benthic trace metal fluxes. These bacteria regulate sulfide concentrations in the surface sediment and, thus, the extent of trace metal retention through their precipitation sulfides. Further, the decrease of cadmium concentrations during benthic chamber incubations suggests that oxygen minimum zone sediment represents an effective sink for cadmium. Our findings can help to
predict how ocean deoxygenation will impact benthic trace metal fluxes in the future.


**El Niño influence on Peruvian shelf trace metal supply to the ocean**

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Shelf sediments in oxygen minimum zones (OMZs) are a major contributor of iron (Fe) and other bioessential trace metals to offshore waters. Future changes in metal fluxes are projected as a result of expansion of OMZs, potentially having important biogeochemical impacts on adjacent ocean systems. Resolving the processes in OMZs that determine trace metal release from sediments, stabilisation preventing loss by scavenging and precipitation, and offshelf transport is thus essential. To this end we measured a suite of bioessential (e.g. Fe, Co, Cu, Zn) and process-diagnostic (e.g. sediment release- Mn; scavenging- Pb) dissolved and total-dissolvable trace metals alongside coupled Fe(III)-Fe(II) measurements to evaluate trace metal release, stabilisation, and offshelf transport in the Peruvian OMZ. We observed high Fe(II), dissolved Fe, and total-dissolvable Fe close to the shelf with concentrations rapidly decreasing further offshore within anoxic waters, suggesting progressive oxidation by nonoxygen electron acceptors followed by subsequent precipitation/scavenging. Offshore, maxima in leachable Fe concentrations (total dissolvable Fe minus dissolved Fe) were always present in the upper OMZ (up to 16 nM), indicating the particulate Fe pool probably dominates offshore Fe transport. The cruise was conducted in Oct 2015 during a developing El Niño event, with atypical upwelling of oxygen-rich water in the North Peruvian Shelf, whereas upwelling of oxygen-depleted water was still occurring over the South Peruvian Shelf. Despite a narrower shelf width, enhanced Fe concentrations persisted offshore over the South Peruvian shelf relative to the North, therefore suggesting a strong impact of El Niño conditions on the regional strengths of offshore Fe transport.
Radium isotopes as tracers of shelf-derived trace element inputs along the Benguela upwelling zone

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The Benguela region is an eastern boundary upwelling system exhibiting seasonally anoxic conditions. The region receives elemental inputs from aeolian, benthic and riverine sources, such as that from the Congo and Orange Rivers. Continental shelves, at the land-ocean interface, play an important role in marine primary productivity by supplying trace elements such as iron (Fe) and cobalt (Co) and other shelf-derived materials to the ocean. As such, quantifying processes occurring within this land-ocean interface is crucial to understand the biogeochemistry of trace elements and isotopes (TEIs), and the lateral inputs of these elements to the ocean. Radium isotopes (\(^{224}\text{Ra}, {^{223}\text{Ra}}, {^{228}\text{Ra}}\), and \(^{226}\text{Ra}\)) have demonstrated to be powerful tracers of sedimentary inputs of TEIs to the oceans and their off-shelf transport processes. Since Ra isotopes integrate off-shelf transport over broad (weekyear) timescales, they can provide important insight into the fraction of TEIs present in relatively TEIs rich waters in ocean margins which are transferred offshore. Here we present the first results from the GEOTRACES section GA08 in the South Atlantic. The aim of this study was to identify processes and quantify fluxes that control the distribution of TEIs in the Benguela Upwelling System. We combine \(^{228}\text{Ra}\) fluxes with the distributions of dissolved TEIs to investigate how effectively they are supplied by benthic and riverine sources on the shelf and transferred to the South Atlantic Ocean; thus gaining insight into the spatial scale over which TEIs supply from oxygen-depleted, and TEIs rich waters over the African shelf can facilitate offshore productivity.

Sources and composition of water-soluble trace elements in aerosols over the Benguela and Peruvian oxygen minimum zones

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Atmospheric deposition of trace elements and nutrients are crucial determinants of ocean biogeochemistry, providing a direct supply of essential macroand micronutrients to surface seawaters. However, very few direct measurements exist to quantify aerosol trace element and nutrient input to remote oceanic regions. Fe is known to limit primary production across the Equatorial pacific and thus a critical question with respect to the potential future expansion of the ETSP OMZ is to what extent Fe supply from atmospheric deposition and lateral advection fuel primary production in this region. To address this we collected 42 high volume
aerosol samples on recent cruises in the South Atlantic (GEOTRACES section GA08 November 2015), and the Equatorial Pacific (SFB cruise M136/7 June 2017). We will present the results from leaching experiments conducted with these samples, which were designed to simulate the release of trace elements and nutrients into seawater following deposition into the surface ocean. Aerosol filters were leached in ultrapure water for a duration of 1 h and the leachates were analysed via ICP-MS (Element XR) for trace element determination and nutrient analyser (QuAAtro AutoAnalyser) for macronutrient analysis. Analysed trace elements included Al, Cd, Co, Cu, Fe, Pb, Mg, Mn, Ni, Th, Sn, Ti, U and Zn, and macronutrients included phosphorous, nitrate+nitrite and ammonia. These data represent some of the first observations of aerosol trace metal and nutrient inputs into these remote, under sampled, yet biogeochemically critical oceanographic systems.

The influence of iron on extended elemental stoichiometries in diazotrophs

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Nitrogen fixing cyanobacteria are autotrophic prokaryotes that require specific trace metals, such as iron (Fe), cobalt (Co), copper (Cu), molybdenum (Mo), manganese (Mn) and zinc (Zn), as cofactors in enzymes. Metalloenzymes regulate physiological processes that are key to life, such as photosynthesis, nitrogen fixation and respiration. Iron is the main limiting trace nutrient in the ocean, and iron status is thought to influence the requirements of other trace nutrients via metal cambialism (Saito et al., 2008). Nevertheless other trace nutrients also influence productivity in certain regions of the ocean (Browning et al., 2017). We studied the effect of iron on extended elemental stoichiometries, including carbon (C), nitrogen (N), phosphorus (P), Fe, Co, Cu, Mo and Mn in mono-batch cultures of two diazotrophic cyanobacterial strains (*Cyanothece* sp. ATCC51142 and *Trichodesmium erythreum* IMS101, respectively). Cellular iron quotas (expressed relative to C) were lower for *Trichodesmium* than for *Cyanothece*. Furthermore *Trichodesmium* appeared to require more Co, Cu and Mn than *Cyanothece* so that the two organisms had distinct extended elemental stoichiometries. Reduction of available iron resulted in decreased Fe quotas and increased quotas for Co, Cu, Mn and Mo in *Trichodesmium*, but not for *Cyanothece*. Our results are discussed in the context of elemental use efficiencies, which describe the elemental quota normalized to growth rate in order to probe the impact of iron limitation on the requirements of other essential trace nutrients. References: Browning, T.J., Achterberg, E.P., Rapp, I., Engel, A., Bertrand, E.M., Tagliabue, A., and Moore, C.M. (2017). Nutrient co-limitation at the boundary of an oceanic gyre. Nature 551, 242. doi: 10.1038/nature24063. Saito, M.A., Goepfert, T.J., and Ritt, J.T. (2008). Some thoughts on the concept of colimitation: Three definitions and the importance of bioavailability. Limnology and Oceanography 53, 276-290. doi: 10.4319/lo.2008.53.1.0276.
Nutrient controls on productivity overlying and offshore of oxygen minimum zones

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Upwelling associated with eastern boundary currents transports nutrients to sunlit surface waters, fuelling phytoplankton productivity. Phytoplankton growth rapidly depletes supplied nutrients such than one or more become limiting; the supply flux of the limiting nutrient(s) is therefore the proximal control on productivity. In this presentation the results of direct experimental tests in surface waters overlying and offshore of two oxygen minimum zones (Peru and Benguela) will be presented, which map the identity of nutrients that are proximally/serially/co-limiting to phytoplankton communities. We find that in the current ocean the relative supply of iron and fixed nitrogen are the most critical proximal controls on productivity in these zones, with cobalt playing a secondary role. The results of these experiments can be interpreted in terms of the ratios of ambient dissolved seawater nutrient concentrations at experimental sites, and by inference, nutrient supply: demand ratios and the processes that control these.

H₂S events in the Peruvian oxygen minimum zone enhances dissolved Fe concentrations

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Dissolved iron (DFe) concentrations in oxygen minimum zones (OMZs) of Eastern Boundary Upwelling Systems are enhanced as a result of high supply rates from anoxic sediments. However, pronounced variaions in DFe concentrations in anoxic coastal waters of the Peruvian OMZ indicate that there are factors in addition to O₂ availability that control the cycling of Fe. Our results show that sediment-derived reduced Fe(II) forms the main DFe fraction in the anoxic/euxinic water column off Peru, which is responsible for DFe accumulations of up to 200 nmol L⁻¹. In contrast, lowest DFe values were observed in anoxic shelf waters in the presence of nitrate and nitrite. This reflects oxidation of sediment-sourced Fe(II) associated with nitrate/nitrite reduction and subsequent removal as particulate Fe(III) oxyhydroxides. Unexpectedly, the highest DFe levels were observed in waters with elevated concentrations of hydrogen sulfide (up to 4 μmol L⁻¹) and correspondingly depleted nitrate/nitrite concentrations (< 0.18 μmol L⁻¹). Under these conditions, Fe removal was reduced through stabilization of Fe(II) as aqueous iron sulfide (e.g., FeSH⁺ and Fe₂S₂ | 4H₂O). Sulfidic events on the Peruvian shelf enhance Fe availability, and may increase in frequency in the future due to the predicted expansion and intensification of OMZs.
How the oxygen concentration can impact the redox processes of trace elements and reactive oxygen species

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Iron (Fe), Manganese (Mn) and Copper (Cu) are three redox active trace metals required for a range of critical biological processes in marine organisms. Iron is known as the essential in photosystem I, for its dust input and it being the limiting element in about 30% of the surface of the Ocean. Manganese is the active metal centre in several redox enzymes, most notably in photosystem II where it converts water (H$_2$O) to oxygen (O$_2$), and in the Mn family of Superoxide dismutases (SODs), which are used as an intracellular defence against reactive oxygen species (ROS). Copper is widely known to be toxic to most species of phytoplankton, in part because it competitively inhibits Mn uptake and once inside the cells is implicated in the production of ROS. However, recent studies have suggested that Cu, in the form of multi-copper oxidases, is essential for the uptake of Fe by phytoplankton. All three micronutrients have a redox pair (Cu(II)/Cu(I), Fe(II)/Fe(III) and Mn(II)/Mn(III)) that can react with reactive oxygen species like superoxide (O$_2^-$) and its daughter hydrogen peroxide (H$_2$O$_2$). The distribution and speciation of Fe, Cu and Mn, contrast markedly in the surface ocean due to organic complexation vs free ions and their solubilities contrast starkly. However, these metals are strongly linked through the competition for metal binding sites in phytoplankton uptake systems and through common redox processes involving ROS. The partitioning of these redox sensitive trace elements are controlled by the dissolved oxygen concentration and therefore under low O$_2$ conditions (< 10 μM) the more soluble lower oxidation states are stabilized leading to longer residence times for these elements in the water column with implications for the distribution of these elements in these waters. Potential feedbacks may also occur whereby enhanced Fe concentrations, fuel surface water productivity resulting in higher fluxes of sinking organic matter which when respired further decreases O$_2$ in the OMZ. In this presentation we will examine a series of datasets collected during 3 cruises in the oligotrophic Eastern Tropical North Atlantic (M80/1, M83/1 and MSM17/4) and 2 cruises in the Eastern South Pacific (M77/4 and M90). Here we use the collected data to identify the respective contributions of Mn and Cu to ROS cycling in the upper ocean and oxygen minimum zone and the implications this has to the residence time for Fe, Cu and Mn in these regions.

Nitrogen fixation in the coastal Peruvian upwelling zone following a simulated upwelling event

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The oxygen minimum zone (OMZ) in the eastern tropical South Pacific (ETSP) promotes the microbial loss of nitrogen from the water column accompanied by release of sediment bound phosphate. Consequently, subsurface water masses depleted in dissolved inorganic nitrogen and enriched in dissolved inorganic phosphorus (low
N:P ratio) are upwelled to the surface layer off Peru. Geochemical tracer studies and biogeochemical models suggest the excess of phosphate (P) in the upwelled waters provides a niche for marine nitrogen fixation in surface waters above the oxygen depleted layers. Two mechanisms have been suggested as to how nitrogen fixation in the surface waters could be stimulated by the upwelled waters: 1) Redfield nutrient assimilation by phytoplankton which leaves behind P that could be consumed by diazotrophs (nitrogen fixers); 2) non-Redfield nutrient uptake by nondiazotrophs where surplus P from biomass is released as dissolved organic phosphorus (DOP). DOP may provide an additional source of phosphorus that could enhance nitrogen fixation. These two mechanisms could also act simultaneously to stimulate nitrogen fixation. However, in addition to mixed evidence on nitrogen fixation, scarcity of data on nitrogen fixation rates in the surface waters of the Peruvian upwelling zone provide a challenge. To better understand the impact of upwelled waters with OMZ influenced N:P ratios and corresponding feedbacks on nitrogen fixation, we measured nitrogen fixation rates during an offshore mesocosm study conducted in the coastal upwelling zone off Peru from February to April 2017. An upwelling event featuring two water masses of different OMZ influenced N:P ratios was simulated to the surface of the mesocosms. Stable isotope incubations of the surface (oxic) and bottom (anoxic) mesocosm waters were used to quantify nitrogen fixation rates. We present the temporal development of nitrogen fixation rates from this study and relate this to inorganic nutrient concentrations, stoichiometry and other relevant biogeochemical parameters. These results will contribute to nitrogen fixation measurements and help shed light on biogeochemical controls and associated feedbacks on nitrogen fixation in the Peruvian upwelling system.

Biologically-associated nitrous oxide accumulation in the euphotic zone

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The largest uncertainty and inconsistency in global marine N₂O emission estimate appear in the euphotic zone where physical disturbances prevents N₂O accumulation if any. Here we presented high vertical resolution N₂O profiles in the euphotic zone with distinctive peaks near the oxycline in the oligotrophic Western Pacific, where the maximum of Chl-a and nitrite appeared correspondingly. Production term is required to support such N₂O deviation from the vertical mixing curve. The intimate association between N₂O excursion and biological parameters suggests that some biological processes, though unclear, must involve. Dual isotope signature of N₂O around these peaks affirmed in-situ biological N₂O production. More high-resolution observation and process studies are urgently needed to explore the spatial-temporal distribution of euphotic zone N₂O production and its controlling mechanisms to fill the knowledge gap. The coupling of the addition of anthropogenic nitrogen and expansion of deoxygenated area in the upper ocean is likely to enhance N₂O in euphotic layer due to the sensitivity of N₂O release to deoxygenation. Unlike N₂O generation in deep ocean, such kind of production in shallow ocean will be more effective in short-term climate feedback according to frequent physical disturbances.
Silicon and Nitrogen cycling in the upwelling area off Peru: A dual isotope approach

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The tropical Oxygen Minimum Zones (OMZs) are key regions of very low oxygen in today's ocean. Recent investigations have shown that the oxygen content of the global ocean is decreasing and OMZs are expanding, and the future ocean may experience significant shifts in nutrient cycling, strongly affecting the biological productivity in surface waters. Besides phosphate (PO$_4$) and nitrate (NO$_3^-$), silicate (SiOH$_4$) is the main nutrient in coastal upwelling systems driving the primary productivity. A change in the availability of these nutrients induced by changing oxygen concentrations and/or circulation can therefore either enhance or diminish productivity. How actively changes in ocean circulation can affect primary productivity is documented during intense El Niño events when weak upwelling leads to reduced primary productivity. Over a time period of nearly ten years, we intensively studied the Si and N cycle in the upwelling area off Peru. To improve our understanding of their biogeochemical cycling in the present as well as in the past, we used stable Silicon (Si) and N isotopes in seawater ($\delta^{30}d$Si, $\delta^{15}$N) as well as particulate material ($\delta^{30}b$Si, $\delta^{15}$PON).

We observed a tight coupling between the Si and nitrogen N cycle. During strong upwelling waters on the shelf showed high Si(OH)$_4$ concentrations accompanied by diminished NO$_3$ concentrations as a consequence of intense remineralization of bSi, high Si fluxes from the shelf sediments, and N-loss processes such as anammox/denitrification within the OMZ. In contrast, week upwelling and a deepening of the thermocline leads to diminished Si(OH)$_4$ concentrations in surface waters. The shift in N:Si ratios was reflected by the stable isotopes and exert significant control on the phytoplankton communities. The combined approach of Si and N isotope data, as well as the comparison with core-top sediment data, helped to significantly improve our understanding of paleo records in upwelling areas.

Long term variability in the denitrification rate in the eastern tropical North Pacific

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As a consequence of global warming oxygen saturations in will increase due to decreasing oxygen solubility and potential changes to biological and physical processes. There is strong observational evidence that deoxygenation has occurred over the last 50 years or so, at least in certain areas. When oxygen concentrations reach very low levels organic matter oxidation proceeds via denitrification, where the terminal electron acceptor for oxidation of organic matte becomes nitrate and nitrogen gas is an end product. Marine fixed Nitrogen, mostly NO$_3$ + PON, controls the fertility of the ocean, and it's concentration is controlled primarily by the balance between the input from biological nitrogen fixation of nitrogen gas and the loss by denitrification. Today, roughly half of the loss by denitrification takes place in the oxygen deficient zones (ODZs) of the eastern tropical pacific and Arabian Sea. Thus,
if in the future these areas expand or new ones form then the denitrification losses should also expand with consequences for the altering the marine fixed nitrogen balance and ocean productivity. Is there any observational evidence that has already begun happening? One indicator of denitrification is parameter N, a stoichiometric parameter calculated from nitrate and phosphate. When N is negative denitrification is assumed to have occurred and the more negative the value the more denitrification. Here we analyze data from 6 cruises through the core of the ODZ in the eastern tropical North Pacific on a section between 23 and 14 degrees N-latitude along 110 west longitude (WOCE P18). The cruises occurred in 1972, 1994, 2007, 2012, 2016, and 2016-17. We integrated the N values in the ODZ for each cruise over the entire section. The results showed that integrated N has decreased over the 50 year period. That decrease suggest either denitrification rate increased or the balance between water residence time within the ODZ and organic matter oxidation shifted, or possibly some combination of both. We discuss potential mechanisms for denitrification signal increase including ENSO, Pacific Decadal Oscillation, tropical hurricane intensity, and variations in thermocline depth.

Benthic N-cycling in the Peruvian oxygen minimum zone in relation to variable bottom water redox conditions

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Oxygen minimum zone (OMZ) sediments were identified as key regions for nitrogen loss as well as for recycling of reactive N species releasing high amounts of ammonium (NH$_4^+$) into the bottom water and thereby affecting the water column elemental ratios and processes. Despite this significance the response of benthic N-cycling in relation to variability in the bottom water redox scheme, i.e. the availability of oxygen (O$_2$), nitrate (NO$_3^-$) and nitrite (NO$_2^-$), is hardly constrained. We compare previous measurements from austral summer (January 2013), where the bottom water in the upper OMZ has been depleted of O$_2$, NO$_3^-$, NO$_2^-$ and even sulfide has been released due to persistent stagnant current conditions, with new measurements that were obtained in austral autumn (April/May 2017) during the passage a coastal trapped wave, which enhanced the southward transport of NO$_3^-$ and NO$_2^-$ and caused a slight ventilation of the bottom water on the shelf. During both campaigns, solute fluxes of NH$_4^+$, NO$_3^-$ and NO$_2^-$ across the sediment water interface were measured at 9 stations on a depth transect at 12° S in the OMZ off Peru encompassing water depths from 70 to 1000 m using benthic lander in situ incubations. The uptake of NO$_3^-$ by the sediment was reestablished on the shallow shelf in 2017 and elevated (with up to 8 mmol m$^{-2}$ d$^{-1}$) in the entire upper OMZ. Despite the significantly different bottom water geochemistry, the NH$_4^+$ fluxes measured in 2017 were equivalent to 2013 across the transect, with values reaching 21 mmol m$^{-2}$ d$^{-1}$ at the shallowest station. As in 2013, the high NH$_4^+$ fluxes measured in 2017 were predominantly caused by mats of filamentous sulfur bacteria via the dissimilatory nitrate reduction to ammonium pathway and were
An experimental and modeling investigation of sediment nutrient cycling during further deoxygenation on the Peruvian margin

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In this study, we present the results from an ex situ incubation experiment of sediment cores from the Peruvian oxygen minimum zone (750 m water depth). The motivation is to understand how the efficiency, timing and magnitude of nutrient recycling responds to lower levels of oxygen and nitrate in the water column. Three sediment cores (one control, two replicates) were incubated for 17 days on board RV Meteor during cruises M136 and M137 in austral summer 2017. The overlying waters were subject to anoxic conditions where nitrate was allowed to become depleted. When nitrate was exhausted, ammonium, phosphate and iron began to accumulate in the water at different rates and at different times. Hydrogen sulphide was released from the sediment around one week after nitrate disappeared. Re-addition of nitrate led to a dramatic reduction in sulphide levels, but had no noticeable effect on dissolved iron. At the end of the experiment all cores were sliced and porewaters were analysed. Further samples were taken for genetic sequencing to relate the geochemical observations with the microbiological community composition. A simulation of the experimental set-up using a 1-D diagenetic model was undertaken to identify key processes and kinetic parameters that explain the observations. The results will improve our predictions of benthic-pelagic coupling across the wider region.

Efficient removal of nitrogen and phosphorus in a eutrophic coastal system recovering from hypoxia

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Increased anthropogenic inputs of nitrogen and phosphorus from land have led to eutrophication of marine environments worldwide. Coastal systems can reduce the sustained by high sulfide concentrations in the sediment. We explore implications of enhanced transport of NO\textsubscript{3}\(^-\) and NO\textsubscript{2}\(-\) for the N budget as well as reasons for the unchanged NH\textsubscript{4}\(^+\) release from shelf sediments also considering new findings which indicate that sulfidic events off Peru occur more frequently than previously thought.
flux of nutrients from land to the open sea, thereby acting as a coastal filter. The key processes that remove nitrogen and phosphorus in coastal areas are denitrification and phosphorus burial [1]. Recent modeling of nutrient dynamics in the Stockholm Archipelago, which is a eutrophic coastal system that is recovering from hypoxia, suggests that at least 72% of the nitrogen input and 62% of the phosphorus input from land is retained in the archipelago [2]. This is a more efficient removal of nutrients than on average for coastal environments in the Baltic Sea, where typically only 16% of nitrogen and 53% of phosphorus is retained [1]. Here, we assess the benthic processes controlling this efficient removal of nitrogen and phosphorus in the Stockholm Archipelago. Based on data for 4 locations, we demonstrate that, similar to model predictions [2], area-specific rates of nitrogen removal due to benthic denitrification are highest in the inner archipelago and decrease towards the open sea. The recycling of N through DNRA and production of N₂ by anammox play only minor roles (generally <1% nitrate reduction) throughout the archipelago. Significant contributions of anammox to N₂ production (>30%) are found only at the outer archipelago site where overall N₂ production is lowest. Rates of phosphorus burial in the archipelago are high due to the combined effect of high concentrations of phosphorus in the sediment and high rates of sediment accumulation. Most of the phosphorus is buried in the form of organic matter. Inorganic forms of phosphorus act as both a temporary and permanent sink for phosphorus. We will discuss the potential future trends in nitrogen and phosphorus removal in the archipelago, the link with changes in bottom water hypoxia, and the potential role of import of nutrients from the open Baltic.


Upwelling induced anoxia in a eutrophic Estuary, Southwest Coast of India: influence of lateral inputs

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Hydrographic observations in the Cochin backwaters (CBW), southwest coast of India during the summer monsoon delineated the spreading of an unusually anoxic water mass in the bottom characterized by intense denitrification and formation of hydrogen sulphide, which have not been previously reported from any tropical estuaries. The coastal zone of western India experiences moderate upwelling during this period. The oxygen deficient (~0.5 ml.l⁻¹ or 22 μM) upwelled waters, as it intrudes into the estuary through the bottom, is quickly depleted in the oxygen content to near-zero levels owing to the excessive demand for the oxidation of organic matter. Increased river inputs countering the penetration of upwelled waters cause strong stratification and poor ventilation leading to reducing conditions near the bottom. It
was also observed that increased latter inputs rich in organic matter have resulted in the development of anoxic conditions (O₂=0), 2-6 kms inside the estuary, where the concentration of hydrogen sulphide increased up to 12 μM. An increase in the nitrite concentrations (up to 2.4 μM) in the oxygen deficient waters compared to its levels at the Cochin inlet and corresponding to a decrease in the nitrate inputs indicated that denitrification was active. The intrusion of upwelled waters seems to be much stronger (up to ~16 kms inside the estuary) compared to its first report in 1968, which is attributed to a decline in the river discharge and deepening of the estuarine channels. The expansion of oxygen deficient zone and formation of hydrogen sulphide are anthropogenically induced and could be destructive to the biological productivity and an increased emission of greenhouse gases from this region.

**Regeneration of phosphorus in the ocean during past greenhouse climates: Role of redox conditions and impact on primary productivity**

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Phosphorus (P) is a key nutrient for marine primary producers. River input is the most important source of P in the ocean while its main sink is burial in marine sediments. Low oxygen in the ocean can lead to enhanced regeneration of P relative to carbon during degradation of organic matter in the water column and in sediments. This process can act as a positive feedback on marine productivity during intervals of widespread deoxygenation. As recycling leads to changes in the ratio of organic carbon to total sedimentary P (Corg/Ptot), this ratio is often used as a proxy for the reconstruction of past redox conditions and P recycling in sediments. However, other processes such as changes in sedimentation rates can also affect this ratio. Here, we compile and compare ratios of Corg/Ptot and other redox proxies in sediments for periods of widespread oceanic anoxia during past greenhouse climates to better understand and quantify the extent of redox-driven enhanced P recycling. We specifically focus on the Toarcian Oceanic Anoxic Event (T-OAE) and Oceanic Anoxic Event 2 (OAE2), two intervals of severe deoxygenation, and the Paleocene Eocene Thermal Maximum (PETM), an interval during which low oxygen conditions were not as widespread. For each period, we also discuss the relative importance of changes in external inputs of P from rivers to P recycling and the impact on primary productivity as deduced from proxy and modelling studies.

**Time-series of the secondary nitrite maximum in the ETSP reveal tight coupling of ENSO and nitrogen processes in the OMZ**

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The El Niño/Southern Oscillation (ENSO) is an irregularly periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, affecting climate
of much of the tropics and subtropics. Only recently model results suggested that both the warm (El Niño) and the cold phases (La Niña) of ENSO are affecting nitrogen processes such as denitrification in the oxygen minimum zones (OMZ) of the eastern tropical Pacific Ocean. The occurrence of a secondary nitrite maximum is usually taken as an indicator for ongoing nitrogen loss processes in OMZ. Here we present a compilation of the maximum nitrite concentrations found in the secondary nitrite maximum (mSNM) from the OMZ off Peru covering a period from 1960 to present. Based on the compilation of mSNM data we reconstruct a time-series of mSNM and correlated this to well-established ENSO indices such as the Oceanic Niño Index (ONI) and the Multivariate ENSO Index (MEI). We found a significant negative correlation of the mSNM with both ONI and MEI with a time lag of one month indicating that high (low) nitrite concentration of the secondary nitrite maximum are associated with La Niña (El Niño). We thus propose a direct impact of ENSO on nitrogen processes in the OMZ off Peru, with La Niña events promoting periods of massive nitrite accumulation. As climate change is suggested to result in more intense ENSO events, our study strongly points towards major changes in future nitrogen processes in the OMZ off Peru.

Nitrogen-carbon connections in a deoxygenating ocean

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Anthropogenic warming is expected to drive oxygen (O₂) out of the ocean causing a massive perturbation of the nitrogen (N) cycle leading to increasing N removal and oceanic N₂O production via denitrification, which would trigger enhanced N₂ fixation. Our intermediate complexity Earth system model simulations reveal that N₂ fixation does not compensate the enhanced N loss due increased phosphorus (P) limitation. However, emerging feedbacks between the carbon (C) and N cycle can stabilize the N-inventory and N₂O emissions under global warming. The expansion of water column denitrification under ocean deoxygenation is offset by decreasing benthic denitrification brought about by a reduction in export production. This latter is related to ocean warming and yields a decline in oceanic N₂O production, which contributes to the reduction in oceanic N₂O emissions by 2100. Our model simulations support the existence of strong regulatory feedbacks among the O₂-C-N and P-cycles that maintain N inventory homeostasis and contribute to stabilize climate against anthropogenic changes.

Symmetric marine biogeochemical responses in warming and cooling worlds

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The marine biological response to atmospheric CO₂ concentration being reduced from a greenhouse to an icehouse climate shows a surprisingly symmetric hysteresis
compared to when it is increased from an icehouse to a greenhouse climate. We equilibrate the University of Victoria Earth System Climate Model, at 280 and 1260 ppm atmospheric CO₂, then force it with a 1% per year increase (the “ramp-up”) and a 1% per year decrease (the “ramp-down”) to compare the 500 year marine biogeochemical response. Both ramp-up and ramp-down simulations start from similar globally-integrated oxygen content due to biological and physical drivers that compensate on thousand-year timescales, though initial ramp-down tropical suboxic volumes are nearly twice those of the ramp-up. In the ramp-up, increasing net primary production (NPP) and enhanced remineralization in the Southern Ocean moves phosphate to deep ocean storage and contributes to a decline in deep ocean oxygen content. NPP in the low latitudes decreases, causing a net gain of oxygen in the subsurface tropical ocean. Global NPP displays a rapid increase after about 3.5 degrees of global mean sea surface temperature warming. In the ramp-down, deep ocean phosphate is mixed back to the surface where the heat content remains relatively high, and high NPP and remineralization rates trap it in the upper ocean despite rapid overturning. This shift in phosphate storage to the near-surface delays the decline in global NPP until about 3.5 degrees of global mean sea surface temperature cooling. High NPP and strong remineralization in the ramp-down decreases subsurface tropical oxygen, despite cooling global mean temperatures. However, deep ocean oxygen increases rapidly due to strong ventilation via Southern Ocean pathways. In both ramp-up and ramp-down the largest oxygen anomalies are held in the abyssal Pacific and Indian Ocean basins, whereas the largest phosphate anomalies are held in the Atlantic and Arctic.

Our study has implications for the past, suggesting a combination of physical and biological drivers are responsible for the delayed transition of greenhouse to icehouse climates relative to transitions of icehouse to greenhouse climates. Furthermore we show a distinct difference in greenhouse and icehouse climate phosphate storage, where greenhouse climates store phosphate higher in the water column.

**Improving the “bio” part of biogeochemical models**

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Biotic processes in biogeochemical models are usually greatly oversimplified in the sense that they are represented by closure terms unrelated to the behaviour of the organisms involved. This applies to both Redfield models of primary production, which ignore the highly variable elemental stoichiometry of phytoplankton and Holling-type models of grazing, which are at odds with observed zooplankton feeding behaviour. Two major difficulties preventing progress have been the complexity of mechanistic biotic process representations and the scarcity of data required to calibrate them. Optimality-based models of phytoplankton and zooplankton have been developed in the SFB 754, which address the complexity problem by allowing the reproduction of observed organism behaviour with relatively simple formulations. These models have been implemented in a 0–1D modelling framework for mesocosm simulations and also in the (3D) UVic Earth System Model. The data provided by the mesocosm experiments of the SFB 754 greatly facilitate calibration of the optimality-based plankton models and identifying model deficiencies. The resulting model formulation is analysed in the UVic model with the help of novel parameter estimation methods.
(52) GEOTRACES Cruise GA08 in the Benguela upwelling region

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The GEOTRACES GA08 section was conducted in the southeast Atlantic in November/December 2015 focusing on the Benguela Upwelling region and the associated oxygen minimum zone. Combining an along-shelf section with off-shelf transects, the main scientific goal of the cruise was the detailed investigation of the impact of continental inputs on the distribution of trace elements and isotopes, such as exchange with the African continental margin, dust input from the Namibian desert, and the inputs of dissolved and particulate loads from the major Congo and Orange rivers. The relationships between the distributions of trace elements, and large and small scale ocean circulation will be subject of data synthesis activities, which will allow an evaluation of the biogeochemical mechanisms affecting the size of the oxygen minimum zone. Here we present a broad over-view of our first results. A trace metal clean laboratory, rosette system and towfish were deployed on board the RV Meteor. Analysis of dissolved Al, H$_2$O$_2$ and Fe(II) via flow injection analysis was undertaken at sea, and dissolved/colloidal/particulate transition elements determined via ICPMS on preserved samples at GEOMAR. Additionally, River Congo freshwater samples were collected throughout the year. The influence of the river Congo plume towards the north of our transect was evident in all terrestrially derived element signals resulting in particularly elevated concentrations of, for example, dissolved Fe, dissolved Al, and Ra over 100 km offshore, and maintaining high concentrations in low salinity waters on the shelf. Towards the south of our study region, an elevated Ra and Fe signal, with the majority of dissolved Fe present as Fe(II), in benthic boundary waters, with a steady decline proceeding into the water column was strong evidence of a benthic trace element source mechanism dominating the supply of trace elements into the water column. These biogeochemical features aligned well with incubation bioassay experiments which demonstrated small scale regional differences in the bottom-up control on primary production between light, nitrate and Fe.
**(53) Vertical carbon flux along a transect at 12°S within the oxygen minimum zone off the Peruvian coast**

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The vertical flux of organic carbon out of the euphotic layer in the Peruvian Oxygen Minimum Zone (OMZ) was estimated indirectly by measuring the pair of natural radionuclides thorium-234 (234Th) and uranium-238 (238U). The “scavenging” of 234Th onto particles produced in the euphotic zone and exported through sedimentation causes a separation between daughter and parent nuclide. The resulting disequilibrium between the two nuclides is used to calculate the flux of particulate organic carbon (POC). Samples were obtained during two expeditions (M92, M137) taking place in the framework of the SFB754 (Collaborative Research Center 754). The sampling stations were all situated along a transect perpendicular to the coastline just south of 12° S and covering a water depth range from 80 m to 1000 m. The first sampling method consisted in the deployment of 4-6 in situ pumps at a time to collect the particulate and dissolved fraction of 234Th, and the second so called “small volume” method consisted in sampling 4 L of seawater from NISKIN bottles and precipitating the total 234Th. All 238U samples were taken from the NISKIN bottles and measured by ICP-MS. A very pronounced OMZ was observed, the water column being depleted of oxygen (< 5 μM) down to some 500 m depth with an oxycline situated between 20-50 m during the first expedition in the austral summer, and between 80-120 m during the second expedition in the austral autumn. POC fluxes out of the photic layer during the first expedition were highest (10 mmol C m⁻² d⁻¹) at the shallowest site (80 m bottom depth). At three other sites with bottom depths within oxygen depleted waters (< 500 m), POC fluxes were around 5 mmol C m⁻² d⁻¹ and < 1 mmol C m⁻² d⁻¹ at the two sites farthest from the coast (750 m and 1000 m bottom depth). The carbon fluxes measured during the austral summer expedition will be compared to those from the autumn season, during which flux measurements were done using also the “small volume” method. They will be discussed within a broader framework of POC flux measurements in the OMZ of the tropical south Pacific. The presented flux data set is one of the most comprehensive ones presented from the Peruvian OMZ, where flux data are generally rare.

**(54) Surprises in the westward penetration of iron and its redox cycling at the Peru Margin**

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The GP16 Eastern Pacific Zonal Transect cruise from Peru to Tahiti in 2013 along 12-15°S crossed the large eastern tropical South Pacific oxygen deficient zone (ODZ), which
was expected to be an important source of dissolved iron into the ocean interior. We however found, there was no significant iron plume in the heart of the ODZ around 300 m that extended beyond the coastal margin, despite the ODZ penetrating several thousand of kilometers into the interior. Surprisingly, a deep coastal iron plume in oxygenated waters centered around 2000 m was observed to penetrate >1000 km into the interior. We examine here the reasons behind the most significant surprise in iron cycling at the Peru Margin: the unexpected high Fe from the oxygenated deep slope relative to the more reducing ODZ above. We find high particulate Fe in the ODZ and show that this is present as Fe(III)-oxyhydroxides whereas most dissolved Fe is in the Fe(II) redox state. This strongly indicates rapid redox cycling of Fe, even in anoxic waters where the two major oxidants of Fe were proven to be absent, which results in trapping of Fe near the coast. Because these long known oxidants for dFe(II), oxygen and Hydrogen Peroxide, are absent in ODZs alternative oxidants must be considered. We found that the highest concentrations of pFe and nitrite (NO₂⁻) are co-located, suggesting that nitrogen species may play a key role in the oxidation of dFe(II) in the ODZ. By contrast, particulate iron in the deep Fe plume has more unweathered, Fe(II)-containing crystalline silicate minerals, consistent with the strong lithogenic particle signal observed. We examine mechanisms for the strong sediment resuspension in the deep slope, as well as reversible exchange mechanisms, that potentially can explain the deep Fe plume.

**Fe(II) as an integral component of the iron cycle in oxygen minimum zones**

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Iron (Fe) is an essential nutrient for all known life. Its low concentration in seawater limits primary production across much of the ocean surface, including most of the eastern tropical South Pacific. For the biological component of deoxygenation to continue to fuel the expansion of the ocean’s oxygen minimum zones (OMZs), shelf supplied Fe must be advected laterally offshore and continue to facilitate primary production at the surface. A key uncertainty in our modelling of future OMZ changes is how this lateral Fe supply changes in response to intensifying deoxygenation over shelf regions. Fe is a conceptually difficult nutrient to model because of the rapid scavenging that follows any Fe addition to seawater and because of its diverse speciation. Dissolved Fe, the main bioavailable fraction in seawater, is normally defined as consisting entirely of Fe(III)-organic ligand species. Despite the validity of this assumption across most of the ocean by volume, this assumption is invalid in the surface ocean due to the presence of dissolved Fe(II) as a result of photochemical process and in OMZs due to the pronounced release of benthic Fe(II) into the water column. Fe(II) is a highly labile form of dissolved Fe and formation of Fe(II) thus expands the bioavailable Fe pool. Resolving the separate biogeochemistry of Fe(II)/Fe(III) within regions affected by OMZs is critical to understanding how Fe sources
and sinks, and thus Fe bioavailability in both shelf and offshore regions, will change in response to shelf deoxygenation. Here we report the concentration of Fe(II) along the Namibian (November/December 2015) and Peruvian (October 2015 and April 2016) shelves, both regions occupied by pronounced OMZs. In both regions a strong benthic and a weaker photochemical source of Fe(II) was evident. Both vertical profiles of Fe(II) and spiked pelagic incubation experiments under low O₂ conditions (1-20 μM) suggested that the dominant removal process of Fe(II) was not oxidation by dissolved O₂. We therefore explore alternative hypothesis concerning the fate of Fe(II) within OMZ regions and the significance of these removal processes for the relationship between intensification of deoxygenation on the shelf and lateral supply of Fe offshore.

(56) The formation of nitrite-accumulating layers in the oxygen minimum zone of the Eastern Tropical South Pacific

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In coastal upwelling regions, high surface productivity leads to high export and intense remineralization consuming water column oxygen. This, in combination with slow ventilation, creates oxygen minimum zones (OMZ) in eastern boundary regions of the ocean, such as the one off the Peruvian coast in the Eastern Tropical South Pacific (ETSP). The OMZ is uniquely characterized by a layer of high nitrite concentration coinciding with water column anoxia. Sharp oxygen gradients are located above and below the anoxic layer (upper and lower oxyclines). Thus, the OMZ harbors diverse microbial metabolisms, several of which involve the production and consumption of nitrite. The sources of nitrite are ammonium oxidation and nitrate reduction. The sinks of nitrite include anaerobic ammonium oxidation (anammox), canonical denitrification, nitrite oxidation to nitrate and dissimilatory nitrite reduction to ammonium. The distribution of nitrite in the water column showed a two-peak structure. A primary nitrite maximum (up to 0.5 μM) was located in the upper oxycline. A secondary nitrite maximum (up to 10 μM) was found in the anoxic layer. Previous incubation experiments showed that, within the layer of the secondary nitrite maximum, in situ nitrite production rates are equivalent to consumption rates within measurement error. Thus the formation of nitrite maximum layer within the OMZ remains poorly understood. A high resolution regional biogeochemical model (ROMS) was applied to decipher the origin and the evolution of nitrite-accumulating layer in the ETSP-OMZ. The formation of primary nitrite maximum in the upper oxycline is the result of ammonium oxidation exceeding nitrite oxidation. The low nitrite concentration at the oxic-anoxic interface is because of net nitrite consumption rates. The net production of nitrite at the coastal waters results in the accumulation of nitrite, which is transported offshore by mesoscale eddies on a time scale of months, forming a stable secondary nitrite maximum in the anoxic layer. Thus, physical and chemical processes shape the nitrite distribution in the Eastern Tropical South Pacific oxygen minimum zone.
(57) The Influence of mixing on N\textsubscript{2}O production in the coastal waters off Peru

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The Peruvian upwelling area is known as an area of high N\textsubscript{2}O emissions. While oxygen-free waters of the OMZ core are depleted in N\textsubscript{2}O, extremely high production is triggered within the sharp gradients of the oxycline in the coastal waters off Peru, and mixing and upwelling processes can effectively transport these waters with extreme N\textsubscript{2}O supersaturations towards the surface. This turns the Peruvian upwelling into the most important ocean area for N\textsubscript{2}O emissions which accounts for about 25% of the global oceanic N\textsubscript{2}O emissions alone. Here we investigate the effect of mixing between oxygenated surface waters with waters from the OMZ core on N\textsubscript{2}O production in a series of incubation experiments with different mixing conditions using GC-ECD and \textsuperscript{15}N tracer incubations. N\textsubscript{2}O production was triggered when water from the OMZ was mixed with oxygenated surface waters.

(58) Hydroxylamine as a precursor for nitrous oxide in the equatorial Atlantic Ocean and eastern tropical South Pacific Ocean

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Hydroxylamine (NH\textsubscript{2}OH), a short-term intermediate in the nitrogen cycle, is a potential precursor of nitrous oxide (N\textsubscript{2}O) formation in the ocean. During nitrification, the oxidation of ammonium (NH\textsubscript{4}+) to nitrate (NO\textsubscript{3}–), N\textsubscript{2}O is produced as a by-product via NH\textsubscript{2}OH and nitrite (NO\textsubscript{2}–). However, measurements of NH\textsubscript{2}OH in the ocean are sparse. Here, we present a dataset of depth profiles of NH\textsubscript{2}OH from the equatorial Atlantic Ocean and the eastern tropical South Pacific (ETSP) and compare it to N\textsubscript{2}O, NO\textsubscript{3}– and NO\textsubscript{2}– profiles under varying oxygen conditions. Overall, the NH\textsubscript{2}OH concentrations were in the lower nanomolar range and lower than N\textsubscript{2}O concentrations. In the equatorial Atlantic Ocean, where nitrification is the dominant N\textsubscript{2}O pathway, stepwise multiple regressions demonstrated that N\textsubscript{2}O, NH\textsubscript{2}OH and NO\textsubscript{3}– concentrations were highly correlated, indicating that NH\textsubscript{2}OH is a precursor of N\textsubscript{2}O and a tracer for nitrification. This relationship weakens in the ETSP and no correlations are found in the oxygen minimum zone (OMZ) off Peru where besides nitrification other N\textsubscript{2}O pathways like denitrification occur.
Nitrogen (N) loss in oxygen minimum zones (OMZ) accounts for around one-third of global fixed N loss and plays a critical role in the oceanic N inventory. Expanding OMZs in tropical oceans may intensify N loss, reduce primary production, and thereby decrease oceanic CO2 uptake. However, major uncertainties exist regarding the transport pathways of nutrients and the magnitude of N-loss in OMZs. In this study, a comprehensive data set from the continental margin of the Peruvian OMZ is used to evaluate benthic-pelagic dissolved inorganic N budgets and to investigate the dominant nutrient transport mechanisms. The data set was collected during a 4-week process study in austral summer 2013 along 12°S and consists of velocity time series from moorings, turbulence measurements, CTD/O2 profiles, nutrient and N2 gas concentration profiles, and benthic nutrient fluxes measured in situ by landers. Resulting sinks and sources allow net N-losses to be determined and compared to the flux divergences of an excess N2 gas budget. On the anoxic shelf, nearstagnant circulation and elevated turbulence due to internal waves resulted in a dominant nutrient transport mechanism via diapycnal mixing. Nutrient fluxes due to vertical advection (i.e. upwelling) were insignificant. Enhanced sediment release of ammonium (NH4) and diapycnal flux convergences of nitrate (NO3) and nitrite (NO2) resulted in a net N-loss of 220 nmol L⁻¹ d⁻¹. This agrees with the divergence of excess N2 fluxes. Benthic NH4 release accounts for about 50% of N-loss, most likely due to coupling with annamox in the water column. On the upper continental slope, N-loss occurred primarily in the near-bottom region of the water column. Here, diapycnal NO3 fluxes and isopycnal eddy and advective fluxes provide NO3 for sedimentary uptake and NO2 production by NO3 reduction. Combining water column NO3 and NO2 flux imbalances with sedimentary NH4 release resulted in an N-loss of 23 nmol L⁻¹ d⁻¹. Again, N-loss of similar magnitude was obtained from an excess N2 budget. The study indicates that water-column NH4 sources play only a minor role for N cycling processes along the continental margin of Peru. Results also highlight diapycnal mixing as a key transport mechanism providing nutrients for benthic uptake.
(60) Spatial and Temporal variability of Physico-biochemical Status of Seawater around the Saint Martin’s Island, Bangladesh

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Saint Martin’s island is a beautiful tourist attractive place and one of the unique coral islands in Bangladesh. Marine biodiversity of Saint Martin’s island is actually enrich due to its favorable environmental condition but its marine environment is facing threats day by day due to natural calamities, various types of pollution, and other anthropogenic activities. So it is very important to know the present physico-biochemical status of seawater of the Saint Martin’s island for the basement study. Seawater samples were collected by two systematic ways. Firstly, coastal seawater samples were collected from 24 sites of the around of Saint Martin’s Island and Secondly, sea surface water and 5 m in depth seawater samples were collected from 18 sites of the almost 1 km far from the Saint Martin’s Island (offshore) by niskin water sampler from 26 February 2018 to 02 March 2018 and 08 to 09 April 2018. Seven physico-chemical parameters were measured directly in-situ position while the biological parameters are awaiting for lab experiment in next 6 months. The surface water (0-20 cm) physico-chemical parameters including temperature, salinity, dissolved oxygen (DO), pH, total dissolved solids (TDS), conductivity & resistivity and the biological parameters include measurement of Chlorophyll-a & nutrients (nitrate, nitrite, phosphate and silicate). The ranges for the physico-chemical parameters of coastal seawater were 25 to 30°C for temperature, 30.8 to 33.4 ppt for salinity, 4.50 to 6.90 mg/L for DO, 8.05 to 8.38 for pH, 29575 to 31980 mg/L for TDS, 48966 to 55235 μS/cm for conductivity and 18.08 to 20.43 Ω-cm for resistivity where the ranges for the physico-chemical parameters of surface water of the offshore were 25 to 27°C for temperature, 32 to 32.88 ppt for salinity, 4.6 to 5.84 mg/L for DO, 7.9 to 8.14 for pH, 31055 to 31980 mg/L for TDS, 48893 to 57089 μS/cm for conductivity and 19.34 to 20.04 Ω-cm for resistivity. The temperature, salinity, pH, DO and conductivity of coastal water were higher than offshore seawater. The highest and lowest salinity was found at the south and north of the Saint Martin’s Island respectively. The salinity and pH of 5m deep seawater are higher than surface seawater but temperature of surface seawater is higher than 5m deep seawater. The highest DO was found almost three sides especially eastern side of the Saint Martin’s Island but lowest DO was found at the west-southern side which connect to the open ocean. It indicates hypoxia may present in the open ocean.
(61) Sediment release of dissolved organic matter in the oxygen minimum zone off Peru

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Due to upwelling of nutrient-rich waters, the eastern tropical South Pacific (ETSP) represents one of the most productive areas in the ocean. The remineralization of organic matter produced in the euphotic zone and sluggish ventilation lead to the formation of an oxygen minimum zone, where oxygen concentrations fall <1μmol kg⁻¹. Part of particulate organic matter (POM) that originates from the euphotic zone is supplied to the anoxic sediments, where it is degraded by microbial communities. Microbial utilization of organic matter under anoxic conditions leads to nitrogen-loss processes and an accumulation of sulfide and methane. The degradation of POM gives rise with dissolved organic matter (DOM) production and reworking. DOM may then undergo mineralization processes within the sediment pore waters or diffuse out into the overlying water column. Benthic DOM release can influence the biogeochemistry of overlying water column, as DOM may serve ligands for micronutrients, such as iron, and serve as an additional organic carbon source for microbial communities to respire. The unaccounted release of DOM from pore waters may also lead to underestimations of POM remineralization in the seafloor. An indication of DOM release from OMZ sediments into the water column was determined during the research cruise M93 to the Peruvian upwelling Feb-March 2013 by high spatial resolution DOM fluorescence (FDOM) measurements. However, the quantification of DOM flux was not possible. Here we present new DOM data from the sediments and the water column, collected during SFB754 research cruises M136-137 to the Peruvian upwelling in 2017. DOM was measured in pore-water samples obtained by a multicorrer (MUC), as well as water samples from sediment incubation (flux) Biogeochemical Observatory chambers (BIGO), and data records, collected by the WETStar CDOM fluorometer (WETLabs, USA) mounted on a mini-lander. We evaluate DOC and dissolved organic nitrogen concentrations and fluxes and compare them to the measurements of FDOM. We discuss the quality of DOM, found in pore waters and in the overlying waters, and possible effects of the DOM release on water column biogeochemistry as well as tracing of the DOM release by in-situ (sensor) measurement techniques.
(62) **A benthic Phosphorus budget for the Peruvian oxygen minimum zone**

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Environmental conditions in oxygen minimum zones generally favour the benthic release of phosphorus and other nutrients into the water column. This process may sustain a positive feedback loop enhancing primary productivity and further expansion of low-oxygen water masses globally. Previous observations along the Peruvian continental margin revealed that dissolved benthic phosphorus fluxes were always higher than the rain rate of total particulate phosphorus to the seabed, indicating a lacking source of phosphorus to the sediments. Non-steady state conditions, e.g. the transient phosphorus release by bacterial mats that had stored P in form of polyphosphates during periods of bottom water oxygenation have been suggested as most likely explanation for this phenomenon. However, new findings call this interpretation into question. We will present a revised benthic phosphorus budget based on new data obtained during RV Meteor expedition M 137 comprising benthic flux measurements, composition of surface sediments and water column particles, as well as data from incubation experiments.

(63) **Quantifying lateral export from the benthic boundary layer to the offshore eastern tropical South Pacific**

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Deoxygenation of shelf waters is known to enhance the sedimentary source of nutrients, including PO$_4$ and Fe, into the water column. Yet substantial uncertainty remains with respect to what fraction of these nutrients are transported into the euphotic layer and ultimately advected offshore and thus how an increased benthic supply of nutrients affects offshore ecosystem productivity. In October 2015 a conservative tracer (CF3SF5) was released within the bottom boundary layer at 3 sites along the Peruvian coastline within the Peruvian Oxygen Minimum Zone (OMZ). During March/April 2017 the dispersion of this tracer along the shelf and laterally into the ETSP was tracked alongside a comprehensive suite of nutrient measurements including macronutrients (NO$_3$, NO$_2$, PO$_4$, Si), dissolved organic nitrogen/phosphorus (DON/DOP) and dissolved trace metals (including Fe and Co). The tracer distribution demonstrated transport northwards along the shelf, in addition to lateral advection
offshore, which was most pronounced along a transect at 17° S. Here we compare and contrast the distribution of our inert tracer with a broad range of nutrients along the 17° S transect in order to understand how internal cycling affects the lateral advection of bio-essential nutrients from anoxic shelf benthic boundary waters to offshore ecosystems. Constraining the relative strength of laterally advected Fe and bioavailable nitrogen/phosphorus sources will be critical to understanding how primary productivity and microbial community structure within the Peruvian Oxygen Minimum Zone will respond to intensified deoxygenation over the Peruvian shelf.

(64) Modeling of the biogeochemical cycle and dispersion of nitrogen off Lake Idku Outlet, Abu Qir Bay, Egypt

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The Egyptian Mediterranean coast hosts five lakes namely the (Northern Lakes). These lakes receive their water mainly from agricultural drainage systems. One of these lakes is Idku Lake, which was suffered from a significant increase of nitrogen levels over the last few decades, and in turn could affect adversely on the water quality of Abu Qir bay that is connected directly to the lake through an outlet. The objective of the present study, is to investigate the fate of nitrogen forms which are driven from the lake into the bay, as well as the biogeochemical cycle of nitrogen. A coupled highly resolved hydrodynamic biogeochemical model was developed on the basis of Delft3D over the period from November 2015 to May 2016. The model comprised most of the nitrogen cycle processes and factors, as well as the hydrodynamics in the study area. This model showed, the temporal and spatial distribution of nitrogen levels in the bay have varied depending on the nitrogen levels concentrations inside the lake as well as the physical parameters that regulate the hydrodynamics of the lake water dispersion into the bay. Regarding the cycle, the Dissolved oxygen levels have played a key role in regulating the cycle processes. As the study area was shallow coastal area, the water column was turbulent oxygenated column, resulting in increasing the rate of nitrification as well as inhibiting the process of denitrification. Furthermore, phytoplankton has had a major role in the cycle. After assimilation of nitrogen, algal mortality has existed significantly, as most of algal species have brackish water characteristics, and due to the significant increase in salinity, algal mortality was observed. Thereafter, detrital nitrogen in algal cells was transferred to sediments by settling. Also, the sedimentary nitrogen mineralization process had a pivotal function in releasing more nitrogen fluxes back to water column. Moreover, the nitrogen budget over the simulation period has shown that, most of nitrogen forms that derived from Idku lake outlet, were dissipated and transported over the open boundaries of the model domain, due to the high interaction between the water masses inside the model domain and those from the area beyond the open boundaries. In addition, the model has observed that the residence time of water masses was very low over the simulation time, decreasing the rate of retention of nitrogen fluxes over the study area.
(65) Coastal hypoxia in the Black Sea: effects on diagenetic pathways and benthic fluxes

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Dissolved oxygen is a fundamental component for marine life involved in the biogeochemical cycling of elements (e.g. N, P, S). The occurrence of hypoxic and anoxic events seems to have broadened in the coastal zones impacted by anthropogenic activities whereas these environments have existed through geological time. The north-western shelf of the Black Sea has been affected by seasonal hypoxia over the last decades. The area has undergone nutrient, organic matter and reactive iron loadings from the discharge of rivers such as the Danube. Oxygen deficiency in the bottom waters induces major changes in biogeochemical processes, giving rise to reactions of anoxic mineralisation of the organic matter. Within the framework of the BENTHOX project, a study focusing on the early diagenesis has been conducted in the Black Sea. It aims to collect a new dataset of biogeochemical measurements in the sediments including porewaters, to investigate the impact of benthic hypoxia on the diagenetic pathways and to reconstruct the long-term hypoxia history using a multi-proxies approach. During two cruises (EMBLAS II May 2016 & August 2017) aboard the R/V Mare Nigrum, sediments, porewaters and bottom waters were sampled on the Ukrainian shelf of the Black Sea. Geochemical analyses have been carried out on the solid phase as well as in the porewaters to determine the speciation of sedimentary sulfur (AVS, pyrite, S°, ΣH2S and dissolved sulfate) and iron (dithionite extractable Fe, total Fe, HCl extractable Fe and dissolved Fe). Indeed, the Fe and S cycles are closely linked which are influenced by the organic matter inputs, the presence of Fe-compounds and the oxygen concentrations in the bottom waters. This study allows a better understanding of the impact of oxygen depletion on the biogeochemical cycling of carbon and nutrients in a shallow coastal area. Moreover, the assessment of benthic fluxes regarding the dissolved nutrients will bring about some information on the response of the sediment biogeochemistry to seasonal hypoxia.

(66) Understanding the linkage between water column oxygen and benthic fluxes in the upwelling system off Peru

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Recent biogeochemical studies have stressed a significant role of benthic dynamics on the pelagic nitrogen (N) cycle in the oxygen minimum zones. Sedimentary denitrification and dissimilatory nitrate reduction to ammonium (DNRA) are important N transformation pathways in these regions and hypothesized to contribute to the biological production and oxygen distribution. Here, using a coupled physical-biogeochemical model, we aim to investigate the effect of benthic dynamics on the
water column nitrogen distributions in the Eastern Tropical South Pacific oxygen minimum zone. Empirical transfer functions that represent the benthic denitrification and DNRA are coupled to the biogeochemical model. Our results highlight an influence of benthic dynamics on water column oxygen distributions as a result of changes in water column N and phytoplankton productivity.

(67) Impact of anthropogenic atmospheric nutrient deposition on ocean deoxygenation and benthic nutrient fluxes

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Most global IPCC climate-biogeochemical models underestimate global deoxygenation by a factor of ~2, but have not yet included anthropogenic impacts of atmospheric nutrient deposition. Here we use the UVic Earth System Climate Model of intermediate complexity to assess the importance of anthropogenic nutrient deposition on ocean deoxygenation. Future climate scenario simulations with and without anthropogenic nutrient deposition are tested in the model. Preliminary results suggest that anthropogenic nutrient deposition may be responsible for a significant amount of current ocean deoxygenation. Sensitivity simulations show the large uncertainty associated with assumptions for atmospheric iron solubility and feedbacks with sedimentary iron fluxes.
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