SECOND INTERNATIONAL SYMPOSIUM ON

THE OCEAN IN A HIGH-CO_2 WORLD

MONACO - OCTOBER 6-9, 2008

BOOK OF ABSTRACTS AND PROGRAMME

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Increasing attention is being given to the carbon footprint of travel, including that of scientists attending meetings. The international Planning Committee for this symposium has agreed to make a US$5,000 contribution to a reputable carbon offset organization, Climate Care (http://www.climatecare.org/). This contribution will at least partially offset the carbon emitted by the travel of participants in this symposium. The sponsors understand that carbon offsets are an imperfect substitute for reduced travel.

SECOND INTERNATIONAL SYMPOSIUM
ON

THE OCEAN IN A HIGH-CO_2 WORLD

The scientific sponsors and the organizing committees of the Symposium gratefully acknowledge the financial and in-kind support received from the following organizations and funding agencies:

U.S. National Science Foundation
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The Scientific Committee on Oceanic Research
International Atomic Energy Agency
International Geosphere-Biosphere Programme
Musée Oceanographique
Centre Scientifique de Monaco

Second Symposium on the Ocean in a High-CO_2 World
Book of Abstracts and Programme
FOREWORD

When we met at UNESCO headquarters in Paris four years ago at the *1st Symposium on the Ocean in a High-CO_2 World*, about 120 scientists gathered to discuss how recent increases in atmospheric CO_2 were affecting ocean chemistry and biology, to evaluate potential strategies to artificially enhance ocean carbon uptake, and to discuss directions for future research. The term ocean acidification was not in wide use, and only a small group of specialists had been studying how increasing marine concentrations of CO_2 and corresponding reductions in pH and carbonate ion concentrations were affecting marine organisms, mostly corals. For years, ocean scientists had thought mostly about the beneficial effects of the ocean's great capacity to take up CO_2, thereby moderating the increase in atmospheric CO_2 from fossil-fuel combustion. But as the meeting progressed, there was a growing awareness of many problems associated with corresponding changes in ocean chemistry and associated biological impacts. That 1st symposium marked a turning point for many of us. We suddenly understood that impacts were as important as air-sea CO_2 fluxes. The media also picked up on these heightened scientific concerns and further increased their fervor when subsequent national reports were released and when three papers presented at the symposium were published in high-profile science journals.

Four years later, we meet again under heightened concern. There is now much wider scientific interest, as illustrated by the 250 scientists from 32 countries who are attending this 2nd symposium, many of whom are now directly involved in ocean-acidification research. Ocean acidification is now widely cited in the press in conjunction with climate change, often being referred to as *the other CO_2 problem*. The convenors of the 1st symposium, IOC-UNESCO and SCOR, have been joined by two other international bodies, the IAEA and IGBP. There has been progress to begin to fund efforts to understand the fundamental science concerns, impacts on key organisms, and how those might affect ecosystems in general. There is now a political urgency to communicate new science findings to economists and policymakers, to educate the public, and to train future scientists. Our 2nd symposium provides a small step in this direction by following up the 3-day science meeting with a 1-day wrap-up session where scientists will meet with both economists and policymakers, in the morning, and secondary-school science teachers, in the afternoon.

It is no accident that the *2nd Symposium on the Ocean in a High-CO_2 World* is being held in Monaco at the Musée Océanographique, which was founded nearly 100 years ago by Prince Albert I, who was himself an oceanographer and whose marine collections are still on display. It is hard to imagine a more conducive environment for you to discuss advances since the 1st symposium, to plan future high-priority research, and to begin to build the critical links among scientists, economists, and policymakers that our society requires in order to realize the full extent of the global and long-term impacts of ocean acidification and to motivate it to take action.

James C. Orr,
Chairman, International Scientific Planning Committee

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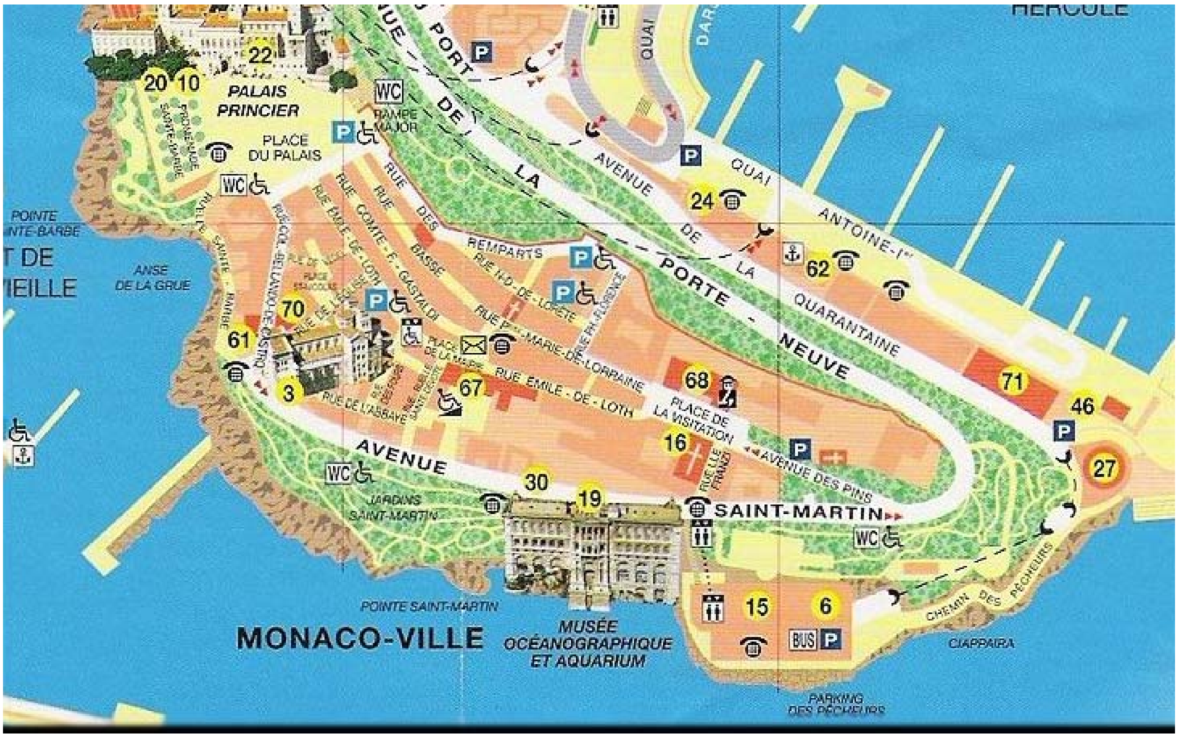
Monaco - Local Information

The schematic maps below will give you a general idea of the areas of Monaco. The lower one gives more detail about "Monaco-ville", the old town close to the Musée Océanographique. We hope to have more detailed maps and a restaurant list available at the registration desk, and your hotel may also provide them.



Public Transportation in Monaco:
As in most European countries, using public transportation is efficient. Although walking distances are short - the whole country is less than 500 acres - you may wish to use the bus to get from your hotel to the Musée Océanographique. The following information is taken from the Web site of the local bus company:

Description of the Bus Routes:

5 bus lines to get you where you are going...

Line 1 : Monaco Ville - Casino - Saint Roman (Round Trip).

Line 2 : Monaco Ville - Casino - Jardin Exotique (Round Trip).

Line 4 : Gare - Larvotto (Plages) (Round Trip).

Line 5 : Gare -Fontvieille - Hôpital - Gare.

Line 6 : Fontvieille - Casino - Larvotto (Plages) (Round Trip).

How to get a Ticket:

In the bus...

Next to the conductor, upon boarding the bus. (Single trip tickets, 8 trip card, 8 trip "Monaco - Beausoleil", 4 trip card and daily tourist card).

At our offices...

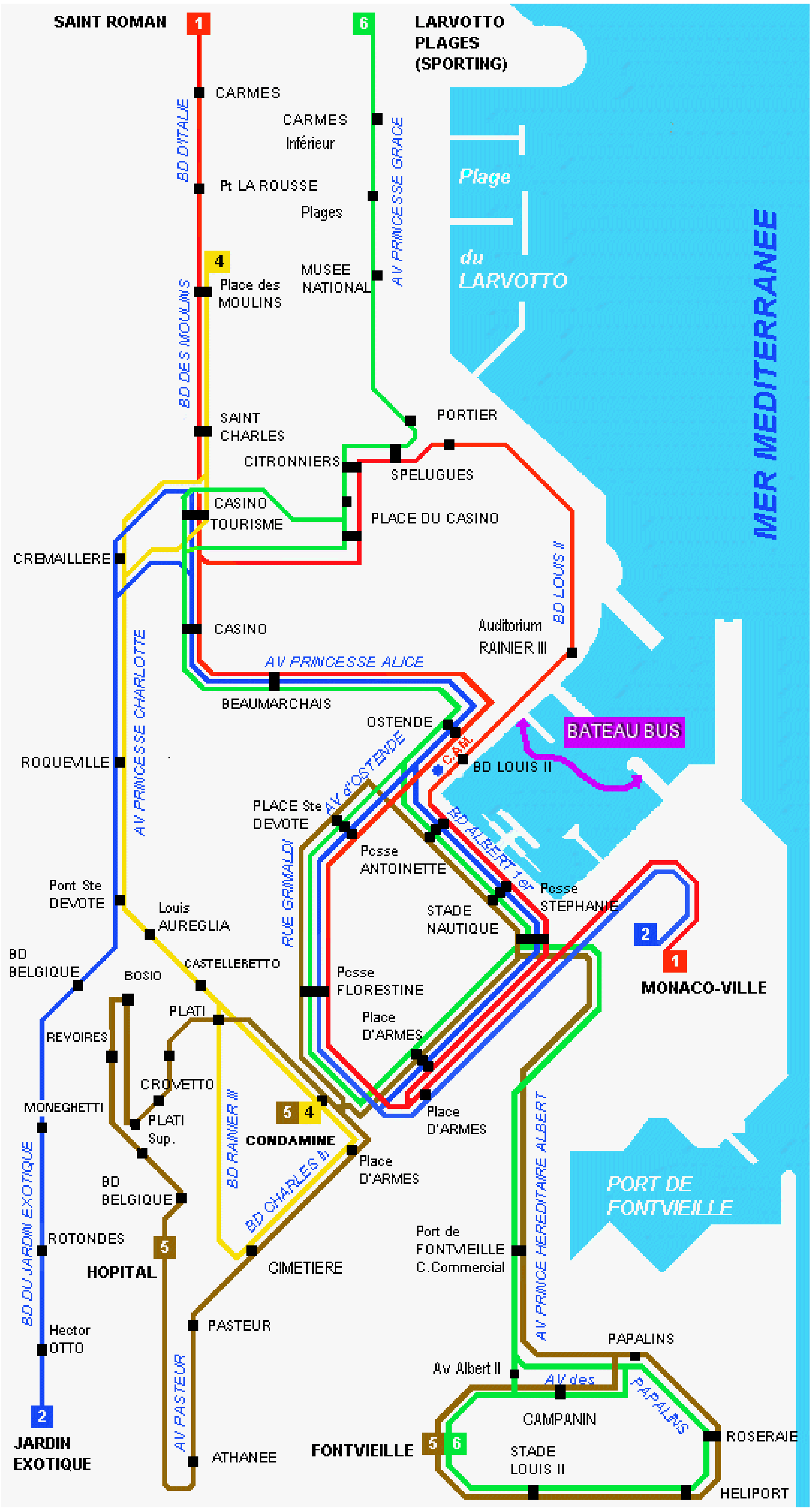
Compagnie des Autobus de Monaco, 3, av. du président J.F. Kennedy, 98000 Monaco. (Only for tickets not sold on the buses)

Riding the Bus:

Go to one of the 141 bus stops of the Principality's network...
Upon boarding the bus...

1. **Boarding the bus is done exclusively by the front unless authorized otherwise by the conductor or ticket inspector of the C.A.M..**
2. **Get your ticket or ask the conductor.**
3. **Validate your ticket in the machine provided for that purpose, then keep the ticket in your possession during the rest of the trip.**

A map of the bus routes is shown on the next page.



SAINT ROMAN
1
6
LARVOTTO
PLAGES
(SPORTING)
CARMES
BD D'ITALIE
CARMES
Inférieur
AV PRINCESSE GRACE
Pt LA ROUSSE
Plages
Plage
du
LARVOTTO
MER MEDITERRANEE
4
Place des
MOULINS
MUSEE
NATIONAL
BD DES MOULINS
SAINT
CHARLES
PORTIER
CITRONNIERS
SPELUGUES
CASINO
TOURISME
PLACE DU CASINO
CREMAILLERE
BD LOUIS II
CASINO
Auditorium
RAINIER III
AV PRINCESSE ALICE
BEAUMARCHAIS
OSTENDE
BATEAU BUS
ROQUEVILLE
AV PRINCESSE CHARLOTTE
AV d'OSTENDE
C.A.M.
BD LOUIS II
PLACE Ste
DEVOTE
RUE GRIMALDI
Pcsse
ANTOINETTE
BD ALBERT 1er
Pont Ste
DEVOTE
Louis
AUREGLIA
Pcsse
STEPHANIE
STADE
NAUTIQUE
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MONACO-VILLE
BD
BELGIQUE
BOSIO
CASTELLERETTO
Pcsse
FLORESTINE
PLATI
Place
D'ARMES
REVOIRES
CROVETTO
MONEGHETTI
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PLATI
Sup.
CONDAMINE
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D'ARMES
BD RAINIER III
Place
D'ARMES
BD CHARLES III
AV PRINCE HEREDITAIRE ALBERT
PORT DE
FONTVIEILLE
BD
BELGIQUE
ROTONDES
5
HOPITAL
CIMETIERE
Port de
FONTVIEILLE
C.Commercial
BD DU JARDIN EXOTIQUE
Hector
OTTO
PASTEUR
PAPALINS
Av Albert II
AV des
PAPALINS
AV PASTEUR
2
JARDIN
EXOTIQUE
CAMPANIN
ATHANEE
FONTVIEILLE
5
6
STADE
LOUIS II
ROSERAIE
HELIPORT

Second Symposium on the Ocean in a High-CO_2 World
Summary Programme

SUNDAY, 5 OCTOER	MONDAY, 6 OCTOBER	TUESDAY, 7 OCTOBER	WEDNESDAY, 8 OCTOBER	THURSDAY, 9 OCTOBER
	Registration 8:00-9:00	First session begins 8:30	First session begins 8:30	***Beyond natural science*** Opening by HSH Prince Albert II 9:00
	Opening 9:00-9:30	***Mechanisms of Calcification***	***Adaptation and microevolution***	***Science Summary*** ***Economics*** ***Policy***
	Scenarios of ocean acidification	***Physiological effects: from microbes to fish***	***New concerns*** ***Biogeochemical consequences and feedbacks***	
	Coffee Break 10:45-11:15	Coffee Break 10:30-11:00	Coffee Break 10:15-10:45	Coffee Break 10:50-11:20
	Impacts on benthic and pelagic calcifiers	***Physiological effects: from microbes to fish*** continued	***Biogeochemical consequences and feedbacks*** continued	***Press Conference*** 11:30-12:30
	Lunch 12:00 - 14:00	Lunch 12:00 - 14:00	Lunch 11:30-13:00	
	Impacts on benthic and pelagic calcifiers continued	***Fisheries, food webs, and ecosystem impacts***	***Breakout Sessions***	***Outreach for local students, teachers*** 14:00-16:00
	Coffee Break 15:15 - 15:45	Coffee Break 15:30 - 16:00	Coffee Break 15:15 - 15:45	
	Ocean carbon system: past & present	***CO_2 Disposal***	***Reports from Breakout Sessions***	
	Effects of ocean acidification on nutrient and metal speciation	***Poster Session 2*** 17:00-19:00	***Closing summaries*** 17:00-18:00	
Registration Opens 17:00	***Poster Session 1*** With refreshments 18:00-20:00	Cocktail reception 19:00-20:00		
Ice-Breaker and registration 18:00-19:30		Dinner 20:00-22:00		

Second Symposium on the Ocean in a High-CO_2 World
Detailed Programme

SUNDAY, 5 OCTOBER

Ice-Breaker Reception (and Registration)

17:00 – 18:00 ***Registration*** (access to the Musée Océanographique after registering)

18:00 – 19:30 ***Ice-Breaker Reception*** (registration continues; access to 1st floor access only)

DAY 1: MONDAY, 6 OCTOBER

8:00 – 9:00 ***Registration***

9:00 - 9:30 ***Opening & Welcome***
9:00 - 9:15 Robert Calcagno – Minister for Public Works, the Environment and Urban Development (Monaco)
9:15 - 9:20 Representative of the Musée Océanographique
9:20 - 9:30 James Orr – MEL/IAEA, Monaco, Chair, Planning Committees

Scenarios of ocean acidification – James Orr, Chair

9:30 – 10:00 *Invited:* Present and future changes of carbonate systems in the global oceans **– Richard Feely**, NOAA/PMEL, Seattle, USA

10:00 – 10:15 Impact of climate change mitigation on ocean acidification projections – **Gian-Kasper Plattner**, ETH Zurich, Switzerland

10:15 – 10:30 CO_2 emission targets for future changes in ocean carbon chemistry – **Richard Zeebe**, University of Hawaii, USA

10:30 – 10:45 High vulnerability of Eastern boundary upwelling systems to ocean acidification **– Nicolas Gruber**, ETH Zurich, Switzerland

10:45 – 11:15 ***Coffee Break***

Impacts on benthic and pelagic calcifiers – Denis Allemand, Chair

11:15 – 11:45 *Invited:* Impact of ocean acidification on benthic organisms **– Jean-Pierre Gattuso**, LOV, Villefranche-sur-mer, France

11:45 – 12:00 Poorly cemented coral reefs of the eastern tropical Pacific: possible insights into reef development in a high-CO_2 world– **Joan Kleypas**, National Center for Atmospheric Research, USA

12:00 – 14:00 ***Lunch***

14:00 – 14:15 The impact of ocean acidification and temperature on the reproduction and development of oysters and the potential of genetic differences to ameliorate climate change **– Laura Parker**, University of Western Sydney, Australia

14:15 – 14:30 Latitudinal variation in calcification: vulnerability of Antarctic benthic calcifiers to ocean acidification – **Sue-Ann Watson**, National Oceanography Centre Southampton, UK

14:30 – 15:00 *Invited:* Pelagic calcifiers: pteropods and forams **– Victoria Fabry**, Cal. State University, San Marcos, USA

15:00 – 15:15 Interannual variability of pteropod shell weights in the high-CO_2 Southern Ocean – **Donna Roberts**, Antarctic Climate & Ecosystems CRC, Hobart, Australia

15:15 ***Coffee break***

Ocean carbon system: past & present – Peter Haugan, Chair

15:45 – 16:15 *Invited:* Controls on evolution of ocean carbonate chemistry over the past 10^9 years – **Ken Caldeira**, Department of Global Ecology, Carnegie Institution, Stanford, USA

16:15 – 16:30 Boron isotope evidence of ocean acidification in the Neoproterozoic **– Simone Kasemann**, University of Edinburgh, UK

16:30 – 16:45 Reduced calcification in modern Southern Ocean planktonic foraminifera **– Andrew Moy (<u>William Howard</u>)**, Antarctic Climate & Ecosystems CRC, University of Tasmania, Australia

16:45 – 17:00 Current rates of change in pH and calcium carbonate saturation in the high latitude North Atlantic Ocean **– Jon Olafsson**, Marine Research Institute, Reykjavik, Iceland

17:00 – 17:15 Low winter $CaCO_3$ saturation in the Baltic Sea and consequences for calcifiers **– Toby Tyrrell**, National Oceanography Centre, Southampton University, UK

Effects of ocean acidification on nutrient and metal speciation – Silvio Pantoja, Chair

17:15 – 17:45 *Invited:* Ocean acidification and metal speciation **– Hein de Baar**, Royal Netherlands Institute for Sea Research, the Netherlands

17:45 – 18:00 Ocean acidification effects on iron speciation in seawater – **Eike Breitbarth**, Department of Chemistry, University of Gothenburg, Sweden

18:00 – 20:00 ***Poster Session 1*** (with refreshments)

<u>DAY 2: TUESDAY, 7 OCTOBER</u>

Mechanisms of Calcification – Joan Kleypas, Chair

8:30 – 9:00 *Invited:* Biomineralization mechanisms in marine calcifiers in view of ocean acidification **– Jonathan Erez**, Institute of Earth Sciences, Hebrew University of Jerusalem, Israel

9:00 – 9:15 Effect of acidification on coral calcification: working hypothesis towards a physiological mechanism – **Francesca Marubini (<u>Denis Allemand</u>)**, Centre Scientifique de Monaco

9:15 – 9:30 Predictions of carbon fixation during a bloom of *Emiliyana Huxleyi* is highly sensitive to assumed response to shift in pCO_2 – **Olivier Bernard**, INRIA-COMORE, Sophia-Antipolis, France

Physiological effects: from microbes to fish – Victoria Fabry, Chair

9:30 – 10:00 *Invited:* Physiological Mechanisms Linking Climate to Ecosystem Change: Effects of Ocean Acidification on Marine Animals in Times of Ocean Warming **– Hans-Otto Pörtner**, Alfred Wegener Institute for Polar and Marine Research (AWI), Germany

10:00 – 10:30 *Invited:* Impacts of Ocean Change on Primary Producers – **Ulf Riebesell,** Leibniz Institute of Marine Sciences (IFM-GEOMAR), Germany

10:30 – 11:00 **Coffee Break**

11:00 – 11:30 *Invited:* Physiology overview of Microbes **– Antje Boetius**, MPI für Marine Microbiology, Bremen, Germany

11:30 – 11:45 Effects of hypercapnic acidification of seawater on the biology of non-calcifying marine organisms – **Erik Thuesen**, Evergreen State College, Laboratory, Olympia, USA

11:45 – 12:00 Predicting the impact of ocean acidification on benthic biodiversity: what can animal physiology tell us? **– Stephen Widdicombe**, Plymouth Marine Laboratory, UK

12:00 – 14:00 ***Lunch***

Fisheries, food webs, and ecosystem impacts (PICES-ICES session) – Patrick Lehodey, Chair

14:00 – 14:30 *Invited:* Consequences of Ocean Acidification for Fisheries **– Jan Helge Fosså**, Institute of Marine Research, Bergen, Norway

14:30 – 15:00 An ocean acidification simulation experiment with benthic animals using a precise pCO2 control system – **Yukihiro Nojiri**, CGER/NIES, Tskuba, Japan

15:00 – 15:15 Natural CO2 vents reveal ecological tipping points due to ocean acidification **– Jason Hall-Spencer**, Marine Institute, Biological Sciences, University of Plymouth, UK

15:15 – 15:30 Salmon pHishing in the northeast Pacific; an archaeological dig in the North Pacific survey data (1956–1964) **– Skip McKinnell**, North Pacific Marine Science Organization, Sidney, Canada

15:30 – 16:00 ***Coffee Break***

CO_2 Disposal – Ken Caldeira, Chair

16:00 – 16:30 *Invited:* Effects of CO_2 capture and storage on ocean acidification – **Peter Haugan**, Geophysical Institute, University of Bergen, Norway

16:30 – 16:45 Modelling of CO_2 dispersion leaked from seafloor off Japanese coast **– Yuki Kano (Toru Sato)**, AIST (and University of Tokyo), Japan

17:00 – 19:00 ***Poster Session 2***

Tuesday Evening Symposium Events:

19:00 – 20:00 Symposium Cocktail – Aquarium (in the Musée Océanographique)

20:00 – 22:00 Symposium Dinner - 1st Floor of Musée Océanographique (stand-up buffet)

DAY 3: WEDNESDAY, 8 OCTOBER

Adaptation and microevolution – Ulf Riebesell, Chair

8:30 – 9:00 *Invited:* A brief history of skeletons in the ocean – **Andrew Knoll**, Harvard University, USA

9:00 – 9:15 Influence of high CO_2 on coccolithophores under long-term cultivation – **Marius Müller**, Leibniz Institute of Marine Sciences, Germany

New concerns – Ulf Riebesell, Chair

9:15 – 9:30 Impact of ocean acidification on underwater sound: reduced low frequency absorption, increased noise levels, potentially higher stress for marine mammals – **David Browning**, Department of Physics, University of Rhode Island, USA

9:30 – 9:45 Experimental approaches of carbonate chemistry manipulation in CO_2 perturbation studies – **Kai Schulz**, Leibniz Institute for Marine Sciences (IFM-GEOMAR), Germany

Biogeochemical consequences and feedbacks to the Earth system – Tom Trull, Chair

9:45 – 10:15 *Invited :* Biogeochemical consequences of ocean acidification – **Laurent Bopp**, Laboratoire des Sciences du Climat et de l'Environnement CEA-CNRS-UVSQ, IPSL, Gif-sur-Yvette, France

10:15 – 10:45 ***Coffee Break***

10:45 – 11:00 Dissolution of $CaCO_3$ in shallow water carbonate environments in the high CO_2 world of the Anthropocene – **Andreas Andersson**, Bermuda Institute of Ocean Sciences, Bermuda

11:00 – 11:15 Impacts of ocean acidification on marine biogenic trace gas production – **Frances Hopkins**, Laboratory for Global Marine and Atmospheric Chemistry, School of Environmental Sciences, University of East Anglia, Norwich, UK

11:15– 11:30 From laboratory manipulations to Earth system models: an 'Eppley curve' for calcification rate? – **Andy Ridgwell**, University of Bristol, UK

11:30 – 13:00 ***Lunch***

13:00 – 15:15 ***Breakout sessions***

1. Natural and Artificial Perturbation Experiments to Assess Acidification (e.g., paleoceanography, spatial variability, and mesocosm studies, modeling)
   Chair**: Ulf Riebesell** Rapporteur**: Steve Widdicombe**

2. Observational Networks for Tracking Acidification and its Impacts (e.g., sensor development, observation networks, ecosystem responses, modelling)
   Chair: **Toby Tyrrell** Rapporteur**: Chris Sabine**

3. Scaling Organism to Ecosystem Acidification Effects and Feedbacks on Climate (e.g., organism dose-response, modeling)
   Chair: **Hans-Otto Pörtner** Rapporteur**: Ken Caldeira**

15:15 – 15:45 ***Coffee Break***

15:45 – 17:00 ***Reports from Breakout sessions***

Closing summaries for 3-day science meeting – James Orr, Chair

17:00 – 17:30 What have we learnt about ocean acidification since 2004 and where should we be in 2012? **Jean-Pierre Gattuso -** LOV, Villefranche-sur-mer, France
Followed by discussion.

17:30 – 18:00 Closing statement **- James Orr**, Planning committee

DAY 4: THURSDAY, 9 OCTOBER

Beyond natural science

09:00 – 09:30 Science summary from first three days of the symposium – **Carol Turley**, Plymouth Marine Laboratory, UK

09:30 – 10:00 Basic Economics of Ocean Acidification – **Hermann Held**, Potsdam Institute for Climate Impact Resrearch, Germany

10:00 – 10:30 Ocean acidification - connecting the science to policy – **John Baxter**, Scottish Natural Heritage, UK

10:30 – 10:50 Opening – H.S.H. Prince Albert II, Monaco

10:50 – 11:20 ***Coffee Break***

Press conference

11:30 – 12:30 Press conference in English and French

12:30 – 13:30 ***Lunch***

Outreach for local students and teachers (in French)

14:00 – 16:00 Presentations and hands-on workshop potentially organized with CarboSchools, EPOCA EU Project, Musée Océanographique, Océanopolis, & l'Education Nationale de Monaco

SPEAKERS' ABSTRACTS

The abstracts in this section are arranged in order of their appearance in the Symposium programme.
I = Invited Speaker C = Contributed Talk

DAY 1 - MONDAY, OCTOBER 6 2008

SCENARIOS OF OCEAN ACIDIFICATION

PRESENT AND FUTURE CHANGES OF THE CARBONATE SYSTEM IN THE GLOBAL OCEANS [I]

Feely, Richard A[1], Christopher L. Sabine[1], James C. Orr[2], Robert H. Byrne[3], Frank J. Millero[4] and Dana Greeley[1]

The addition of fossil fuel carbon dioxide to the atmosphere is rapidly changing seawater chemistry and the calcium carbonate saturation state of the world's oceans as a result of the acidifying effects of CO_2 on seawater. This acidification makes it more difficult for marine organisms (e.g., corals, plankton, calcareous algae, and mollusks) to build skeletons, tests, and shells of calcium carbonate. Impacts on these calcifying organisms will lead to cascading effects throughout marine ecosystems. Repeat hydrographic cruises and modeling studies in the Atlantic, Pacific and Indian Oceans show evidence for increased ocean acidification. The dissolved inorganic carbon increases, of about 10-15 μmol kg^{-1} in surface and intermediate waters over the past 15 years, are consistent with corresponding pH decreases of approximately 0.025 units in surface waters. These dramatic changes can be attributed, in most part, to anthropogenic CO_2 uptake by the ocean. These data verify earlier model projections that the oceans are undergoing ocean acidification as a result of the uptake of carbon dioxide released as a result of the burning of fossil fuels. From these results we have estimated an average upward migration of the aragonite saturation horizon of approximately 1-2 m yr^{-1} in the Pacific and Indian Oceans. Such shoaling is due to the effects of anthropogenic CO_2, ventilation and biological respiration processes in the surface and intermediate waters.

[1]Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, Seattle, Washington 98115, USA (Richard.A.Feely@noaa.gov).
[2]Marine Environment Laboratory, IAEA, 4 Quai Antoine 1[er], MC-98000, Monaco.
[3]College of Marine Science, University of South Florida, 140 Seventh Avenue South, St. Petersburg, FL 33701, USA
[4]University of Miami/Rosensteil School of Marine and Atmospheric Sciences, Miami, FL 33149, USA

IMPACT OF CLIMATE CHANGE MITIGATION ON OCEAN ACIDIFICATION PROJECTIONS [C]

Plattner, Gian-Kasper[1], Fortunat Joos[2,3], Kuno M. Strassmann[2], Marco Steinacher[2], and Nicolas Gruber[1]

Ocean acidification due to rising atmospheric CO_2 concentrations lowers ocean pH and $CaCO_3$ saturation and might eventually lead to undersaturation and dissolution of $CaCO_3$ shells in parts of the ocean with potentially negative consequences for marine ecosystems. The magnitude and timing of changes in surface pH and $CaCO_3$ saturation state are largely driven by atmospheric CO_2 levels and thus critically depend on the amount of future CO_2 emissions. Here we investigate the effect of

climate mitigation actions on ocean acidification projected with the Bern2.5CC carbon cycle-climate model for a set of newly-developed multi-gas reference and climate mitigation emissions scenarios from Integrated Assessment Models. These scenarios cover a wide range of plausible 21st century emissions based on projected evolutions of the socio-economic-technological system. Reduced CO_2 emissions in climate mitigation scenarios compared to reference scenarios lead to lower projected atmospheric CO_2 concentrations and to smaller reductions in surface pH and CO_3^{2-}-ion concentrations. In addition, climate mitigation also results in a substantial delay in the timing when critical thresholds will be passed, e.g. when the surface ocean becomes undersaturated with regard to $CaCO_3$. We will quantify these climate mitigation-induced differences in ocean acidification projections, both in terms of absolute values as well as in terms of temporal evolution. The effects of climate sensitivity and carbon cycle related uncertainties on projected ocean acidification will also be discussed, highlighting the substantial uncertainties associated with these projections.

[1] Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zurich, Zurich, Switzerland (gian-kasper.plattner@env.ethz.ch)
[2] Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[3] Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

CO_2 EMISSION TAGETS FOR TOLERABLE FUTURE CHANGES IN OCEAN CARBONATE CHEMISTRY [C]

Zeebe, Richard E.[1], James C. Zachos[2], Ken Caldeira[3], and Toby Tyrrell[4]

The extent of acidification and pH decline in the surface ocean is controlled by the total amount and release time of anthropogenic carbon dioxide. In turn, these variables will determine the degree of detrimental consequences for marine organisms. This includes possible reduction in calcification rates in coccolithophores, foraminifera, and corals, as well as potential negative implications for coral reef communities and shore protection. The allowable drop in surface ocean pH, which would prevent such effects, is not yet known because of our incomplete understanding of the physiological response of the various marine organisms. Intensified research efforts are therefore required to close this gap. Nevertheless, for a prescribed target decline in future surface ocean pH, the corresponding total amount and release time of anthropogenic carbon can be calculated. Fortunately, and in contrast to climate model predictions, such future ocean chemistry projections are largely model-independent on a timescale of a few centuries, mainly because the chemistry of CO_2 in seawater is well known. We present results from a coupled carbon cycle model (including deep-sea sediments) to address this issue. Our results provide specific constraints on future CO_2 emissions, if a shift in surface ocean pH and carbonate saturation state beyond a given threshold is to be avoided. Our projected changes in ocean carbonate chemistry should serve as a guideline for policy protocols that identify CO_2 emission targets to reduce the effects of man-made ocean acidification.

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[2]Earth and Planetary Sciences Dept., UCSC, Santa Cruz, CA 95060, USA.
[3]Department of Global Ecology, Carnegie Institution, Stanford, CA 94305, USA. [4]National Oceanography Centre, Southampton University, European Way, Southampton, SO14 3ZH, U.K.

HIGH VULNERABILITY OF EASTERN BOUNDARY UPWELLING SYSTEMS TO OCEAN ACIDIFICATION [C]

Gruber, Nicolas[1], Hartmut Frenzel[2], Claudine Hauri[1], Zouhair Lachkar[1], and Gian-Kasper Plattner[1]

Eastern Boundary Upwelling Systems (EBUS), such as the California or Canary Current Systems are particularly sensitive to ocean acidification as their pH is already low and their change in pH for a given uptake of anthropogenic CO_2 is particularly high. This is mostly a consequence of the upwelling of waters with low pH and high concentrations of dissolved inorganic carbon in the absence of high alkalinity, i.e. waters with very low carbonate ion concentrations. This effect is particularly strong in the Pacific Ocean, as evidenced by the dramatic shoaling of the aragonite saturation horizon off the U.S. West Coast to depths of less than 100 m as recently reported in the literature. We investigate this high vulnerability to ocean acidification of EBUS by conducting eddy-resolving simulations with the Regional Oceanic Modeling System (ROMS) coupled to a state-of-the art ecosystem model for three of the four major EBUS, namely the California, the Canary, and the Humboldt Current Systems. We will investigate the past, present and future changes in pH, $CaCO_3$ saturation horizons, and other biogeochemical and ecological processes in response to elevated atmospheric CO_2 using the observed atmospheric CO_2 record over the historical period and prescribing a business as usual emission scenario over the 21st century. A particular focus of our analyses is on the rate of change and on the timing when critical thresholds will be passed in the different EBUS, e.g. when the aragonite saturation horizon will enter the euphotic zone.

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IMPACTS ON BENTHIC AND PELAGIC CALCIFIERS

IMPACT OF OCEAN ACIDIFICATION ON BENTHIC ORGANISMS [I]

Gattuso, Jean-Pierre[1]

The response of marine organisms to ocean acidification was first investigated using perturbation experiments on benthic organisms (tropical coralline algae and corals). At the time of the 1st meeting on "The Oceans in a High-CO2 World" (2004), very little information on the response of benthic organisms to environmentally relevant pH or pCO2 levels was available, except on corals and, to a lesser extent, echinoderms. Only one study had examined the interaction between elevated pCO2 and temperature. Calcification and net primary production were, by far, the main processes investigated.
This presentation will briefly summarize the current knowledge on the response of benthic organisms, highlight the progress made since 2004 and will point to research gaps. The new studies generally confirm the overwhelming evidence that calcification of almost all organisms assayed decreases at low pH/high pCO2. Among the new information now available is the effects on other processes, mostly physiological processes such as immune responses, new or additional organisms (seagrasses, molluscs, echinoderms, benthic foraminifera), larval stages (molluscs), and ecological processes such as recruitment (coralline algae) and predator-prey relationships (between a mollusk and a macroalga). An innovative development is the recent use of natural changes in the carbonate chemistry, resulting from diurnal patterns or occurring in areas naturally enriched in CO2, to investigate the impact of ocean acidification at organism and community levels. Calcification and dissolution of CaCO3 remain the processes the investigated the most and very few other processes have been considered.

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POORLY CEMENTED CORAL REEFS OF THE EASTERN TROPICAL PACIFIC: POSSIBLE INSIGHTS INTO REEF DEVELOPMENT IN A HIGH-CO_2 WORLD [C]

Manzello, Derek P.[1], Joan A. Kleypas[2], David A. Budd[3], C. Mark Eakin[4], Peter W. Glynn[5], and Chris Langdon[5]

Ocean acidification describes the progressive, global reduction in seawater pH that is currently underway due to the accelerating oceanic uptake of atmospheric CO_2. Acidification is expected to reduce coral reef calcification and increase reef dissolution. Inorganic cementation in reefs describes the precipitation of $CaCO_3$ that acts to bind framework components and occlude porosity. Little is known about the effects of ocean acidification on reef cementation and whether changes in

cementation rates will affect reef resistance to erosion. Coral reefs of the eastern tropical Pacific (ETP) are poorly developed and subject to rapid bioerosion. Upwelling processes mix cool, sub-thermocline waters with elevated pCO_2 (the partial pressure of CO_2) and nutrients into the surface layers throughout the ETP. Concerns about ocean acidification have led to the suggestion that this region of naturally low pH waters may serve as a model of coral reef development in a high-CO_2 world. We analyzed seawater chemistry and reef framework samples from multiple reef sites in the ETP and found that a low carbonate saturation state (Ω) and trace abundances of cement are characteristic of these reefs. These low cement abundances may be a factor in the high bioerosion rates previously reported for ETP reefs, although elevated nutrients in upwelled waters may also be limiting cementation and/or stimulating bioerosion. ETP reefs represent a real-world example of coral reef growth in low-Ω waters that provide insights into how the biological-geological interface of coral reef ecosystems will change in a high-CO_2 world.

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THE IMPACT OF OCEAN ACIDIFICATION AND TEMPERATURE ON THE REPRODUCTION AND DEVELOPMENT OF OYSTERS AND THE POTENTIAL OF GENETIC DIFFERENCES TO AMELIORATE CLIMATE CHANGE [C]

Parker, Laura M.[1], Pauline M Ross[1] and Wayne A. O'Connor[2]

Studies have found that elevations in atmospheric carbon dioxide (CO_2), predicted as early as 2065, are expected to have impacts on organisms in oceanic environments. While studies have investigated the effect of elevated pCO_2 on the calcification of adult marine organisms, less is known about the effect of elevated pCO_2 and temperature on the early life history stages nor their synergistic effect We examined the synergistic effect of elevated pCO_2 (375, 600, 750 and 1000 ppm) and temperature (18, 22, 26 and 30°C) on the fertilisation and embryonic development of the Sydney Rock Oyster *Saccostrea glomerata* (Gould, 1850) and the Pacific Oyster *Crassostrea gigas* and determined whether there were genetic differences which may have the potential to ameliorate the impacts of climate change. Overall as pCO_2 increased, fertilisation decreased. The temperature of 26°C was the optimum temperature for fertilisation, as temperature increased and decreased from this optimum, fertilisation decreased. There was also an effect of pCO_2 and temperature on embryonic development. Generally as pCO_2 increased, the percentage and size of D-veligers decreased and the percentage of D-veligers that were abnormal increased. *S. glomerata* spat from mass selected and pair mated fast growth lines were reared at ambient (present concentration: 375 ppm) and elevated CO_2 (1000 ppm). There were significant differences in the growth of selected lines of *S. glomerata* between elevated and ambient CO_2. This research provides preliminary data that selective breeding of *S. glomerata* and other estuarine molluscs, maybe a potential strategy to overcoming impacts of climate change.

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LATITUDINAL VARIATION IN CALCIFICATION: VULNERABILITY OF ANTARCTIC BENTHIC CALCIFIERS TO OCEAN ACIDIFICATION [C]

Watson, Sue-Ann[1], Paul A. Tyler[1] and Lloyd S. Peck[2]

Heavily calcified marine animals such as molluscs, brachiopods and echinoderms have essential roles in ocean ecosystems and contribute to a large proportion of the total biomass in Antarctic benthic communities. How will these heavily calcified animals cope in a high-CO_2 world? Ocean acidification caused by anthropogenic CO_2 emissions will affect the ability of these calcareous organisms to build their shells and skeletons, particularly in the polar oceans where even modest CO_2 emission scenarios predict aragonite structures will enter a dissolution state by 2100. In order to assess the likely effects of ocean acidification on these calcareous invertebrates, we present data from polar, temperate and tropical latitudes on shell and skeleton size, calcium carbonate crystal form and elemental composition. Metabolic data were used to calculate the cost of shell production and wavelength dispersive spectroscopy was used to determine variation in shell composition between latitudes. Results show Antarctic snails, brachiopods and sea urchins have thinner shells and less shell per unit body mass than closely related temperate and tropical species. Scanning electron microscope imaging of crystal type shows shells of Antarctic bivalves and gastropods are composed predominately of aragonite. Having a smaller, more soluble shell raises particular concern for Antarctic molluscs as a reduction in shell deposition could increase their vulnerability to predation.

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IMPACTS OF OCEAN ACIDIFICATION ON CALCAREOUS ZOOPLANKTON [I]

Fabry, Victoria J.[1], Stephen Eggins[2], Bärbel Hönisch[3], Fabien Lombard[4], and Howard J. Spero[5]

Oceanic uptake of anthropogenic CO_2 is changing the seawater chemistry of the world's oceans towards reduced pH conditions, with profound consequences for many marine organisms. Marine zooplankton are fundamental to food webs, carbon dynamics, nutrient recycling and other ecosystem processes, yet little information exists on the response of many groups of these heterotrophs to elevated PCO_2. Increased PCO_2 in seawater can impact marine zooplankton both via decreased calcium carbonate saturation state, which may affect rates of shell secretion and dissolution, and via physiological processes involving acid-base reactions. Evidence suggests that two important groups of calcareous heterotrophs — the aragonitic pteropod molluscs and calcitic planktonic foraminifers — are sensitive to elevated PCO_2/reduced pH conditions. Only three species of these groups have been examined, however, and no direct measurements of calcification rates as a function of calcium carbonate saturation state are available. Shelled pteropods in the Southern Ocean are thought to be particularly at risk from ocean acidification because surface waters in that region may become persistently undersaturated with respect to aragonite as early as 2050. This presentation will focus on planktonic foraminifers and euthecosomatous pteropods. The available data will be summarized and new observations will be discussed to assess the potential impacts of present and projected changes in ocean carbonate chemistry on foraminifer and pteropod calcification rates. Critical knowledge gaps will be identified and directions for future research will be suggested.

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INTERANNUAL VARIABILITY OF PTEROPOD SHELL WEIGHTS IN THE HIGH-CO_2 SOUTHERN OCEAN [C]

Roberts, Donna[1], William R. Howard[1], Andrew D. Moy[1], Jason L. Roberts[1,2], Thomas W. Trull[1,3,4], Stephen G. Bray[1] and Russell R. Hopcroft[5]

Anthropogenic CO_2 added to the atmosphere during and since the industrial revolution is entering the global ocean. Addition of extra (anthropogenic) CO_2 to the ocean changes the carbonate chemistry and the pH of the surface ocean, decreasing the concentration of carbonate ions and increasing ocean acidity. The ecological effects of changing ocean carbonate chemistry are uncertain, but are believed to include reductions in the calcification rates of marine organisms such as shelled pteropods.
The Southern Ocean contains a disproportionate amount of the oceanic inventory of anthropogenic CO_2, making it a biogeochemical harbinger for the impacts of ocean acidification, which may spread throughout the global ocean and might be expected to contain some of the first signals of impacts of increasing atmospheric CO_2.
Through an *in situ* sustained monitoring sediment trap deployed at 47°S in the deep (2000 m) Southern Ocean we've measured a significant drop in shell weight of a common cold-water Southern Ocean pteropod, *Limacina helicina antarctica* forma *antarctica*, of 1.17 ± 0.47 µg yr^{-1} since 1997/98. With increasing levels of CO_2 entering the Southern Ocean the potential for further shell weight loss for this, and other, cold-water marine calcifiers could result in the change of distribution or complete removal of keystone species from the Southern Ocean ecosystem.

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OCEAN CARBON SYSTEM: PAST & PRESENT

CONTROLS ON EVOLUTION OF OCEAN CARBONATE CHEMISTRY OVER THE PAST BILLION YEARS [I]

Caldeira, Ken

On time-scales that are long relative to the residence time, whatever materials enter the oceans (e.g., CO_2 from volcanoes etc, Ca^{2+} in rivers from rock weathering) must be balanced by materials deposited to the sediments. On long timer scales (> 10^4 yr), the carbonate mineral saturation states of the ocean adjust to supply $CaCO_3$ to the sediments at the rate needed to balance inputs. The future high CO_2 ocean will be less saturated than today's whereas those of the extended high CO_2 (and high weathering rate) periods of the ancient past were likely more saturated. I will describe results of various methods to estimate past ocean chemistry, including both modeling and more observationally based approaches. Qualitative trends in paleo-ocean chemistry are clear, but quantitatively uncertain. The trend through evolutionary time is towards more efficient calcifiers, which would likely result in decreasing ocean saturation states. Thus, the ocean of the distant past it is likely to have been more saturated with respect to carbonate minerals than was the modern ocean. If current carbon dioxide emissions trends are not reversed, surface ocean pH will be lower than it has been in at least tens of millions of years and perhaps hundreds of millions of years. If these trends are not reversed, later this century ocean carbonate mineral saturation states could be lower than at any time in the past billion years with the exception of rare catastrophic events in Earth history such as the extinction events 65 and 250 myr ago.

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BORON ISOTOPE EVIDENCE OF OCEAN ACIDIFICATION IN THE NEOPROTEROZOIC [C]

Kasemann, Simone A.[1], Anthony R. Prave[2] and Anthony E. Fallick[3]

The Neoproterozoic is a period of exceptional Earth System change marked by extreme fluctuations from icehouse to greenhouse climatic conditions. These severe environmental changes are preserved in the geological record of warm water carbonates sharply overlying glaciogenic strata. In concert with the environmental changes, the carbonate rocks display large amplitude fluctuations in their stable isotopic composition. These fluctuations are stratigraphically systematic, occur in many sections worldwide and are interpreted as being globally significant. Thus, the Neoproterozoic carbonates provide a unique geological and isotopic archive to improve our understanding of major non-anthropogenically influenced changes in Earth System behaviour.
The most intriguing isotopic signal is a characteristic negative C-isotopic excursion (down to -6 ‰). This signal has been used to assess atmospheric pCO_2, organic productivity and carbon cycling during the extreme Earth System changes. Because of the relationship between carbonate $\delta^{13}C$, pCO_2, ocean acidification and B isotopic composition of seawater, we analysed Neoproterozoic carbonates to obtain their B-isotopic signature and reconstruct ocean pH variation. We collected a B-C-O isotopic dataset on postglacial cap carbonates from two discrete glacial intervals in Namibia (~750-630 Ma). Systematic B-isotope excursions (up to 9‰) in the postglacial carbonates appear to be associated with fluctuations in atmospheric pCO_2 and changing weathering rates and can be interpreted as directly reflecting periods of acidification of the surface ocean. These data provide new insights into the nature of the initiation and termination of Neoproterozoic glaciations and into the B-isotopic composition of ancient oceans.

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REDUCED CALCIFICATION IN MODERN SOUTHERN OCEAN PLANKTONIC FORAMINIFERA [C]

Moy, Andrew D.[1, 2], William R. Howard[1], Stephen Bray[1] and Tom Trull[1, 3, 4]

Laboratory experiments suggest that decreased ocean carbonate-ion concentrations due to anthropogenic CO_2 will result in reduced calcification rates in marine calcareous organisms. Here we use sediment trap and Holocene sediment evidence to show reduced calcification in Southern Ocean planktonic foraminifera since the industrial revolution. Our sediment trap results provide the first field observations for reduced calcification (inferred from planktonic foraminiferal shell weights) in Southern Ocean carbonate organisms and indicate there has been a 30-34% reduction in calcification (in the planktonic foraminifer *Globigerina bulloides*) , consistent with the impact due to altered ocean chemistry resulting from anthropogenic CO_2 storage. Down-core shell weight variations show reduced calcification during glacial-interglacial CO_2 increases that are similar to the post-industrial increase. Planktonic foraminifera contribute ~23 – 50 % of the total open-marine carbonate flux in the modern ocean, thus a reduction in the calcification of planktonic foraminifera may imply a corresponding decrease in calcium carbonate export from the surface ocean.

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CURRENT RATES OF CHANGE IN PH AND CALCIUM CARBONATE SATURATION IN THE HIGH LATITUDE NORTH ATLANTIC OCEAN [C]

Olafsson, Jon[1], Solveig R. Olafsdottir[1], Alice Benoit-Cattin[1], Magnus Danielsen[1] and Taro Takahashi[2]

The rates of change in pH and calcium carbonate saturation are evaluated from observations at two time series stations in the vicinity of Iceland over the period 1983-2006. One station is in the northern Irminger Sea with relatively warm and saline Modified North Atlantic Water derived from the North Atlantic Current. The other is in the Iceland Sea where cold Arctic Intermediate Water usually predominates but the Polar Water influence in the surface layers is variable. These are source regions of the North Atlantic Deep Water. The pH and values were calculated from TCO2 and pCO2 observations.
Seasonal surface water observations show large variations on account of biological productivity, respiration and mixing. For pH the observed seasonal range in the Irminger Sea is 0.17 and for the Iceland Sea it is 0.23 pH units.
Winter observations, when biological activity is at seasonal minimum, show that the local rates of pH change are for the Irminger Sea $-0.0012\ yr^{-1}$ and $-0.0025\ yr^{-1}$ for the Iceland Sea. We show that the influence of hydrographic variability, e.g. temperature, on pH and calcium carbonate saturation must also be considered. The rates of change in calcium carbonate saturation decrease with depth in the Iceland Sea. However, at about 1800 m depth there the aragonite saturation is in transition to a state of undersaturation. Considering the hypsographic characteristics of the Iceland Sea, this transition may influence large areas of the sea floor.

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LOW WINTER $CACO_3$ SATURATION IN THE BALTIC SEA AND CONSEQUENCES FOR CALCIFIERS [C]

Tyrrell, Toby[1] and Bernd Schneider[2]

We should attempt to understand the consequences of ocean acidification through a variety of techniques: not only through laboratory and mesocosm experiments but also through field observations of living communities in low pH (low saturation state) environments. Such observations are likely to be most useful when made in extreme environments that resemble in at least some regard the acidification-related changes predicted for the future.
Carbonate chemistry measurements in the Baltic Sea show that in winter it experiences the lowest surface saturation states yet observed for any ocean or sea region; the central Baltic Sea is undersaturated with respect to aragonite and borderline undersaturated ($\Omega \approx 1$) with respect to calcite. CaCO3 saturation state is even lower in the northern parts of the Baltic Sea. We will discuss the success or failure of some calcifying organisms (with particular emphasis on coccolithophores) to cope with this winter undersaturation, and the implications for their likely fate in a future more acidic ocean.

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EFFECTS OF OCEAN ACIDIFICATION ON NUTRIENT AND METAL SPECIATION

EFFECTS OF CHANGES IN CARBONATE CHEMISTRY ON NUTRIENT AND METAL SPECIATION [I]

De Baar, Hein[1,2], Loes Gerringa[2] and Charles-Edouard Thuroczy[2]

Ocean ecosystems tend to be limited due to limited availability for biological uptake of major nutrients (N, P, Si) and trace nutrients (Fe, Zn, Co, Mn, Cu, Cd) essential for life. Until recently the essential major element carbon (C) was deemed to be available in excess, but since about one decade we realize its chemical speciation (HCO_3^-, CO_3^{2-}) does affect uptake and growth by phytoplankton. Similarly the major nutrients P and Si exist as weak acids in seawater, with their chemical speciation depending on the ambient pH. Hence the ongoing acidification of surface ocean waters due to invasion of anthropogenic CO_2 will affect their chemical speciation, and this in turn may, or may not, affect their uptake by phytoplankton.
The chemical speciation hence biological availability of all trace nutrients (Fe, Zn, Co, Mn, Cu, Cd) is affected by the ongoing change in ocean carbonate chemistry, both directly in their speciation with HCO_3^- and CO_3^{2-} but even more indirectly due to the acidification, the latter also affecting the oxidation/reduction chemistry of crucial elements Fe, Co and Mn. Iron (Fe) is the dominant limiting nutrient in circa 40% of the world oceans, and therefore is of most interest, but happens to have a very complicated and dynamic chemistry in seawater, including its strong organic complexation. Moreover there is the formation and dissolution of Fe-colloids which in themselves are deemed unavailable for uptake by plankton. Ocean acidification affects both the organic complexation and the colloid state of Fe in seawater.

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OCEAN ACIDIFICATION EFFECTS ON IRON SPECIATION IN SEAWATER [C]

Breitbarth, Eike[1, 2], Richard J. Bellerby[2], Craig C. Neill[2], Murat V. Ardelan[3], Michael Meyerhöfer[4], Eckart Zöllner[4], Peter L. Croot[4], and Ulf Riebesell[4]

The changing pH of seawater may influence the speciation of bio-relevant trace metals in the future oceans. We investigated the consequences of ocean acidification in coastal mesocosm CO_2 perturbation experiments, studying natural phytoplankton blooms under atmospheric CO_2 scenarios of 350, 700, and 1050 µatm pCO_2. Our experiments show significant increases in dissolved iron (<0.2 µm) concentrations for the high CO_2 treatments during and after the blooms. Furthermore, the future ocean scenarios revealed higher Fe^{2+} values than the lower CO_2 treatments. Our findings suggest that biological feedback mechanisms in the future scenarios result in increased organic complexation of iron and thus increase the dissolved fraction of iron. Iron chelates are more photolabile at lower pH and together with slowed Fe^{2+} oxidation rates result in the increased Fe^{2+} concentrations. These trends may lead to higher iron bioavailability and could thus provide a negative feedback mechanism to the rising atmospheric CO_2 by fuelling primary production in the future ocean. This may be particularly relevant, if the mechanisms observed here also apply to currently iron limited open ocean high nutrient low chlorophyll (HNLC) regions.

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DAY 2: TUESDAY, 7 OCTOBER

MECHANISMS OF CALCIFICATION

BIOMINERALIZATION MECHANISMS IN MARINE CALCIFYERS IN VIEW OF OCEAN ACIDIFICATION [I]

Erez, Jonathan, Shmuel Bentov, Alon Braun, Mor Grinstein, Jack Silverman, Kenneth Schneider, and Boaz Lazar

Biomineralization of $CaCO_3$ is major process in the global carbon cycle. The major calcifyers in the ocean are Coccolithophores, foraminifera, corals and mollusks. Atmospheric CO_2 increase lowers the pH of the surface ocean and consequently the carbonate ion concentration is decreasing. While reports are conflicting with respect to coccolithophores, experiments and observations on corals and foraminifera show dramatic decrease in the rates of calcification with lower carbonate ion concentrations. This is also true for community calcification of an entire coral reef ecosystem.The sensitivity of corals and foraminifera to ocean acidification can be readily explained because both groups bring seawater to the site of biomineralization. Using confocal microscopy we found that in foraminifera, seawater is supplied to the biomineralization site by vacuolization . In corals we can demonstrate that cell-impermeable fluorescent probes (Calcein and FITC-dextran) added to the seawater are incorporated into the growing coral skeleton, suggesting the presence of seawater at the calicoblastic space. While the exact mechanism for the seawater supply is unknown, it may be associated with paracellular pathways, or gaps between the tissue and the porous skeleton. In both groups the main modification that the organisms exert on the seawater in order to calcify is elevation of pH by roughly 1 pH unit relative to ambient levels. Ocean acidification increases the pH elevation gap as well as the buffer capacity of the seawater, thus even a small pH decrease of 0.2-0.3 pH units is strongly affecting the calcification rates. Implications for other groups will be discussed.

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EFFECT OF ACIDIFICATION ON CORAL CALCIFICATION: WORKING HYPOTHESES TOWARDS A PHYSIOLOGICAL MECHANISM [C]

Marubini, Francesca, Denis Allemand and Christine Ferrier-Pagès

In order to determine what are the factors involved in the seawater acidification-induced decrease of coral calcification, we assessed the effect of seawater acidification on the calcification and photosynthesis of the scleractinian tropical coral *Stylophora pistillata in different physico-chemical conditions*. Coral nubbins were incubated for 8 days at three different pH (7.6, 8.0 and 8.2) obtained by adding HCl or NaOH. For each pH, corals were maintained under bicarbonate-ambient (2 mM) and bicarbonate-enriched (4 mM) conditions. Bicarbonate-enriched condition was achieved by adding into the tanks 2 mM bicarbonate (HCO_3^-) using a peristaltic pump. Photosynthesis of *S. pistillata* was insensitive to changes in pH and pCO_2, but was increased in the tanks enriched with 2 mM HCO_3^-, suggesting carbon-limited conditions. Seawater acidification decreased coral calcification by ca. 0.1 mg $CaCO_3$ g^{-1} d^{-1} for a decrease of 0.1 pH units. As previously shown, decrease in calcification was correlated with a decrease in the availability of the CO_3^{2-} substrate, and thus a decrease in the saturation state, W. However, our results show that the decrease in coral calcification could also be attributed either to a decrease in extra-or intracellular pH or to a change in the buffering capacity of the medium, impairing supply of CO_3^{2-} from HCO_3^-.

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PREDICTION OF CARBON FIXATION DURING A BLOOM OF EMILIANIA HUXLEYI IS HIGHLY SENSITIVE TO ASSUMED RESPONSE TO SHIFT IN pCO_2 [C]

Bernard, O.[1], A.Sciandra[2] and S.Rabouille[2]

Large scale precipitation of calcium carbonate in the oceans by coccolithophorids is a phenomenon that plays an important role in carbon sequestration. However, there is a controversy on the effect of an increase in atmospheric CO_2 concentration on both calcification and photosynthesis of coccolithophorids. Indeed recent experiments, performed in conditions of nitrogen limitation, revealed that the associated fluxes may be slowed down, while other authors claim the reverse response. We have designed models to account for various scenarii of calcification and photosynthesis regulation in chemostat cultures of *Emiliania huxleyi*, based on different hypotheses of regulation mechanism. These models, which are kept at a general and generic level, consider that either carbon dioxide, bicarbonate, carbonate or pH is the regulating factor. These models are calibrated to predict the same carbon fluxes in nowadays pCO_2, but they turn out to respond differently to an increase of CO_2 concentration. Thus, we simulated a bloom of *Emiliania huxleyi* using the 4 considered regulation scenarii. For high biomass concentration, the coccolithophorids can significantly affect the inorganic carbon and the pH in their environment, thus leading to a feedback in their growth rate which is, depending on the model, positive or negative. It results that the prediction of the carbon fixed during the bloom varies by a factor 2, depending on the assumed regulating mechanism hypothesized for growth and calcification.

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PHYSIOLOGICAL EFFECTS: FROM MICROBES TO FISH

PHYSIOLOGICAL MECHANISMS LINKING CLIMATE TO ECOSYSTEM CHANGE: EFFECTS OF OCEAN ACIDIFICATION ON MARINE ANIMALS IN TIMES OF OCEAN WARMING [I]

Pörtner, Hans O.

Climate change causes ocean warming and acidification on global scales. In contrast to well established effects of warming on marine ecosystems, specific effects of rising CO_2 are expected but evidence is still equivocal. However, future scenarios indicate a threatening of marine life through the specific or synergistic effects of rising CO_2 levels, warming and more frequent hypoxia events. Beyond empirical observations, development of a cause and effect understanding and of realistic scenarios is required for a secure projection of ecosystem effects. Such understanding builds on the identification of key physiological mechanisms and their responses to progressive acidification, warming and hypoxia. In changing oceans, these are physiological characters which define species performance, including their capacity to interact, e.g. in food webs. Many current ecosystem changes likely occur when ambient temperature drifts beyond species specific thermal tolerance windows and causes a shift in phenology. Specific sensitivity to elevated CO_2 levels may involve a key role for acid-base regulation, with low capacities found in lower marine invertebrates. Extracellular acid-base status feeds back on the costs of ion and acid-base regulation, on processes involved in growth, on calcification, neural functions, blood gas transport or behavioural capacities. The capacities of metabolic pathways shift to new equilibria. Present evidence indicates elevated sensitivity to elevated CO_2 levels towards the edges of thermal windows. The key consequence may be a narrowing of thermal tolerance windows and associated ranges of geographical distribution, of the scope for performance at ecosystem level and thus, an exacerbation of warming effects on marine ecosystems.

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IMPACTS OF OCEAN CHANGE ON PRIMARY PRODUCERS [I]

Riebesell, Ulf

Rising atmospheric CO_2 and the resulting climate change cause the ocean to undergo two major alterations: sea surface warming and ocean acidification/carbonation. While there is strong evidence that both of these changes are in progress at an ocean-wide scale, little is known about their individual and combined effects on the marine biota. Hence, our ability to forecast the resulting impacts on ocean productivity, elemental cycling and air/sea exchange is rudimentary and model scenarios of future ocean changes are mostly based on simplifying concepts of possible ecosystem and biogeochemical alterations.
Despite much uncertainty about the impacts on marine biota, there is growing evidence that there will be both winners and losers of ocean carbonation (increasing pCO_2) and acidification (decreasing pH). Calcareous organisms will for the most part be on the losing side as increasing seawater acidification incurs a greater metabolic energy requirement to precipitate calcium carbonate. Some photoautotrophic groups are likely to be on the winning side as increasing ocean carbonation makes it energetically less expensive to obtain the CO_2 required for photosynthesis. In addition, sea surface warming effects marine biota both directly, due to the strong temperature sensitivity of most biological processes, and indirectly through changes in surface layer stratification, overturning circulation, and the resulting effects on nutrient supply and light intensities. This presentation will review the observed biotic responses in pelagic systems and assess their possible impacts on ocean productivity, biogeochemical cycling and their feedback potential to the climate system.

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CO2 LEAKAGE IN THE DEEP OCEAN AND ITS EFFECT ON BIOTA AND BIOGEOCHEMISTRY – LESSONS FROM NATURAL ANALOGUES ON CO_2 DISPOSAL IN THE OCEAN [I]

Boetius, Antje[1,2], Dirk de Beer[1], Judith Ufkes[1], Matthias Haeckel[3], Fumio Inagaki[4], Koichi Nakamura[5], Gregor Rehder[6]

One of the future strategies to deal with excess CO_2 in the atmosphere is its disposal and storage in the ocean. The environmental risks of this mitigation strategy are not well constrained. Critical questions to any disposal scenario are as to the tipping points at which endemic species are affected by increasing pCO_2 and decreasing pH, and as to the threshold for CO_2 leakage from the seafloor to prevent negative effects on biodiversity and ecosystem services. During a recent expedition with FS SONNE and ROV QUEST to the Okinawa Trough we have investigated the potential effects of natural CO_2 leakage on deep-water benthic ecosystems at 1350 m water depth. At the Yonaguni Knoll vent system, volcanic CO_2 emissions lower the pH of the bottom water down to 7.2, with dramatic effects on megafauna distribution and composition. Furthermore, subsurface accumulations of liquid CO_2 cause a decrease in pH down to pH 4.5 in the ocean seafloor, altering considerably biogeochemical processes in the sediments and affecting microbial communities. This presentation discusses direct and indirect effects of CO_2 accumulation and leakage on deep-water ecosystems and relevant biogeochemical processes.

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EFFECTS OF HYPERCAPNIC ACIDIFICATION OF SEAWATER ON THE BIOLOGY OF NON-CALCIFYING MARINE ORGANISMS [C]

Thuesen Erik V.[1] and Brad A. Seibel[2]

Human activity is quickly increasing the carbon dioxide concentration (PCO_2) in the Earth's atmosphere, resulting not only in rapid climate change but an increase in the PCO_2 content of ocean waters above normal levels, a condition know as hypercapnia that leads to a decrease in the pH of seawater. The acidification of ocean waters due to hypercapnia can have extensive effects on marine life. For example, snails and bivalves may not be able to maintain their calcified shells and calcium carbonate reefs may dissolve due to the equilibrium shifts in the carbonate in seawater. For non-calcifying organisms, a whole other suite of problems may occur. This presentation reviews the potential effects of hypercapnic acidification on biological processes not related to calcification. It has been proposed that animals with lower metabolic potentials will be the most challenged by declining ocean pH because they lack adequate buffering systems and ion exchange mechanisms to cope with intracellular acidosis promoted by extracellular hypercapnia. Other examples include the following: increased metabolic cost to maintain intracellular pH, lower protein synthesis and decreased growth rates, proper function of transmembrane proteins, the production and function of mucus, cell-cell signaling. These and other biological impacts are reviewed and mechanistic models are presented in order to begin to prioritize productive areas of research into the effects of ocean acidification on non-calcifying marine organisms.

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PREDICTING THE IMPACT OF OCEAN ACIDIFICATION ON BENTHIC BIODIVERSITY: WHAT CAN ANIMAL PHYSIOLOGY TELL US? [C]

Widdicombe, Stephen[1] and John I. Spicer[2]

For the past 200 years, the oceans have been absorbing carbon dioxide at an unprecidented rate. It is now evident that this ongoing process has already significantly altered seawater carbon chemistry at a global scale and will continue to do so for hundreds of years to come; a phenomenon termed “ocean acidification”. The challenge currently facing scientists is to predict the long term implications of ocean acidification for the diversity of marine organisms and for the ecosystem functions this diversity sustains. This challenge is all the more difficult considering that empirical data which specifically address the impact of ocean acidification on marine biodiversity are currently lacking. In the face of growing political and public pressure to provide answers, what predictions can be made and how reliable are the assumptions on which those predictions depend? Here we review the extent to which the few existing data, and understanding gained from previous physiological studies, can be used to make predictions for marine biodiversity. In doing so we also scrutinise some established paradigms concerning the impact of hypercapnia, resulting in seawater acidification, on marine organisms.

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FISHERIES, FOOD WEBS, AND ECOSYSTEM IMPACTS (PICES-ICES SESSION)

CONSEQUENCES OF OCEAN ACIDIFICATION FOR FISHERIES [I]

Fosså, Jan Helge[1], Richard Bellerby[2] and Tore Jakobsen[1]

The distribution of major fisheries is compared with model predictions of pH change in different regions of the world ocean to identify fisheries in ecosystems that may be affected by a change in ocean chemistry and associated biogeochemical and ecological change. The potential impact of ocean acidification on marine fish will be assessed by reviewing how higher seawater CO_2, and associated changes to the marine carbonate system, can affect, both directly and indirectly, the reproduction, growth and mortality of fish populations. Case studies of collapsed fish stocks will be presented to illustrate how a combined effect of environmental change and high fishing pressure can be detrimental to fish stocks and the fisheries that depend upon them.

There has been no direct research on the consequences of ocean acidification for fisheries. There is, however, growing evidence of effects of ocean acidification on important processes within marine ecosystem functioning and on key organisms in the marine food web. On this basis, potential impacts from ocean acidification on ecosystem structure and function related to the position of fish in the food webs will be discussed for a range of ecosystems, e.g. the Norwegian Sea, the Benguela upwelling system, and tropical coral reefs.

The main conclusion is that the threat from ocean acidification urgently calls for a fisheries management that aims at maintaining strong and robust fish stocks with minimum loss of genetic variation in order to secure maximum potential for adaptation to the expected and possibly irreversible changes in the environment.

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AN OCEAN ACIDIFICATION SIMULATION EXPERIMENT WITH BENTHIC ANIMALS USING A PRECISE PCO$_2$ CONTROL SYSTEM [I]

Nojiri, Yukihiro[1], Yoshihisa Shirayama[2], Hideshi Kimoto[3], Takeshi Egashira[3] and Katsumoto Kinoshita[3]

Japan started a research program entitled as 'Experimental study of ocean acidification impact on benthic calcifiers' funded for 2008-2010 by Ministry of Environment. In this program, precise CO_2 controlling system for culturing benthic calcifiers, such as sea urchin, shellfish and coral, will be operated to experiment the impact of CO_2 increase on the coastal benthic animals. Preliminary study and numerical consideration demonstrate difficulties in controlling seawater pCO_2 using a regular aquarium tank and gas bubbling. It is because of insufficient equilibration efficiency with several tens centimeters of bubbling height in the tank. In sufficient equilibration is especially enhanced when aquarium is maintained by overflowing water. Carrying CO_2 away by the overflowing water gives insufficient equilibration and then it needs very high equilibration sufficiency of bubbling air. In case the experiment is done without monitoring pCO_2 of the aquarium tank may give an artifact. We developed a new type of air-seawater equilibrator by combination of a 'counter current dissolution water tower (CCDWT)' and a 'measurement water tower (MWT)'. The system can produce seawater with target pCO_2 and record pCO_2 by a LICOR gas analyzer. Seawater having target pCO_2 can be supplied to an aquarium tank at around 20L/hour rate, which enables the turnover time of several hours for regular size tank. The system can simulate diurnal cycle of pCO_2, generally occurs in coastal area. Our culture experiment has been stared to research long term and low level exposure of CO_2 for benthic animal species in Japanese coastal environment.

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NATURAL CO_2 VENTS REVEAL ECOLOGICAL TIPPING POINTS DUE TO OCEAN ACIDIFICATION [C]

Hall-Spencer, Jason M. and Riccardo Rodolfo-Metalpa

Our understanding of how increased ocean acidity may affect marine ecosystems is currently severely hampered, since almost all studies have been in vitro, short-term, rapid perturbation experiments on isolated elements of the ecosystem. Here we show the effects of acidification on benthic ecosystems at shallow coastal sites where volcanic CO_2 vents lower the pH of the water column. Along gradients of normal pH (8.1-8.2) to lowered pH (mean 7.8-7.9), typical rocky shore communities with abundant calcareous organisms shifted dramatically to communities lacking scleractinian corals with significant reductions in sea urchin and coralline algal abundance. This is the first ecosystem-scale validation of predictions that these important groups of organisms are susceptible to elevated levels of pCO_2 and offers insights into community shifts to be expected in 2100 and beyond. Seagrass production peaked in an area at mean pH 7.6 (1827 µatm pCO_2) where coralline algae were eradicated and gastropod shells were dissolving due to periods of carbonate sub-saturation. Volcanic CO_2 vent sites reveal a suite of marine organisms that are resilient to naturally high levels of p CO_2, which would be difficult to predict using modelling and mesocosm approaches, and that ocean acidification may benefit highly invasive alien algal species. Our results provide the first in situ insights into how shallow water marine communities might change when susceptible organisms are removed due to ocean acidification.

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SALMON pHISHING IN THE NORTHEAST PACIFIC; AN ARCHAEOLOGICAL DIG IN THE NORTH PACIFIC SURVEY DATA (1956-1964) [C]

McKinnell, Skip[1], Kerim Aydin[2], Jim Christian[3], Nancy Davis[4], and David Mackas[3]

Pacific salmon eat pteropods; yet until the threat of a shoaling aragonite saturation level in the North Pacific emerged, scant attention was paid to where, when, in what quantities, and with what preference. This presentation provides a synoptic view of the distributions of pH, pteropods, and Pacific salmon and their diets in the North Pacific during the only period in history when all were surveyed simultaneously. Following the establishment of the International North Pacific Fisheries Commission in the mid-1950s, comprehensive, multi-vessel surveys of the physical, chemical, and biological oceanography, and the biology of Pacific salmon were conducted in the Gulf of Alaska for nearly a decade. The data include hydrographic and chemical profiles from hundreds of bottle casts, zooplankton tows, and 10,000 stomach samples analyzed for diet. These data have been lying fallow for decades and their resurrection facilitates the creation of baseline conditions at the beginning of the "Keeling Curve" that can serve as a basis for comparisons with recent and future samples.

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CO_2 DISPOSAL

EFFECTS OF CO_2 CAPTURE AND STORAGE ON OCEAN ACIDIFICATION [I]

Haugan, Peter M.

The presently ongoing ocean acidification is the result of global scale indirect ocean storage of CO_2 via emissions to the atmosphere. The ocean uptake reduces the immediate greenhouse forcing on climate, but may increase stress on ocean ecosystems. In addition to this unintended indirect ocean storage, schemes for capture of CO_2 primarily from fossil fuel power plants and direct storage in the ocean or in geological reservoirs (CCS), have recently gained substantial support. The main aim of this paper is to provide a review of such schemes and discuss their possible future impact on local and large scale ocean acidification as well as global carbon cycling and climate.

Recent changes in global and regional conventions and regional and national legislation have opened up possibilities for direct storage of CO_2 in geological reservoirs on land or underneath the seabed on continental shelves. A range of projects are approaching implementation. If CO_2 leaks from offshore storage sites, local acidification will be strong. Due to the energy penalty associated with capture, the amount of CO_2 stored will be higher than that vented to the atmosphere in the case of no capture. Some greenhouse warming can be avoided by CCS compared to emissions, but the risk of leakage remains, with implications for future acidification and climate effects. Uncertainties about geological storage in hot rocks where CO_2 is buoyant, suggests that alternative deep ocean seafloor storage options may be reconsidered. In that case mechanisms for spreading into the water column become crucial for acidification effects.

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MODELLING OF CO_2 DISPERSION LEAKED FROM SEAFLOOR OFF JAPANESE COAST [C]

Yuki Kano[1], Toru Sato[2], Jun Kita[3]

A numerical study was conducted to predict the rise of pCO_2 in the ocean on a continental shelf by the leakage of CO_2, which is originally stored in the aquifer under the seabed, in an extreme case, such as a large fault connects the CO_2 reservoir and the seabed accidentally by a big earthquake or other large diastrophism. The target space in this study was limited to the ocean above the seabed and does not include subsea underground. First, parameter studies were conducted in a small domain to see the impacts of CO2 leakage and seawater conditions. The CO_2 takes a form of bubbles or droplets, depending on the depth of water, and their behaviour and dissolution were numerically simulated during the rise in constant background flows perpendicular to the fault. Also simulated was the advection-diffusion of dissolved CO_2. Next, a more realistic case simulation was conducted with topography and tidal current at the offshore of a selected coast of Japan. As a result, it was suggested that the rises of CO_2 concentration were smaller than 500 ppm, even in such an extreme case with specific assumptions.

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DAY 3: WEDNESDAY, 8 OCTOBER

ADAPTATION AND MICROEVOLUTION

A BRIEF HISTORY OF SKELETONS IN THE OCEANS [I]
Knoll, Andrew H.

Eukaryotes existed for more than a billion years before the biomineralized skeletons entered the fossil record. Consistent with phylogenetic evidence for the widespread use of silica by protists, the earliest mineralized elements are chromalveolate and rhizarian scales in 750-800 Ma rocks. Carbonate and silica skeletons occur as part of Ediacaran animal diversification, but a relatively late and taxonomically limited part. In contrast, carbonate, phosphatic and siliceous skeletons all diversified markedly as part of the greater Cambrian radiation of animal life. By the mid-Ordovician Period, animal and benthic algal skeletons had come to play much the same biomechanical, ecological and biogeochemical roles they do today. But the course of skeletal evolution never did run smooth. A remarkable decline in skeletal abundance and diversity occurred at the end of the Permian Period (252 Ma), when mass extinction devastated marine ecosystems. Patterns of extinction versus survival match predictions informed by physiological research on hypercapnia; rapid imposition high P_{CO2} at a time when deep ocean water masses already tended toward dysoxia may explain this greatest of all extinction events. Other mass extinctions show differing biological patterns, suggesting that Permo-Triassic scenarios cannot be applied to all such events. Episodic crashes of hypercalcifiers (including reef builders), however, may reflect transient but repeated intervals of high P_{CO2} and deep water anoxia in the world's oceans. Deep ocean oxygen levels have rarely been higher than they are at present. In this respect, at least, the present day challenges of ocean acidification depart from some deep time analogs.

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INFLUENCE OF HIGH CO_2 ON COCCOLITHOPHORES UNDER LONG-TERM CULTIVATION
Müller, Marius N., Kai G. Schulz, Peter Wiebe, and Ulf Riebesell

Studies on the sensitivity of coccolithophores to elevated CO_2 have generally relied on relatively short-term incubations over <20 and in some cases <5 generations. A critical issue in the assessment of ocean acidification impacts on marine biota is the ability of CO_2/pH sensitive organisms to adapt to changing environmental conditions. To approach this question we have exposed three coccolithophore species to gradually increasing CO_2 concentrations over more than 140 generations, namely *Emiliania huxleyi* (max. pCO_2 1150 µatm), *Coccolithus pelagicus braarudii* (max. 930 µatm) and *Calcidiscus leptoporus quadriperforatus* (max. 740 µatm). All three species showed significant decreases in cellular division rates ranging from 10 to 30%, whereas organic matter production rates increased. Surprisingly, the increase of cellular organic matter was not reflected in an increase in cell diameter. In fact, *C. pelagicus braarudii* even shrank in size. Responses in cellular calcification rates were found to be species-specific as shown in previous studies. Whereas *C. pelagicus braarudii* reduced the calcification rate by 25 % and was covered with partly malformed coccoliths, an effect on *E. huxleyi* could not be detected due to high standard deviations. Additionally, we tested the effect of temperature in combination with high CO_2 on the performance of *Emiliania huxleyi*. Increased temperature amplified the decrease in cell division rate under high CO_2, but partly compensated the observed effect on calcification. These results are generally consistent with published data, but indicate a higher sensitivity of coccolithophores to ocean change than previously reported.

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NEW CONCERNS

IMPACT OF OCEAN ACIDIFICATION ON UNDERWATER SOUND: REDUCED LOW FREQUENCY ABSORPTION, INCREASED NOISE LEVELS, POTENTIALLY HIGHER STRESS FOR MARINE MAMMALS. [C]

Browning, David[1] and Peter M. Scheifele[2]

The principle absorption mechanism for low frequency, (<1,000 Hz), sound in the sea is a boron – boric acid reaction that is pH dependent. As a result, ocean acidification will reduce the low frequency sound absorption. To illustrate, the present difference between the average pH value in the ocean sound channel in the North Pacific Ocean (7.7) and that for the North Atlantic Ocean (8.0) results in the low frequency absorption being twice as large in the North Atlantic. Acidification will progress from the surface downward but since the dominant noise sources (shipping and wind wave generation) are also located at or near the surface, the impact on increasing noise levels should be starting also. As a result, marine mammals migrating at a shallow depth would be exposed to increasing noise levels which could potentially be a source of stress.

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EXPERIMENTAL APPROACHESOF CARBONATE CHEMISTRY MANIPULATION IN CO_2 PERTUBATION STUDIES [C]

Schulz, Kai G. and Ulf Riebesell

Invasion of anthropogenic carbon dioxide (CO_2) into the surface ocean alters the seawater carbonate chemistry, increasing CO_2 and bicarbonate (HCO−3) at the expense of carbonate ion concentrations. This redistribution in the dissolved inorganic carbon (DIC) pool decreases pH and carbonate saturation state (Ω). The latter, for instance, is thought to be a key variable determining calcium carbonate precipitation rates in many marine organisms such as coccolithophores, foraminifera and corals. The future survival of some marine ecosystems will rely on the success of calcifying organisms. Hence, more and more studies focus on the potential effects of changes in seawater carbonate chemistry on marine life. This requires accurate carbonate system manipulations and well controlled experimental setups. Here we describe and analyze the chemical consequences of increasing anthropogenic CO_2 in seawater. Furthermore we present several experimental approaches for carbonate chemistry manipulation, including acid/base, CO_2 and combined HCO−3 /acid additions, and compare their potential to simulate future ocean change. This will result in some fundamental guidelines for conducting CO_2 perturbation experiments.

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BIOGEOCHEMICAL CONSEQUENCES AND FEEDBACKS TO THE EARTH SYSTEM

BIOGEOCHEMICAL CONSEQUENCES OF OCEAN ACIDIFICATION [I]

Bopp, Laurent

In the past 200 years, the ocean has absorbed half of the CO_2 emitted by human activities. This uptake has clearly slowed down anthropogenic climate change but it has led to changes in the chemical equilibrium of seawater and to a reduction of seawater pH by 0.1 since pre-industrial times. With increasing CO_2 emissions in this century, ocean surface pH could decrease by another 0.2-0.4 in 2100.The impacts of ocean acidification on marine biogeochemistry are still poorly understood. But we can ask the questions of the potential large-scale biogeochemical consequences and the potential to feedback on climate of such chemical changes?
Several lab experiments and field studies have shown that acidification would affect calcification, and hence the equilibrium between calcifying and non-calcifying species. I will review here the potential effects that these changes would produce on air-sea CO_2 exchanges and dimethylsulfide (DMS) emissions to the atmosphere.
In addition to calcification, acidification is also believed to potentially impact organic matter production, N-fixation, metal speciation…. I will review the potential effects of some of those modifications on the large-scale biogeochemistry of the ocean and on air-sea CO_2 and N_2O exchanges.
In the last part, I will show how future climate change, mainly through changes of ocean circulation, could interact with acidification: dampening or amplifying acidification in the different regions of the world ocean but also amplifying or dampening some of the consequences of acidification

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DISSOLUTION OF $CaCO_3$ IN SHALLOW WATER CARBONATE ENVIRONMENTS IN THE HIGH CO_2 WORLD OF THE ANTHROPOCENE [C]

Andersson, Andreas J.[1], Fred T. Mackenzie[2], Nicholas R. Bates[1], Ilsa B. Kuffner[3], Abraham Lerman[4], Paul L. Jokiel[5], Ku'ulei S. Rogers[5], and Adrian Tan[2].

Acidification of surface seawater owing to fossil fuels and land use change CO_2 emissions has raised serious concerns as to its consequences for marine organisms and ecosystems, especially those organisms producing shells, tests or skeletons of calcium carbonate. The effects of increasing seawater CO_2 and decreasing pH and carbonate saturation state on the rate and the ability of calcifying organisms to produce calcium carbonate have received significant attention. Much less attention has been given to the effects on carbonate mineral dissolution, although it is well known that dissolution of carbonate minerals will increase as a result of decreasing seawater carbonate saturation state. Numerical modeling simulations using the Shallow-water Ocean Carbonate Model (SOCM) demonstrate that the rate of dissolution of carbonate minerals in the global coastal ocean could exceed the rate of calcification in this region within the next century. Similarly, observations from a carbonate dominated environment in Bermuda exposed to elevated levels of CO_2 similar to projections for the future show carbonate dissolution rates sufficiently high to exceed the average rate of calcification on coral reefs within the present century. Furthermore, results from a mesocosm experiment subject to seawater conditions anticipated by the year 2100, show evidence of a net loss of carbonate material at the ecosystem scale, but also at the scale of individual organisms including coralline algae. These robust findings from three independent studies demonstrate that ocean acidification can push shallow water ocean environments and even some calcifying organisms to a state of net dissolution of carbonate material.

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IMPACTS OF OCEAN ACIDIFICATION ON MARINE BIOGENIC TRACE GAS PRODUCTION [C]

Hopkins, Frances E.[1, 2], Suzanne M. Turner[1], Philip D. Nightingale[2], Michael Steinke[3], and Peter S. Liss[1]

The rapid and dramatic changes to ocean carbonate chemistry that will occur as result of ocean acidification are expected to have a detrimental impact on marine biological and biogeochemical processes. A potential consequence of this is that the sea-to-air flux of marine trace gases may be affected, which would impact on the oxidative capacity of the atmosphere, the production of particles in the marine boundary layer, air quality and climate. We have used three approaches to investigate whether trace gas production is affected by experimental changes in seawater pH: laboratory incubations of natural assemblages, a mesocosm experiment in Bergen, Norway, and a naturally-acidified coastal site in the Gulf of Naples, Italy. During the mesocosm experiment, the concentrations of a number of trace gases, including dimethyl sulphide (DMS) and volatile iodocarbon compounds, were significantly reduced under future atmospheric CO_2. We will present results from the recent fieldwork campaign in Italy, which will include an assessment of the suitability of the site as a model of the affects of future acidification on the pelagic community and associated biogeochemical processes.

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FROM LABORATORY MANIPULATIONS TO EARTH SYSTEM MODELS: AN 'EPPLEY CURVE' FOR CALCIFICATION RATE? [C]

Ridgwell, Andy [1], Daniela N. Schmidt [2], and Carol Turley [3]

The apparent incongruence between coccolithophore calcification responses observed across different experimental manipulations, particularly those involving *Emiliania huxleyi*, raises new challenges for modelers. This is because the global models used for predicting future fossil fuel CO_2 uptake by the ocean base their parameterizations for calcification closely on laboratory results. Predictions of such models will be unreliable if rooted in unrepresentative and/or poorly understood laboratory experiments.

To help address this, we have examined the specific details of available experimental manipulations. We find fundamental differences between laboratory culture studies, particularly in the strain (ecotype or likely even genotype) of *E. huxleyi* cultured. This, combined with the observations that: (1) experiments using other coccolithophore species have delineated the existence of a calcification 'optimum' in environmental conditions (*p*H), and (2) there is an unambiguous direction to the calcification-CO_2 response in mesocosm and shipboard incubations, lead us to propose a new formulation for describing ocean acidification impacts on planktonic marine carbonate production.

We suggest an equivalence can be drawn between species or even ecosystem integrated phytoplankton calcification rate as a function of *p*H (or saturation), and widely used descriptions of plankton growth rate vs. temperature (the Eppley curve). By doing so, we provide a conceptual framework for reconciling the results of available experimental manipulations of coccolithophores and a route-map to a simple quasi-empirical relationship for use in carbon cycle models. The implications of an 'Eppley' like calcification formulation for future fossil fuel CO_2 uptake are explored in the GENIE-1 Earth system model.

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DAY 4: THURSDAY, 9 OCTOBER

BEYOND NATURAL SCIENCE

A SCIENCE SUMMARY OF THE SYMPOSIUM [I]

Carol Turley, Plymouth Marine Laboratory, U.K.

AN ECONOMIC PERSPECTIVE ON OCEAN ACIDIFICATION AND ATMOSPHERIC CARBON DIOXIDE STABILISATION [I]

Held, Hermann and Ottmar Edenhofer

Ocean acidification represents one of the most significant impacts of a rising CO2 concentration in the atmosphere. Within the upcoming negotiations about a Post-2012 'global climate deal', it should therefore shift the balance towards further CO2 emission mitigation efforts. Here we condense the strain of arguments that are hampering stringent mitigation measures until today and that were academically overcome only recently, summarised in two major reviews: Stern's report to the British government (2006) as well as the latest IPCC report (2007). Both reports outline that 'binding mitigation measures' (such as a 2° or a 450 ppm CO2 target) could be implemented at almost negligible reduction in economic welfare, while at the same time avoiding CO2-induced damages that are potentially an order of magnitude larger. We outline the key shifts in investment streams necessary to build-up emission-free capacities, and sketch structural elements of the 'global deal' that could mobilise the according investment switches. When designing such a deal, it will be necessary to weigh the impacts avoided through mitigation against potential impacts induced by mitigation technologies such as bio-energy, CCS (carbon capture and sequestration) or nuclear energy. We put ocean acidification into that context and argue that the ocean acidification community must increasingly become an active player in the upcoming negotiations on such a 'global deal'. This would facilitate better-informed political decisions as it would stimulate early-on additional research priorities in the ocean acidification community.

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OCEAN ACIDIFICATION- CONNECTING THE SCIENCE TO POLICY [I]

John M Baxter[1] and Dan Laffoley[2]

Undertaking original scientific research has always been the response to seeking understanding of new issues. By nature scientists are curious animals but once they have identified and answered the questions that interest them, they publish their findings in a peer-reviewed journal and move on to the next question that interests them.
The complexity and range of issues that we face today means that no longer can anyone be expert or even well-informed about everything, and as such there is great danger that important emerging facts

about some key issues may be overlooked. Ocean acidification is one such area where we can't afford that to happen. The world is at last more-or-less now aware of the challenges presented by global climate change but to most the consequences of this translates to rising temperatures, melting ice-caps, perhaps increased storminess and changing rainfall patterns, but not ocean acidification which remains one of the largest unrecognised ticking time-bombs.
It is essential that as scientists gain a greater understanding of the mechanisms, rates and implications of this process, this is done in such a way as immediately informs a response by those in the position to act – the decision and policy makers.
We present an approach that has been adopted by EPOCA involving a Reference User Group (RUG) that connects the researchers with a range of relevant people ('the customers') providing the opportunity to interact throughout the lifetime of the project. This helps give the scientists a steer to think about how their research can help answer the burning policy questions, provides an on-going forum to share understanding and to react to changing policy priorities, and provides a platform for better targeted and tailored communications to different audiences who need to know but would never look at the peer-reviewed literature. The UK Marine Climate Change Impacts Partnership (MCCIP) Annual Report Card (ARC) is presented as an example of how complex messages can be distilled down to the headline points and made accessible to policy advisers and government ministers.

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POSTER ABSTRACTS

The abstracts in this section are arranged in alphabetical order by the family name of the first author, whether or not that person is presenting the poster. The presenting author's name is underlined. All posters will be available for viewing throughout the Symposium. There will be poster sessions on Monday and Tuesday evenings. At each of these sessions half of the authors will present their posters. The poster titles are followed by an M (for presentation on Monday evening) or by a T (for presentation in the Tuesday poster session). See the index at the back of this book for a list of all authors.

RECENT CHANGES IN THE INORGANIC CARBON SYSTEM IN A LARGE, COMPLEX ESTUARY (PUGET SOUND, WASHINGTON, USA) M1

Alin, Simone R.[1], Richard A. Feely[1], Christopher L. Sabine[1], Jan Newton[2], Skip L. Albertson[3], and Cynthia G. Peacock[1]

Puget Sound is a large estuary complex with a diversity of habitat types and 10,000 rivers and streams draining into it. Circulation within the basin and between the basin and the open ocean is limited by relatively shallow sills, making Puget Sound quite sensitive to changes in freshwater and nutrient inputs related to changes in land use, streamflows, climate, and coastal ocean conditions. Rising regional air temperatures, decreasing freshwater inputs, and human alterations to the coastline during the 20th century have likely changed the carbon distributions in the Sound, but historical carbon data are very limited. In 2008, we conducted the first extensive high-quality surveys of inorganic carbon distributions in the Puget Sound. To understand how the carbon system has changed over time, we have analyzed the Puget Sound Assessment and Monitoring database (1989–2008) for changes in water chemistry that may have implications for the Sound's inorganic carbon system and food web. Over the period of record, average annual deep water temperatures have increased by 2°C, and salinity has decreased by 2. A preliminary model suggests that the effects of these changes may correspond to a reduction in aragonite and calcite saturation levels in the deep water environment. Using discrete samples collected for dissolved inorganic carbon, alkalinity, and oxygen during the 2008 survey cruises, we are calibrating this model to more accurately represent changes in the inorganic carbon system associated with climate change.

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PHYSIOLOGY DRIVES CORAL-REEF COMMUNITY SHIFTS UNDER CLIMATE CHANGE T1

Anthony, Ken and Guillermo Diaz-Pulido

The fate of coral reefs under climate change is of global concern. Our knowledge of how coral-reef organisms respond to thermal stress and ocean acidification is growing, but we know little about the linkages between organism-level stress responses and the behaviour of reef communities. The dynamics of benthic reef communities and their implications for reef resilience are mostly studied from the perspective of top-down control processes (e.g. algal grazing) and the frequency and severity of major physical disturbances (e.g. cyclones). Here, we analyse the relative importance of physiological susceptibility to high-CO_2 scenarios in driving benthic community dynamics. We use the functional responses of growth and mortality risk of corals and macroalgae to a combined temperature-acidification gradient as input into a community dynamics model and analyse changes in equilibrium compositions. Relative response strengths of coral and algal growth and mortality were derived from experimental studies and partly from varying stress responses in set of sensitivity analyses. Model projections demonstrated that the location of thresholds for shifts between coral and macroalgal dominated states depends strongly on how sensitive coral and algal growth rates and mortality risks are to climate change. Interestingly, climate-change effects interacted synergistically with grazing intensity and nutrient loading in driving the system to algal dominance. High sensitivity of some macroalgal species to acidification can shift reef systems to barrens as an alternate stable state. Our results suggest that bottom-up processes from acidification and thermal stress are a stronger determinant of future reef compositions than top-down control processes.

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EFFECTS OF CO_2 SEEPAGE ON SOLUBILITY AND TRANSPORT OF TRACE ELEMENTS IN SEAWATER AND SEDIMENT M2

Ardelan, Murat V. and Eiliv Steinnes

Two lab-scale chambers have been developed to study the effects of CO_2 leakage on trace metal/elements biogeochemistry in seawater and the sediment-water interface
During the initial phase of CO_2 seepage (15 days) "dissolved" (< 0.2 µm) concentrations of all trace transition metals (Al, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd and Pb) increased significantly (> 50 %) in the water. During a second phase of additional 10 days with the same sediment but replenished seawater Al, Cr, Cd, and Zn were partly removed from the water column in the CO_2 chamber, Cu still increased but at reduced rates, whereas Pb increased faster than during the first period. Dissolved fractions of all other 20 elements increased substantially during early CO_2 seepage except Sc, Ga, Ge, As, Sn and Cs. DGT-labile fractions (Easily diffusive forms through the DGT sampling) of all trace transition metals increased during early CO_2 seepage, and continued to increase during the second phase except for Cu and Zn. In the sediment pore water all trace metals, except Mn, increased drastically during CO_2 seepage. DGT labile Sc, Ti, V, As, Y, Sn, Cs, La, Ce, Pr, Sm, Tb, Th and U increased with CO_2 seepage in both sediment pore water and in the overlying water.
There are distinct patterns among different trace elements regarding effects of CO_2 seepage. More "realistic" experiments with the high-pressurize TiO_2 tank soon ready for use will definitely yield give important information on CO_2 effects on bioactive and toxic trace element distributions in the sediment – seawater system.

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DMS AND DMSP CYCLING IN A CHANGING MEDITERRANEAN SEA– AN ACIDIFICATION APPROACH T2

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Changing seawater pH is likely to have a major impact on the marine sources of climatically active gases such as dimethyl sulphide (DMS), as it has been shown previously. The production of DMS by phytoplankton and its atmospheric oxidation products have been coupled to climate forcing. This work presents a first attempt to investigate the link between increasing pCO_2 and DMS concentrations as well as bacterial protein production and abundance, in the Eastern Mediterranean Sea; an area characterised by extreme oligotrophy and phosphorus limitation. The Eastern Basin of the Mediterranean Sea is highly sensitive to climate change and anthropogenic activity and is considered as one of the most oligotrophic areas in the world, where heterotprophic bacterial production is tightly coupled to primary productivity. The current study describes the potential effect that increasing atmospheric CO_2 concentrations may have on the DMS concentrations and bacterial biomass and activity, derived from natural phytoplankton communities. Acidification experiments are presented, in which natural phytoplankton assemblages have developed in enriched CO_2 environments and current CO_2 concentrations. Recent pCO_2 measurements carried out in the area where water has been collected from indicate that throughout the year, surface seawater is undersaturated with respect to atmospheric pCO_2. We report changes in the concentrations of DMS and its cellular precursor DMSP, in response to this CO_2 enrichment and investigate the role of bacteria on the DMS and DMSP cycling in a high CO_2 world.

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SATURATION STATE OF SEA WATER FOR CALCITE AND ARAGONITE IN CANADIAN ARCTIC ARCHEPELAGO AND THE LABRADOR SEA M3

Azetsu-Scott, Kumiko[1], David Slauenwhite[1] and Philip Yeats[2]

Channels of the Canadian Arctic Archipelago (CAA) and the Hudson Bay region provide the main pathway for the flow from the Arctic Ocean to the North Atlantic. Rapidly changing physical conditions in the Arctic, such as hydrological cycles, sea water temperature and reduction of ice cover impact biogeochemical cycles in the Arctic and propagate through the CAA and the Hudson Bay to the Labrador Sea, where deep convection occurs in winter and influences the global thermohaline circulation. Saturation state of seawater with respect to calcite and aragonite was calculated from dissolved inorganic carbon and total alkalinity collected from the CAA to the Labrador Sea in 2003-2004. Transects include Nares Strait, Barrow Strait, Baffin Bay, Hudson Bay, Hudson Strait, Davis Strait, and the Labrador Sea. While Barrow Strait was supersaturated for both calcite and aragonite through the entire water column (deepest 280m), shallow saturation depths, at 150m for calcite and at 75m for aragonite, were observed in the Hudson Bay. Saturation depths for aragonite in Davis Strait and in the Labrador Sea were 800m and 2500m, respectively. Variation in saturation depths in different transects is described from water mass structure, circulation and organic matter production/respiration.

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SHORT-TERM RESPONSE OF THE COCCOLITHOPHORE *EMILIANIA HUXLEYI* TO AN ABRUPT CHANGE IN SEAWATER pCO_2 T3

Barcelos e Ramos, J., M. N. Müller and U. Riebesell

The response of the coccolithophore *Emiliania huxleyi* to future CO_2 increase is well documented in acclimated cultures where cells are exposed to the CO_2 conditions for several generations before the experiment. However, the time necessary to reach a new physiological "equilibrium" (acclimation) remains unknown. Here we show that *Emiliania huxleyi's* short-term response (hours to 1 day) to increasing CO_2 is similar to previous studies with acclimated cultures under comparable conditions. Indeed at CO_2 levels from glacial (190 µatm) to year 2100 (750 µatm), calcification decreased and organic carbon fixation increased already 8 h after exposing the cultures to the changed CO_2 conditions. This led to a decrease in the ratio of $CaCO_3$ to organic carbon production. Our results show that with the change in CO_2 concentration a new physiological "state" is established in a matter of hours, apparently independent of cellular division. If these results apply to other phytoplankton species, it has implications for the interpretation of mesocosm studies and on board incubations, where often it is not feasible to allow for a pre-conditioning phase before starting experimental incubations.

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OCEAN ACIDIFICATION AND THE DEMISE OF BRACHIOPODS M4

Barry, James P., Eric F. Pane, Kurt R. Buck, Chris Lovera, and Christina Tanner

Brachiopods, commonly called lamp-shells, were a dominant element of Paleozoic seas when perhaps 30,000 species thrived. During the Permian-Triassic extinction brachiopod diversity dropped to ~300 species, perhaps related to ocean acidification, hypoxia, and other stresses during this event. The survivors diversified slightly during the Mesozoic, but once again were overwhelmed during the mass extinction at the end of the Cretaceous. Today, brachiopods are a somewhat rare member of marine ecosystems, found principally in intertidal ~1 km depths throughout the world ocean.
Although brachiopods are thought to be susceptible to stresses caused by ocean acidification, including reduced calcification, respiratory stress, acidosis, and metabolic depression, no studies have investigated their tolerance to ocean acidification. We examined the physiology, survival, and growth of brachiopods (*Laqueus* sp.) common on the continental shelf and upper continental slope in the eastern Pacific, in response to various levels of environmental hypercapnia (ocean acidification). Under mild (~-0.2 pH units) to severe (~-1.0 pH units) environmental hypercapnia, the internal fluids of brachiopods were mostly isotonic with seawater, indicating that they have little capacity to regulate internal fluid chemistry, or buffer acidosis caused by ocean acidification. Metabolic rates (oxygen consumption) were initially elevated under high pCO2 / low pH treatments, compared to controls, but slowed with continued exposure. Longer-term studies are evaluating the effects of hypercapnic stress on growth and survival. Our results confirm that brachiopods suffer reduced metabolic function under stresses associated with ocean acidification, which likely lead to death and perhaps species extinctions.

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VULNERABILITY OF SOUTHERN OCEAN PTEROPODS TO ANTROPOGENIC ACIDIFICATION T4

Bednarsek, Nina[1,2], Geraint Tarling [1,] Dorothee Bakker[2], and Sophie Fielding[1]

Uptake of anthropogenic carbon dioxide (CO_2) is changing the carbonate chemistry in the Southern Ocean. It has been suggested that marine calcifiers, among them pteropods, will be affected by the resulting decrease in ocean pH (Kleypas et al., 2005). Orr et al. (2005) demonstrated rapid shell dissolution in low pH waters, however a comprehensive study of the effect of ocean acidification on Southern Ocean pteropods is lacking. Well advanced research is ongoing to determine the life cycle of *Limacina helicina* by studying net samples from historic James Clark Ross cruises (early 90's -2008). Additional net samples from the JR177 (2008) cruise in the Scotia Sea will be combined with vertical profiles of carbonate parameters, thus allowing the study of pteropod abundance versus the aragonite saturation state. Furthermore, high CO_2 experiments were carried out on cruise JR177, which focused on the susceptibility of the pteropod larval stages to ocean acidification. Sampled individuals of *Limacina helicina* were incubated at different levels of the partial pressure of CO_2 (375, 500, 750 and 1200 p.p.m.v.) for up to 13 days to mimic ocean acidification. Upon the return of the samples to the U.K., the organisms will be analysed for the effect of acidification on their morphology and mineral composition of the shell. Water samples were also preserved for analysis of total alkalinity (TA) and total dissolved inorganic carbon (TCO_2). From these studies the capability of pteropod larvae to withstand changes in carbonate chemistry will be assessed.

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THE CHALLENGES OF MODELLING ECOSYSTEM RESPONSE TO OCEAN ACIDIFICATION. M5

Blackford, Jerry

The chemistry of ocean acidification is relatively predictable but the precise response of the many sensitive ecological and biogeochemical processes remains speculative. Experiments have revealed diverse responses for different species although few species have been studied. Over the same timescale as acidification, global warming will alter the physical drivers of the marine system, prediction therefore requires an integrated multi-driver approach. Modelling provides our only predictive tool but is limited by contentious parameterisations, a lack of evaluation data and complexity. Given these uncertainties, it is important not to be overly deterministic with models, however models do have an important role. These include: predicting carbonate system parameters and carbonate saturation states under different emission scenarios, assessing the sensitivity to parameter uncertainty and model structure, producing probabilistic ensemble scenarios rather than deterministic assessments, testing if a given response is by itself capable of altering key system properties, assessing if an acidification response might be affected by changing climate or other drivers, asking how do process responses identified in (mono-)culture type studies express within a virtual complex ecosystem and finally as provocateurs of debate and experimentation. To illustrate these approaches, results from 3D simulations of the North West European Shelf will show predictions for the carbonate system, an assessment of the vulnerability of the nitrogen cycle and benthic coupling due to the inhibition of nitrification, an illustration of how phytoplankton species specific carbon uptake rates might provoke changing community structure and an examination of the sensitivity of acidification response to changing climate.

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KIEL CO_2 MANIPULATION EXPERIMENTAL FACILITY (KICO2) T5

Bleich, Markus[1], Frank Melzner[2], Claas Hiebenthal[2], Helgi Mempel[2], Kai Schulz[2], Ulf Riebesell[2], Martin Wahl[2], Frank Sommer[2], Ulrich Sommer[2], Armin Form[2], Uwe Piatkowski[2], Reinhold Hanel[2], Dieter Piepenburg[3], Michael Spindler[3], Anton Eisenhauer[2], Andrea Franke[2], Volker Möller[5], Gunnar A. Baumert[4], and Catriona Clemmesen[2]

We will present the technical details and our first experiences with a new CO_2–manipulation facility, set up at IFM-GEOMAR in March 2008. The system adds pure CO_2 to pressurized air to create 5 different CO_2–air mixtures (380-4,000 ppm of CO_2), which are distributed into 6 different temperature constant rooms at gas flow rates of up to 1000 l/h per room and per CO_2 concentration. Precise addition of CO_2 is achieved via computer controlled valve systems (red-y smart series) that respond to variations in gas flow according to the gas demand by the experiments. CO_2 flow is detected by pressure and temperature independent thermal measurement of mass. High precision of final CO_2 values is achieved within 1-100% of maximal gas flow rate. Actual values and set points are continuously monitored and documented online via PC interface. The facility is completed by a security and alarm system. The gas mixtures are used to equilibrate different types of experimental setups: (1) large flow-through Baltic Sea systems for benthic invertebrate long-term incubations, (2) small flow-through systems for short- and long-term incubations of Baltic- and North Sea invertebrates, (3) small-scale larval incubation systems for simultaneous manipulation of CO_2 and temperature. All types of experimental setups will be described in detail and quantitative information of crucial parameters (e.g. water and gas flow rates, TA, DIC, pH, experimental animal biomasses, and nitrogenous waste accumulation) will be given and discussed. This contribution is an effort towards establishing guidelines for highly controlled and reproducible CO_2 manipulation experiments.

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OCEAN ACIDIFICATION AND HARMFUL ALGAL BLOOMS M6

Boisson, Florence, Jean-Louis Teyssié, François Oberhansli, and Ross Jeffree

Scientific knowledge on biomineralization suggests that changes in pH associated with ocean acidification will have consequences on the physiology of planktonic calcifiers such as coccolithophores, foraminifera, and pteropods, modifying the equilibrium within plankton communities. Then, in the context of ocean acidification, we can ask what potential is there for an increase in non-calcifying plankton that is responsible for Harmful Algal Blooms (HABs), which strongly affect seafood resources worldwide? Harmful algae physiology and toxin content may be impacted by changes in seawater chemistry, as well as simultaneous warming and associated variations in metal bioavailability and nutrient supply. Here we will present plans to use experimental radiotracer-assay methods developed at the Radioecology Laboratory of the IAEA-Marine Environment Laboratories to contribute to future studies of harmful algal cultures (namely those responsible for Paralytic Shellfish Poisoning) that need to be designed to test the hypothesis that HABs will increase in a future High-CO2 world.

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INCREASED CONTENT OF CO_2 IN THE ATMOSPHERE CAN REDUCE PRIMARY PRODOCTION IN THE OCEAN T6

Børsheim, Knut Yngve

Recently it has been showed that the average C:N ratio may increase in a high CO_2 world, which may imply an increased availability of organic carbon in the future ocean. This may stimulate heterotrophy, but heterotrophic prokaryotes are not only dependent on DOC for their life support, they also compete with the primary producers for mineral nutrients. In our group based in Bergen, Norway, we have conducted several studies on the flow of carbon in pelagic plankton, using both laboratory culture experiments and field work including mesocosm perturbation methodology. In a series of experiments both mineral nutrients and glucose were added at a suite of combinations. Glucose was envisaged as a proxy for labile dissolved organic carbon. The results showed that when the system was nutrient limited, adding more organic carbon resulted in smaller total accumulation of organic carbon in the system. We argue that stimulation of the heterotrophs under mineral nutrient limitation represents a cost to primary producers, and under such conditions increased availability of organic carbon decreases the total production in the system.

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HIGH FREQUENCY MONITORING OF THE PARTIAL PRESSURE OF CO_2 (pCO_2) USING A CARIOCA SENSOR ON A MAREL BUOY IN A TEMPERATE COASTAL ECOSYSTEM (2003-2008) – A TOOL FOR INVESTIGATING THE OCEAN IN A HIGH CO_2 WORLD M7

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Long-term monitoring of the marine carbon chemical species is necessary to assess the chemical and biological modifications occurring in the ocean in a "High CO_2 World". Coastal marine ecosystems are directly impacted by human activities and are crossing a threshold of changing from their pre-industrial state, during which ocean margins are widely viewed as heterotrophic and a CO_2 source, to a current or future state as a CO_2 sink.
The CARbon Interface Ocean Atmosphere (CARIOCA) sensor allows for both long term and high frequency measurements of the partial pressure of CO_2 (pCO_2). The CARIOCA sensor is therefore an excellent tool for investigating the high variability and the evolution of pCO_2 in coastal environments. Here we present high-frequency pCO_2 data recorded for 5 years during the first deployment of a CARIOCA sensor on a MAREL buoy in the surface waters of a temperate coastal ecosystem, the Bay of Brest, which is impacted by both coastal and oceanic variability. High frequency measurements allowed for the quantification of the diurnal, tidal and seasonal variability in the assessment of the annual CO_2 air-sea fluxes. The preliminary results indicate that biological activity is the main process controlling the pCO_2 variability in surface waters on a seasonal time-scale. On a shorter scale, the tidal and diurnal cycle are shown to be responsible for high pCO_2 variability. The 5 years of investigation revealed that the surface waters of the Bay were near equilibrium with the atmosphere and that the inter-annual variability was small.

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SYNERGISTIC EFFECTS OF CO_2 CONCENTRATION AND TEMPERATURE ON OXYGEN EXCHANGE IN CORALS T7

Buxton, Lucy[1], M. Badger[2] and P. Ralph[1]

In the last 100 years, human activities have contributed considerably to atmospheric CO_2 emissions. CO_2 is recognized as a major greenhouse gas and causal links have now been drawn between atmospheric CO_2 and increases to global mean temperatures. However, high atmospheric CO_2 levels have recently been shown to cause chemical changes in oceanic surface waters, including increased concentrations of dissolved CO_2, decreased bicarbonate ion concentration (CO_3^{2-}). Impacts of altered carbon concentration are in addition to that of temperature alone, and the negative effects on oceanic flora and fauna will be substantial. Amongst the systems likely to be impacted by these biochemical changes, coral reef ecosystems are thought to be especially vulnerable because of their complex carbon budgets linked to photosynthesis and calcification.
The interactions of temperature and C_i concentration remain poorly understood because physiological responses have been primarily examined by manipulating one parameter at a time. This has been exacerbated by the fact that previous investigations have relied on either oxygen evolution rates, or measurement of effective quantum yield of PSII as an indicator of photosynthetic functionality. Used for the first time on corals, membrane inlet mass spectrometry (MIMS) allows the continuous measurement of gas exchange ($O_{2\ evol}$ and $O_{2\ uptk}$) and chlorophyll fluorescence to occur non-invasively Results are presented using combined measurement photosynthesis determined by of O_2

evolution, O_2 uptake and chlorophyll *a* fluorometry of the branching coral *Pocillopora damicornis* exposed to a range of C_i concentrations (0.1 – 12 mM) at 26 and 30 °C over short-term incubations.

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IMPACT OF SEAWATER ACIDIFICATION ON SEA URCHIN SKELETAL GROWTH M8

Catarino, Ana I. and Philippe Dubois

Sea urchins are particularly exposed to seawater acidification due to the nature of their well developed high-magnesium calcite skeleton. This is formed trough an amorphous calcium carbonate precursor form whose solubility far exceeds that of aragonite. As sea urchins are keystone species in numerous ecosystems, the adverse effects they might experience will have severe ecological repercussions. In this study we assessed the impact of seawater acidification on skeletal growth in both larvae and adults of the temperate sea urchin *Paracentrotus lividus*.
Experiments were carried out at controlled temperature and lower pHs were obtained by bubbling CO_2 in seawater. The total alkalinity and pH (seawater scale) were measured and the pCO_2 and total inorganic carbon calculated, as well as the magnesium-calcite saturation state. The larvae were grown in pHs between 8.0-6.8 until the echinopluteus stage and their development was characterized using embryotoxicity protocols to distinguish normal and altered morphologies. The spicules development was quantified. At lower pHs significantly more larvae showed an abnormal morphology and a reduced size, going together with frailer spicules. Adult sea urchins were grown at pHs between 7.8-7.2. Spine regeneration was experimentally induced and regenerate sizes were measured using microscopy techniques. Their magnesium content was analysed and alteration of mechanical properties was evaluated.
Available data already indicate that both stages of the sea urchin life cycle are affected by sea water acidification. This suggests that ecosystems structured by sea urchins will be seriously affected by ongoing ocean acidification.

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EXPLORING THE RESPONSE OF *IN SITU* COCCOLITHOPHORE POPULATIONS IN THE NORTH EAST ATLANTIC TO ACIDITY AND CALCITE SATURATION GRADIENTS. T8

Charalampopoulou, Anastasia[1], Cynthia Dumousseaud[1], Alex Poulton[1], Mike Lucas[2], Darryl Green[1], Toby Tyrrell[1] and Eric Achterberg[1]

Ocean acidification is expected to have a negative impact on marine calcifiers, specifically on coccolithophores. Coccolithophores are of particular importance as they comprise a great proportion of pelagic biogenic calcification (50-80%). Moreover, calcite is considered to be an important ballast material for organic carbon transport from the surface to the deep ocean and therefore plays an important role in the global carbon cycle.
The fate of coccolithophores in a future acidic ocean has been intensively researched during the last few years. Most of our knowledge comes from laboratory experiments on monospecific cultures, the results of which are sometimes contradictory, and research on natural populations has been limited. To investigate how natural assemblages might respond to ocean acidification we simultaneously sampled natural coccolithophore populations and the ocean carbonate system during a cruise to the eastern Iceland basin in July-August 2007. Specifically, we made simultaneous *in situ* measurements of particulate inorganic carbon (PIC), particulate organic carbon (POC) and calcification rates (ρPIC),

and we used Scanning Electron Microscopy (SEM) to assess coccolithophore abundance and morphology. We also measured dissolved inorganic carbon (DIC) and alkalinity (TA) to derive other parameters of the carbonate system and specifically the calcite saturation state of the study area. This work describes the observed relationships between the different biological parameters above, one of them being a positive linear relationship between PIC and ρPIC, and also between them and the carbonate system chemistry.

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DISPERSION OF CO_2 LEAKED FROM SEABED IN SEAWATER M9

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We have developed a numerical model of the dispersion of CO_2 droplets/bubbles in seawater to simulate the fate of CO_2 leaked or released from seabed naturally or artificially.
The model has been applied to predicting the dynamics of leaked CO_2 in seawater at various depths from 10-800m (temperature from 5 °C to 25 °C) and for initial droplet/bubble sizes from 3.0 to 40.0mm diameter. A diagram of CO_2 ascending distance *vs* dissolution time is obtained from model simulations. It is found that CO_2 droplets ascend at a mean speed of 11cm/sec and a mean shrinking rate of 7.0 x10^{-3} mm/sec in diameter approximately if leaked from a deep-ocean (800–1000m) source. This speed and shrinking rate increase to 16 cm/sec and 30 x10^{-3} mm/sec at middle deep ocean (500–650m) and finally reach to 22 cm/sec and 0.2 mm/sec at shallow ocean (<150m). At shallow depths, a CO_2 bubble with initial diameter of 40 mm released from 40 m depth might be just dissolved completely before reaching the sea surface, while a bubble with size smaller than 40mm leaked from seabed at the same depth will be fully dissolved.
The two-phase turbulent plume model predicts that the pH change in seawater due to CO_2 dissolution is directly proportional to the leakage rate and inversely proportional to initial droplet/bubble size (*d*o) and ocean current speed (*V*c). At a leakage rate of 1.0 kg/sec, *d*o=8.0mm, and *V*c =2.5cm/sec, the maximum pH change is –1.6. This pH change increases to –2.5 when leakage rate increases to 10kg/sec and reduces to –1.2 when leakage rate decreases to 0.1kg/sec, respectively. The mean CO_2 enriched seawater volume developed from CO_2 leakage position in a turbulent ocean is also simulated. The results show that the volume with pH changes larger than –0.1 could increase up to 2.0x10^6 m^3 within 30 minutes of onset of the source.

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BIOGEOCHEMICAL INVESTIGATIONS OF COCCOLITHOPHORE BLOOMS ALONG THE CONTENTAL MARGIN OF THE NORTHERN BAY OF BISCAY: HIGHLIGHTS OF THE PEACE PROJECT T9

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Recent studies have demonstrated that changing ocean chemistry due to ocean acidification poses a growing threat for marine organisms such as corals, coccolithophores and many others that form calcareous skeletons. Its biogeochemical feedbacks and impact on the oceanic carbon cycle are yet to be quantified. Coccolithophores are the major calcifying phytoplankton in the sub-polar and temperate regions of the world's ocean. They produce furthermore Transparent Exopolymer Particles (TEP), which are known to promote aggregate formation. Combined with the $CaCO_3$ ballast effect, large-scale coccolithophore blooms could thus contribute to the export of organic carbon to deep waters on relatively short time scales. During the PEACE project, funded by the Belgian Federal Science Policy Office, we have conducted in three consecutive years interdisciplinary biogeochemical surveys, assisted by remote sensing, along the continental margin of the Northern Bay of Biscay where coccolithophore blooms dominated by *Emiliania huxleyi* are frequently and recurrently observed. Rates of various processes governing the coccolithophore ecosystem dynamics have been determined. They include for example primary production, calcification, pelagic and benthic respiration and dissolved esterase enzyme activity. Particle dynamics and organic carbon export have also been assessed, based on thorium isotope measurements. The data are complemented by other relevant biogeochemical parameters such as chlorophyll *a*, HPLC-pigments, TEP, nutrients, and particulate organic and inorganic carbon. The key results will be presented and discussed in attempt to elucidate the oceanic coccolithophore ecosystem response in a high-CO_2 world.

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THE EFFECT OF pCO_2 ON THE EGG DEVELOPMENT AND THE CONDITION OF NEWLY-HATCHED LARVAE OF ATLANTIC HERRING (CLUPEA HARENGUS L.) M10

Clemmesen, Catriona and Andrea Franke

The study addresses the effect of hypercapnia (elevated pCO2) on the early development of the Atlantic herring (*Clupea harengus* L.), the most sensitive stages in the life history of a fish. Eggs of the Atlantic herring were fertilized and incubated in artificially acidified seawater (pH 7.67, 7.49, 7.33, 7.28 and 7.05) and a control treatment (pH 8.08) until the main hatch of herring larvae occurred. The development of the embryos was monitored daily and newly-hatched larvae were sampled to analyze their morphometrics and their condition by measuring the RNA/DNA ratios. Elevated pCO2 neither affected the fertilization rate nor the embryogenesis, the mortality rate or hatch rate. Furthermore the results showed no linear relationship between pCO2 and yolk sac area, dry weight and total length of the newly-hatched larvae. For pCO2 and RNA/DNA ratio, however, a significant positive linear relationship was found. The RNA concentration at hatching time was lowered, which consequently should lead to a reduced protein synthesis rate. The results indicate that an increased pCO2 can affect the metabolism of fish embryos negatively and therefore further somatic growth of the larvae could be reduced. An additional experiment was conducted using controlled air CO2 mixture with a newly developed automated CO2 manipulation system with concentrations of 380, 560, 870, 1120 and 1400ppm. The effects on the condition of herring larvae at hatch will be analysed and compared.

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RESPONSE OF MEDITERRANEAN AND ARCTIC PTEROPODS TO OCEAN ACIDIFICATION T10

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Thecosome pteropods (molluscs) can play an important role in the food web of various ecosystems. For example, polar species are reported to be an important food source for herring, salmon and whales. Ocean acidification driven by the increase of pCO2 could have an important impact on these

animals because they harbour an aragonitic shell which was shown to be very sensitive to changes in the carbonate chemistry. Experiments are carried out in the NW Mediterranean sea (*Cavolinia inflexa, Limacina inflata*) and in Spitzbergen (*Limacina helicina*). Specific attention is paid to juveniles which could be the most sensitive to a decrease in pH. Despite the fact that pteropods are notoriously difficult to maintain in the laboratory, specimens have been maintained successfully several weeks under controlled conditions of pCO2 (380 and 760 ppm) and temperature, and precipitation of CaCO3 was observed. New culture conditions are being tested to keep them alive in the laboratory for longer periods of time. The fluorochrome calcein and 45Ca are useful tools to investigate calcification. The latest results of the on-going perturbation experiments will be presented.

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SUBANTARCTIC WATER – NO EVIDENCE OF A CO_2 INCREASE. M11

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The Southern Ocean is known to be a sink for atmospheric CO_2, however models do not reproduce the observations well, the processes determining the carbonate chemistry in this area are not yet well understood. Inverse models based on atmospheric CO_2 data estimate that the Southern Ocean sink is decreasing due to greater mixing of high carbonate deeper waters to the surface.
pCO_2 and pH in subantarctic water have been directly measured bi-monthly for the last ten years as part of a time series transect programme off the east coast of the South Island of New Zealand (171.50 ^oE 45.85 ^oS). The pCO_2 seasonal cycle has a mean value of 360 □atm, with an amplitude of 10 □atm, the maximum occurring in early spring. This is out of phase with the effect of changing seawater temperature, biological activity is the main determinant of the seasonal cycle in these waters. There has been no apparent long-term change in either the pCO_2 or the pH since 1998. This has resulted in an increase in the air-sea pCO_2 difference due to the increasing atmospheric carbon dioxide concentration, and thus there has been an increase in the magnitude of the sink for atmospheric carbon dioxide in these waters.

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INFLUENCE OF FUTURE CO_2 CONCENTRATIONS ON GROWTH AND NITROGEN FIXATION OF THE BLOOM FORMING CYANOBACTERIUM *NODULARIA SPUMIGENA* T11

Czerny, Jan T. B., Joana Barcelos e Ramos, and Ulf Riebesell

Anthropogenic CO_2 emissions are resulting in elevated CO_2 concentrations and acidification in the surface ocean. Phytoplankton physiological responses to these chemical alterations may influence ocean primary production and thereby impact pelagic ecosystems and biogeochemical cycling. Diazotrophic cyanobacteria are able to fix carbon independently of the external supply of combined nitrogen, the nutrient limiting primary production in most ocean regions. Recent investigations indicated that in *Trichodesmium*, a predominant diazotroph in large parts of the oligotrophic oceans, carbon and nitrogen fixation are stimulated by rising pCO_2. In this study we investigate the physiological response of *Nodularia spumigena*, a heterocystous bloom-forming cyanobacterium of the Baltic Sea, to elevated [CO_2] and corresponding acidification as projected for the year 2100. *N. spumigena* reacts with strongly impeded growth and reduced nitrogen fixation. These effects are accompanied by storage of nutrients and significant changes in elemental composition of the cells. Our observation of adverse effects of seawater acidification/carbonation on growth and nitrogen fixation of *N. spumigena* are contrasting previous findings on *Trichodesmium* and eukaryotic marine phytoplankton. Possible explanations for the opposed physiological responses may be found in the different ecological strategies of non-heterocystous *Trichodesmium* and the heterocystous *Nodularia.*

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BEHAVIOR OF SUBTROPICAL COASTAL REEF ENVIRONMENTS UNDER RISING ATMOSPHERIC CARBON DIOXIDE AND OCEAN ACIDIFICATION, THE EXAMPLE OF HAWAII AND BERMUDA M12

De Carlo, Eric H.[1], F.T. Mackenzie[1], A.J. Andersson[2], C.L. Sabine[3], and R.A. Feely[3]

Ocean acidification has potentially significant implications for *both* carbonate mineral production and dissolution. Here we demonstrate how the response of subtropical reefs to existing conditions can help predict how future higher atmospheric CO_2, lowered seawater pH and carbonate saturation levels will impact marine carbonates. We use results of studies in Hawaii (CRIMP-CO_2) and Bermuda and modeling with the Shallow-water Ocean Carbonate Model (SOCM) to illustrate the response of the subtropical coastal ocean to ocean acidification. Nearly three years of high frequency measurements at CRIMP-CO_2 show that Kaneohe Bay is annually a net source of CO_2 to the atmosphere, mainly due to intense calcification. With CO_2 in bay waters averaging ~450 µatm, if atmospheric CO_2 increases at the rate of 2.1 µatm/yr observed during our study, the bay will switch from being a net source to a net sink of CO_2 within ~30 years. At such time, reefs will increasingly be at risk of decreased calcification rates and particulate carbonate minerals, especially high magnesian calcites, of dissolution. The latter already occursnaturally in Bermuda, where CO_2concentrations reach well above 1000 µatm during the summer in the stratified bottom waters of Devil's Hole, leading to dissolution of phases with an average mol % $MgCO_3$ of ~16. The SOCM predicts that under these conditions, similar to those predicted in the latter part of this century under the BAU scenario, dissolution of carbonates will exceed production by the year 2150 or sooner, leading to a net loss of carbonate minerals from the world's coastal ocean.

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QUANTIFICATION OF pH AND INORGANIC CARBON USING AUTONOMOUS SENSORS T12

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We will present the latest technologies developed in our lab for autonomous quantification of inorganic carbon parameters. An improved version of the Submersible Autonomous Moored Instrument for CO_2 (SAMI-CO_2) that is in the advanced stages of development will be described. A design of a new sensor, SAMI-pH, developed directly from the SAMI-CO_2 technology, is also discussed. Results from recent field studies using SAMI-pH are presented. The sensor has been deployed on Scripps pier, in Monterey Bay (MBARI M0 mooring), in the northeast Pacific , and on a coral reef in Puerto Rico. These studies are characterizing the natural range of pH variability over diurnal to seasonal time scales. Calculation of total dissolved inorganic carbon (DIC) from combined autonomous measurements of the partial pressure of CO_2 (pCO_2) and pH is examined. These preliminary results show that, as expected, the pH-pCO_2 combination is sensitive to errors; however, very good DIC prediction is obtained from both pH and pCO_2 when combined with salinity-derived alkalinity. Our future plans are to combine pH and pCO_2 sensors with an autonomous total alkalinity system currently under development. These combined measurements will make it possible to quantify DIC while simultaneously checking internal consistency of the inorganic carbon parameters.

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THE EFFECT OF HIGH CO_2 CONCENTRATIONS ON ENERGY BUDGETS OF ISOLATED GILLS FROM ANTARCTIC NOTOTHENIOIDS M13

Deigweiher, Katrin; Magnus Lucassen, Christian Bock, and Hans-O. Pörtner

Little to no information is available on the sensitivity to hypercapnia of Antarctic fish. Living in a stable environment for Millions of years may make Antarctic fish more sensitive to environmental changes than any other (e.g. temperate or Arctic) species. In this study we investigated the effect of high CO_2 (10.000 ppm) concentrations on energy turnover of fish gills overall as well as on individual energy consuming processes in two Antarctic Notothenioids (*Gobionotothen gibberifrons* and *Notothenia coriiceps*). Oxygen consumption of isolated gills was measured under normo- vs. hypercapnic conditions using specific inhibitors to determine the fractional costs of ion regulation, protein and RNA synthesis in the energy budget. The fraction of the three processes was similar in both species. However, absolute costs of all three processes were higher in *N. coriiceps* than in *G. gibberifrons*. This may be attributed to the sluggish benthic life style of *G. gibberifrons,* whereas benthopelagic *N. coriiceps* actively feed on small fish and krill. Under hypercapnia, gill preparations from *G. gibberifrons* displayed a drastic rise in energy consumption rates of ion regulation (197%), protein (237%) and RNA synthesis (220%). In contrast, the cost of ion regulation (156%), protein (128%) and RNA synthesis (107%) rose more moderately in *N. coriiceps*. Evidently, high CO_2 concentrations induce strong increments in the energy demand of cellular processes. Future experiments will show whether these shifts play a role under more realistic CO_2 accumulation scenarios and cause a reduction in energy availability for growth and reproduction.

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UNCERTAINTIES IN THE OCEAN CARBONATE SYSTEM AT HIGH P(CO_2) T13

Dickson, Andrew G

The state of the ocean carbonate system is typically described by providing values for two of the four canonical analytical variables: pH, $p(CO_2)$, total alkalinity, and total dissolved inorganic carbon together with the salinity, temperature and pressure so as to allow estimation of the requisite equilibrium constants as well as the total boron concentration. Once this basis set of information is known, it is possible to compute the concentrations of the various carbonate species, and hence infer the remaining analytical variables.
Each of these input variables – including the estimated equilibrium constants – is subject to some uncertainty, resulting in an overall uncertainty that can be ascribed to any individual item of computed information such as the carbonate ion concentration or the pH. In this presentation, I shall discuss how one estimates the likely magnitudes of the various uncertainty terms and infer the overall uncertainty of the various computed information over a range of conditions, including over a range of pressures.
In particular, I will examine the previously observed discrepancies for the ratio of the equilibrium constants: K_1/K_2 at high $p(CO_2)$ values, and will indicate the likely consequences of this discrepancy for the accurate prediction of carbonate ion concentrations in systems with high $p(CO_2)$.

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IMPACT OF OCEAN ACIDIFICATION ON CALCIFYING MARINE ORGANISMS M14

Dissard, Delphine, Jelle Bijma Jelle, Regine DaRocha, and Gernot Nehrke

Recently, field and laboratory studies have demonstrated the significant impact of variations in seawater [CO_2] and related changes in carbonate chemistry on both planktic and benthic marine calcifying organisms. (e.g. *Bijma et al.,* 1999; *Kleypas et al.,* 1999; *Leclercq,* 2000 et al., *Riebesell et al*., 2000; *Zondervan et al*., 2001; *Delille et al.,* 2005; *Gazeau et al*., 2007). For foraminifera a model has been proposed to explain the calcification process (*Bentov and Erez,* 2005, 2006): Seawater is taken up via endocytosis and transported to the site of calcification. During transport the composition of the solution inside the vesicle is modified (concentrating Ca^{2+} while removing other divalent cations, notably Mg^{2+}, and at the same time pumping H^+ to acidic vesicles, thereby increasing pH and CO_3^{2-} in the "calcification vesicles"). Because the calcification is based on ambient seawater, foraminifers are among the best recorders of paleo-proxies. This also explains why foraminifera are so sensitive to ocean acidification. A similar model has been proposed for corals (Erez, personal com.). The similarity in the ultra-structures of different calcifying organisms also suggests a common ancestral calcification mechanism. We report in more detail on the impact of ocean acidification on planktonic and benthic foraminifera, through controlled laboratory culture experiments. The impact was monitored by weighing shells and using SEM and AFM techniques. The overall aim of this study is to develop/improve a process based understanding of biocalcification in foraminifera which would allow predicting how these calcifiers cope with an acidifying ocean and which consequences this has for the structural properties of their skeletons.

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BORON ISOTOPES IN SCLERACTINIAN CORALS: pH OR TEMPERATURE PROXY? T14 WITHDRAWN

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No proxy is perfect! While boron isotopes in tropical corals such as Porites sp. are a powerful tool to accurately reconstruct past temporal changes of the sea surface pH at high resolution, they appear relatively sensible to temperature when they incorporate in North Atlantic deep-sea coral Lophelia pertusa. We present here first results concerning a recent "$pH_{seawater}$ – □$^{11}B_{coral}$" field calibration at seasonal timescale involving modern Porites sp. and surface seawater samples monthly collected from New Caledonia lagoon during 18 months. Obtained data tends to show the high potential of the boron isotopes to reconstruct paleo-pH on seawater scale (SWS) with an accuracy of +/- 0.2 pH-unit including analytical uncertainties. Thus, external reproducibility obtained from boron isotope measurements using MC-ICPMS Neptune was inferior to +/- 0.2 ‰. pH calculations were performed with an isotopic composition of boron for seawater of 39.9 ‰ and an isotopic fractionation factor of 0.981. Such results reinforce the high potential of Porites sp. to quantify Ocean Acidification in tropical latitudes since the beginning of the industrial era. In contrast, preliminary measurements of boron isotopes in deep-sea coral Lophelia pertusa collected between 40°N and 70°N along the European margin of the eastern North Atlantic showed a strong influence of the temperature on the isotopic composition of boron ranging between 26 and 29 ‰. Moreover these relatively high values indicate a strong "vital effect" and their use for paleo-pH reconstruction for intermediate or deep waters require field or experimental calibrations.

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SURFACE WATER PH MEASUREMENTS AND CARBONATE CHEMISTRY IN THE SUB-TROPICAL NORTHEAST ATLANTIC OCEAN M15

Dumousseaud, Cynthia[1], Eric Achterberg[1], Nick Hardman-Mountford[2], David Hydes[1], Matt Mowlem[1], and Toby Tyrrell[1]

In order to get a better understanding of how ocean acidification will affect the plankton community, and particularly calcifying organisms, we need to understand the seasonal biological and physical controls on pH. To observe and consequently predict changes in the ocean, precise measurements of all the carbonate chemistry parameters in the ocean are important. Direct measurement of pH would offer the possibility of making highly detailed observations that can allow precise correlations to be made with the different hydrographic and biogeochemical processes driving changes in pH. Achieving this in practice currently presents a considerable analytical challenge.

A high precision pH measurement system (accuracy and precision of 0.01 pH unit) was tested in the Sub-Tropical Northeast Atlantic during January 2008 aboard the RRS Discovery. High resolution potentiometric pH_F measurements along with partial pressure of CO_2 (pCO_2) were made continuously from the ship's underway supply. Discrete sample were taken for Dissolved Inorganic Carbon (DIC) and Total Alkalinity (TA) measurements. The area studied was under the Saharan dust plume, where atmospheric inputs can be of particular importance on primary productivity in areas where nutrients are limiting. We were able to determine small-scale changes in pH related to response of biology associated with the dust inputs. A comparison of the relative changes in the four carbonate parameters measured will be discussed, in relationship with changes in the physics and biogeochemistry.

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CO_2-DRIVEN ACIDIFICATION RADICALLY AFFECTS LARVAL SURVIVAL AND DEVELOPMENT IN MARINE ORGANISMS – III. TUNICATES T15

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Tunicates have not been a priority target for research on the consequences of OA, and yet several tunicates are keystone species, aggressive invasives due to their ability to spread rapidly and endanger native taxa, and in some cases a major threat to aquaculture. We have used computerised monitoring and regulation of pH in natural sea water by controlled injection of CO2 to investigate the impact of pH changes predicted by the year 2100 (0.2 – 0.4 pH units) on the long term development of three tunicate species: the sessile species *Ciona intestinalis* and *Ascidiella aspersa*, which can occur at extremely high densities of several thousands of individuals per square meter, and *Oikopleura dioica*, an important component of the pelagic ecosystem bridging the gap between small primary producers and higher consumers. Our results show that tunicates performed better in acidified water for all tested parameters. Notably, tunicates in acidified water grew and developed more rapidly and we observed a significant increase in fecundity. These results will be discussed at the light of potential consequences on future ecosystems.

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A NUMERICAL STUDY OF TRANSPORT AND SPREADING OF GASES FROM GAS-SEEPAGE THROUGH THE SEAFLOOR M16

Enstad, Lars Inge[1,2], Peter M. Haugan[2], and Guttorm Alendal[1,3]

Gas seeps through the seafloor at several locations around the world oceans. These seeps are observed as both CO_2 rich liquid/gas in volcanic areas such as Mid Ocean Ridges, and as hydrocarbon gases, consisting mainly of CH_4, in hydrocarbon rich areas such as the North Sea. The release of CO_2 through the ocean bottom is a contribution to the global CO_2 budget. These events are interesting from a phenomenological perspective and have been studied through observations and modeling the last decades. In order to describe the role of such sources in ocean biogeochemical cycles, it is necessary to understand how the gas is dissolved and spreads in plumes above the leakage. In this investigation we combine modeling efforts on the dissolution and spreading from the leakage point and compare with in situ data.

In this specific study a modeling tool has been developed where the MIT general circulation model (http://mitgcm.org/) has been coupled with an improved version of a single bubble/droplet model. The MITgcm model has previously been modified to make it capable of simulating transport and spreading of CO_2 as a dynamically active tracer. The vertical mixing of CO_2 is parameterized employing state-of-the-art models using the General Ocean Turbulence Model (http://www.gotm.net/). The coupled droplet/bubble-OGCM has been compared with the existing single-droplet model and also plume models to verify the implementation. At the current stage the gas flux through the seafloor is given at a fixed rate, with a statistical distribution to set the bubble/droplet sizes.

To check the model capabilities in a natural environment the model will be applied to an area where there exist in-situ data for the environmental parameters and for the plume spreading. We hope to be able to present comparison using different parameters of these data with model results at the conference.

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THE PROCESSES INFLUENCING THE DISTRIBUTION OF INTERTIDAL COMMUNITIES IN A HIGH CO_2 OCEAN T16

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The barnacle *Semibalanus balanoides* is a major space occupier on rocky shores in Northern Europe and hence changes in its population ecology can have a broad influence on other species. Despite its ecological importance, the impact of a warmer, more acid ocean on this species, and hence on intertidal communities, remains unclear. In this paper we demonstrate how temperature and carbon dioxide interact to affect *S. balanoides* egg development, nauplii development and cyprid development. Changes in abundance and viability of the early life stages will impact the supply of larvae arriving in the intertidal and post settlement mortality will determine the number of individuals reaching reproductive age. Laboratory experiments indicated that changes in pH and temperature slowed the metamorphosis of cyprids thereby increasing their exposure to desiccation. Nevertheless, increased temperature and CO_2 concentration had greatest impact on smaller individuals prior to metamorphosis; with poor survival being linked to slow growth and ability to calcify. The paper also also discusses how this experimental data can be used to develop models for the prediction of changes in population distributions as well as aspects such as secondary production and calcium carbonate production.

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THE IMPACT OF MODEL RESOLUTION ON PROJECTIONS OF FUTURE OCEAN ACIDIFICATION M17

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Ocean acidification with the associated shift of the calcite and aragonite saturation horizons is likely to have a negative impact on pelagic organisms producing calcite and aragonite shells, such as coccolithophores, foraminiferas and pteropods. In order to quantify these effects, comprehensive and thorough model studies of both the changing calcite and aragonite saturation state and its effect on calcite and aragonite production and dissolution are essential.

We have used the pelagic biogeochemical ecosystem model PISCES in combination with two dynamical models of different resolutions. The PISCES model simulates the marine biological productivity and describes the biogeochemical cycles of carbon and main nutrients. It distinguishes two phytoplankton and two zooplankton size classes. The production of calcite is assigned to nanophytoplankton as a function of temperature, saturation state, nutrient and light availability, whereas the production of aragonite is assigned to mesozooplankton as a function of saturation state. The PISCES model is originally connected to the global dynamical NEMO/OPA8.2 model which is of relatively high resolution. We have additionally coupled PISCES to the global dynamical low spatial resolution Bern3D model. Both the OPA/PISCES model and the new Bern3D/PISCES model were run until equilibrium state was reached and the models were forced with increasing atmospheric CO_2 concentrations following the SRESA2 scenario. Here we show the effect from using two dynamical models of different resolutions on the projected ocean acidification in addition to presenting potential changes in the pelagic calcite and aragonite budget with increasing concentrations of atmospheric CO_2.

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EUROPEAN PROJECT ON OCEAN ACIDIFICATION (EPOCA) T17

Gattuso, J.-P., L. Hansson, and the EPOCA Consortium

The *European Project on Ocean Acidification* (EPOCA) was launched in May 2008 with the overall goal to advance our understanding of the biological, ecological, biogeochemical, and societal implications of ocean acidification. Its consortium includes 105 principal investigators from 27 institutes. The budget of this 4 year long project is 16,5 M€, including 6,5 M€ from the European Union. The research efforts of EPOCA are divided into four different themes. First, EPOCA will focus on past and present spatiotemporal changes in ocean chemistry and biogeography of key marine organisms. Second, EPOCA will quantify impacts of ocean acidification on marine organisms and ecosystems. Molecular, physiological and ecological approaches will be used to study climate-relevant biogeochemical processes, including calcification, primary production and nitrogen fixation. Laboratory and field perturbation experiments will focus on key organisms in terms of their ecological, biogeochemical, or socioeconomic importance. Third, EPOCA will improve biogeochemical, sediment, and coupled ocean-climate models to better account for how ocean acidification will affect ocean biogeochemistry and ecosystems. Special attention will be paid to feedbacks of physiological changes on the carbon, nitrogen, iron, and sulfur cycles and how these changes will affect and be affected by future climate change. Finally, EPOCA will evaluate uncertainties, risks and thresholds (tipping points) related to ocean acidification at molecular, cellular and organismal levels from local to global scales. It will also assess the decrease in CO_2 emissions required to avoid these thresholds and describe the change to the marine environment and Earth system, should these emissions be exceeded.

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EFFECT OF SEAWATER ACIDIFICATION ON THE GROWTH OF MYTILUS EDULIS M18

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The Intergovernmental Panel on Climate Change (IPCC) predicts atmospheric CO_2 partial pressure (pCO_2) ranging from 490 to 1,250 ppmv in 2100, depending on the socio-economic scenario considered. Because one third of anthropogenic CO_2 emissions has been stored in the oceans, ocean pH has already declined by 0.1 unit compared with pre-industrial values and is predicted to decrease by another 0.4 unit by the end of the century. Seawater acidification lowers the concentration of carbonate ions, one of the building blocks of calcium carbonate ($CaCO_3$), which can in turn greatly affects the ability of calcifying organisms to precipitate $CaCO_3$. Few studies have investigated the detrimental effect of acidic waters on bivalves and none investigated the response of calcification to pCO_2 levels within the range of values projected by IPCC. Here, we report experimental data showing that calcification and growth of mussels (*Mytilus edulis*) is significantly impacted by a decrease of seawater pH. In the laboratory, mussels were incubated during 4 months at two different pCO_2: 400 and 800 ppm. Calcification rates estimated using the alkalinity anomaly method and shell length vs. shell weight relationships showed a significant decrease of calcareous production between the 400 and the 800 ppm treatment. A shift in shell mineralogy has also been evidenced as aragonite/calcite ratios decreased significantly with increased pCO_2. Finally, an important decrease of mussel health determined using the Neutral Red Retention technique has been shown at 800 ppm, suggesting elevated levels of calcium ions in the haemolymph, generated by dissolution of the shells.

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21[ST]-CENTURY CHANGES IN BOTTOM-WATER PH IN THE HIGH-LATITUDE NORTH ATLANTIC. T18

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Data-based estimates indicate that anthropogenic CO_2 has already penetrated deep into water masses of the abyssal high-latitude North Atlantic. A suite of models hindcasting similar present-day patterns project that if atmospheric CO_2 continues to increase following the IPCC IS92a (business-as-usual) scenario, these same water masses will reach levels of anthropogenic DIC by 2100 exceeding 100 $\mu mol\ kg^{-1}$. This is twice the present-day surface concentration. We translated these perturbations into corresponding reductions in pH of bottom waters and found that they exceed 0.2 pH units in most bottom waters of the North Atlantic situated poleward of 50ºN. Reductions in pH beyond this threshold are considered by environmental agencies to be dangerous in natural waters, and have been reported to be detrimental to deep-sea benthic organisms. Moreover, these pH reductions are much larger than the amplitude of natural variability of pH in North Atlantic bottom waters. To study how effects of climate change may alter projected changes in bottom-water pH, e.g., by slowing Atlantic Meridional Overturning, we exploited simulations from a coupled climate-carbon cycle model and a sensitivity test to isolate effects from melting of land ice. Generally, 21[st]-century climate change was found to render bottom-water pH reductions somewhat less severe, especially when considering effects from land ice melt. Yet in all simulations, with or without climate change, there are large reductions in pH in bottom waters of the North Atlantic. These will expose sediments and benthic organisms to changes in conditions during the 21[st] century that are much larger than any variability that they have experienced during at least the last 420,000 years.

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EFFECT OF SEAWATER ACIDIFICATION ON EPIBIONT-BEARING CIDAROID SPINES M19

Guibourt, Virginie, Ana I. Catarino, and Philippe Dubois

Due to their well-developped high-magnesium calcite endoskeleton, echinoderms will particularly suffer from seawater acidification. Among them, cidaroid sea urchins could be especially affected since, in this group, fully-grown spines are no more covered by an epidermis, leaving the skeleton in direct contact with seawater. These « naked » spines are usually heavily colonized by epibionts making these sea urchins « islands of biodiversity ». This is particularly well evidenced in the Southern Ocean where the presence of cidaroids and their epibionts significantly increase biodiversity of the muddy substrates on which they live. Most models of the ocean-carbon cycle predict that the shallowing of the calcium carbonate saturation horizons due to increasing anthropogenic CO_2 emissions will be particularly important in the Southern Ocean. So, effects of acidification on cidaroid spines are particularly relevant to the ecology of this region.
In the present study, we assessed the impact of magnesium-calcite saturation level on cidaroid spines of both experimental and field specimens. In experimental conditions, spines were incubated for up to three weeks in CO_2 enriched seawater of controlled pH (7.2, 7.6 and 8.2) and temperature. Total alkalinity was measured and saturation level calculated. The spine immerged weight was measured, morphological evidence of etching was monitored by scanning electron microscopy and cover of epibionts was evaluated. Dried field specimens from different depths below and above the current saturation horizon were obtained from museum collections. Morphological evidence of etching and magnesium concentration in the skeleton were determined.

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GROWTH, CALCIFICATION AND ACID-BASE REGULATION IN THE CEPHALOPOD *SEPIA OFFICINALIS* UNDER ELEVATED CO_2 T19

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Changes in seawater pH and carbonate chemistry associated with ocean acidification negatively influence calcification in all marine invertebrates studied to date. Our experimental work, with the cephalopod mollusc *Sepia officinalis*, is the first to show that in some invertebrates, neither calcification nor somatic growth decrease under low seawater pH and low Ω_{arag}. During a six-week period, juvenile *S. officinalis* maintained under both ~4,000 and ~6,000ppm CO_2 grew at the same rate (4% body mass daily) and gross growth efficiency as control animals, increasing the mass of their calcified internal shell by >500%. Closer examination of the tissue and blood acid-base status of the animals revealed that during long-term exposure they had fully compensated the initial acidification and maintained elevated bicarbonate levels in their blood. Accumulated bicarbonate did not result from internal shell dissolution as in other molluscs, extracellular $[Ca^{2+}]$ was maintained at control levels. On the contrary, high CO_2 (6,000 ppm) animals were able to deposit significantly higher amounts of $CaCO_3$ in their shells and also were characterized by altered shell morphology. SEM images revealed strong increases in the number of shell-chambers constructed by high-CO_2 animals. Whether observed changes in shell morphology under high-CO_2 conditions constrain the ecological fitness of the animal in any way needs to be investigated. We conclude that cephalopods possess a certain level of pre-adaptation to long-term increments in carbon dioxide levels, as indicated by their efficient pH compensation, maintained growth and calcification performance.

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BIOGEOCHEMICAL APPROACH OF ENVIRONMENTAL ASSESSMENT FOR CO2 OCEAN STORAGE M20

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Ocean should be a good candidate for storage of CO_2 collected from large sources because it can receive a large amount of CO_2 without significant change of pH and DIC due to its large water mass. However, significant changes in chemical properties could occur near release points of CO_2. Storage of CO_2 into geological formation under seabed is also considered and it has a possibility of leakage of CO_2 into bottom water. If the significant changes in chemical properties occur near the release and/or leakage points, not only marine organisms but also biogeochemical processes can be affected. To understand effects onto the biogeochemical processes including dissolution and degradation of inorganic and organic particles, we studied how low pH and high CO_2 can effect onto dissolution of calcium carbonate and also activities of microbial processes.
Laboratory experiments were conducted under high pressure and high pCO_2 condition to understand change of the dissolution rate of calcium carbonate. As a result, rapid dissolution was observed at above 5000 ppm of pCO_2. The initial dissolution rate was well correlated with initial concentration of dissolved inorganic carbon. Dissolution of calcium carbonate increased dissolved inorganic carbon and total alkalinity in the seawater. Then, degrees of undersaturation and dissolution rate of calcite in the seawater were decreased with time. Dissolution rates normalized with apparent surface area were well fit to the rate law in the empirical kinetic showed in previous studies.
We will also show result of laboratory experiment for bacteria growth in our poster.

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FUTURE ECOSYSTEM CHANGES PROJECTED BY A 3-D HIGH-RESOLUTION ECOSYSTEM MODEL T20 WITHDRAWN

Hashioka, Taketo[1,2], Takashi T. Sakamoto[1], Takeshi Okunishi[3], Hiroshi Sumata[4], and Yasuhiro Yamanaka[1,2,4]

In recent years impacts of global warming on physical environment have been projected through some scenario experiments using climate models (CO-AGCMs). As a challenge of modelling responses to global warming on marine ecosystem, we developed a 3-D high-resolution ecosystem model, COCO-NEMURO, with off-line calculation method which can directly use projected results of CO-AGCMs as a physical field of the ecosystem model. The COCO-NEMURO consists of PICES NEMURO (North Pacific Ecosystem Model for Understanding Regional Oceanography) coupled with COCO (CCSR Ocean Component Model) which has a horizontal resolution of 1/4 by 1/6 degrees. As a first step, we applied this model to the western North Pacific, and conducted a global warming experiment using physical fields from a high-resolution climate model (the CCSR/NIES/FRCGC CO-AGCM which contributed to the IPCC-AR4, and will contribute to the AR5). The experiment is conducted following a scenario in which atmospheric CO_2 concentration increases by 1% per year. Our model well reproduced the seasonal and regional variations of lower-trophic level ecosystem associated with meso-scale features in the present-day simulation. Under the global warming condition, it is interesting that our model projected the increase in Chl-a concentration during spring bloom by 10 to 20 % in the subarctic region even though annually averaged Chl-a concentration decreases. Since these changes would affect the higher-trophic level ecosystem, we have been also developing an integrated marine ecosystem model explicitly representing linkages between the lower-trophic level ecosystem and major pelagic fishes based on COCO-NEMURO. We present some highlights in our first stage results.

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OBSERVATIONS OF ACIDIFICATION IN THE WEDDELL SEA ON A DECADAL TIME SCALE M21

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The amount of anthropogenic CO_2 (C^{ant}) that entered the Weddell Sea between 1992 and 2008 is assessed using extended multiple linear regression. Two multiple linear regressions for total dissolved inorganic carbon (C_T) were conducted independently for two data sets from 1992 and 2008 based on potential temperature, salinity and oxygen. Subtracting these two relationships leads to an estimate of C^{ant} accumulated in the considered time span (ΔC_T) assuming that the relations between input parameters and C_T do not change with time.
Invasion of C^{ant} appears to have occurred in agreement with the general knowledge of the circulation indeed. In the Antarctic Circumpolar Current and in the Warm Deep Water ΔC_T values are close to zero, whereas values as high as 10 µmol kg^{-1} are observed in the surface layer. ΔC_T concentrations at the surface vary with latitude between 1 and 15 µmol kg^{-1}. Also the intrusion of C^{ant} into deep layers was demonstrated, near the sea floor ΔC_T yields 5–6 µmol kg^{-1}.
The invasion of C^{ant} provokes a shift in the equilibria of the carbonate system, resulting in acidification and depletion of CO_3^{2-}. A detailed account of the changes that occurred between 1992 and 2008 will be given. The mean decrease of pH in the upper 200 m layer is 0.015.
Further effects are decrease of calcite and aragonite saturation levels. In contrast to other studies, results of this analysis suggest that aragonite undersaturation of surface waters in the Weddell Sea won't be reached before the year 2150.

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THE UTILIZATION OF PHYSIOLOGICAL MEASUREMENTS TO PREDICT FUTURE 'WINNERS' IN A HIGH-CO_2 WORLD – A CASE STUDY USING THE MODEL AMPHIPOD *GAMMARUS LOCUSTAi* T21

Hauton, Chris, Toby Tyrrell, and John Williams

It is almost universally accepted that the current atmospheric CO_2 concentration of ca. 380 ppmv is set to rise by an estimated 1% y^{-1} over the next few decades. However, it currently remains difficult to predict the future impacts of acidification, especially in coastal and estuarine species which may have evolved to accommodate episodic low pH environments.

We report an investigation of the effects of increases in pCO_2 on the growth and molecular physiology of the neritic amphipod *Gammarus locusta*, which has a cosmopolitan distribution in estuaries. Amphipods were reared from juvenile to mature adult (~ 28 days) in laboratory mesocosms at three

different pCO_2 concentrations. pCO_2 was regulated by computer-controlled addition of 100% CO_2 which maintained pH set points of nominally pH 8.1 (control) and pH 7.8 and 7.6 (experimental).

Growth rate was estimated from weekly measures of body length and converted to AFDW. At sexual maturity the amphipods were sacrificed and assayed for changes in expression of the genes coding for a heat shock protein and the metabolic enzyme glyceraldehyde-3-phosphate dehydrogenase.

The presented data show that this species of amphipod is not significantly impacted by a decrease in sea water pH of up to 0.5 units. These data highlight the fact that in a future 'High CO_2 World' there will be winners as well as losers, which may lead to shifts in the biogeographic distribution of many species. Future experiments modeling the effects of increased pCO_2 on the reproductive success and other trans-generational impacts will be discussed.

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CO_2-DRIVEN ACIDIFICATION RADICALLY AFFECTS DEVELOPMENT AND LARVAL SURVIVAL IN MARINE ORGANISMS – I. IMPACT ON FERTILIZATION M22

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CO_2-induced ocean acidification threatens the viability of keystone calcifying taxa such as corals, coccolithophores, and pelagic molluscs. Research to date has focussed on the adult stages of calcifying taxa, using gross pH changes relevant for the years 2200 – 2400. We investigated the consequences of exposure to CO_2-induced acidification by -0.4 pH units (the upper limits of predictions for the year 2100, IPCC AR4 2007) for gametes and larvae of keystone marine species. We found statistically significant reductions in sperm swimming performance, fertilization success, and post-metamorphic juvenile survival in acidified treatments. We discuss the implications of these findings for fertilization success and development of the larvae of both non-calcified and calcified taxa, and for the population viability of marine invertebrates.

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GLACIAL LESSONS FOR HIGH CO_2 – LIMITATIONS AND CHANCES T22

Heinze, Christoph

Glacial atmospheric CO_2 partial pressures were about 200 μatm lower than today and 100 μatm lower than at the preindustrial. It is tempting to use the glacial low CO_2 world as a reverse paleo-analog to a high CO_2 world. For the ocean, the last climatic cycle is very well documented by marine sediment core data. However, the glacial low CO_2 world was probably created through an internal redistribution of "already circulating carbon" between the Earth system reservoirs, rather than through extracting or adding carbon to or from an external reservoir (fossil fuel resources). Apart from this fundamental difference, several questions with relevance to the high CO_2 world may be answered through glacial evidence: (1) Was the $CaCO_3$:POC rain ratio enhanced under higher pH conditions at the sea surface? (2) What were the consequences of high DIC concentrations in glacial deep waters? (3) Why seem both the physical and the biological CO_2 feedback to act positively for glacial-interglacial changes? For addressing these questions, the method of synthetic sediment cores was developed. We demonstrate how it can be used to combine biogeochemical ocean general circulation models with sediment and ice core data to inversely estimate the glacial-interglacial changes in governing carbon cycle parameters. The method is the foundation for a systematic data assimilation of the marine paleo-

record into Earth system models for calibrating their sensitivity to internal and external forcings. It opens the possibility to include all our knowledge of the past in models for predicting an as yet uncertain future.

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HYPERCAPNIC STRESS IN EARLY LIFE STAGES OF THE SQUID LOLIGO VULGARIS DUE TO ELEVATED ENVIRONMENTAL CO_2 M23

Hu, Marian Y.-A., Andrea Y. Frommel, Catriona Clemmesen, and Frank Melzner

Cephalopods are high performance organisms and key predators in marine food webs. The effects of rising CO_2 and resulting changes in the ocean's carbonate system on these animals are yet poorly understood. In this study, we test the impact of elevated CO_2 concentrations on the development and performance of early life stages of cephalopods. *Loligo vulgaris* eggs were incubated at 15°C in sea water equilibrated with three different CO_2-air mixtures (380ppm, 1,400ppm or 4,000ppm CO_2 fraction). Under high CO_2 concentrations (4,000ppm), stage 26 embryos exhibit significantly shorter dorsal mantle lengths and slower developmental rates when compared to larvae incubated at lower CO_2 levels (380ppm and 1,400ppm). After hatch, somatic growth rates will be compared to biochemical indicators of growth and condition. Protein and lipid concentrations, as well as RNA/DNA ratios will serve as measures for energy stores and growth potential, respectively. The energetic investigations are complemented by the study of ion regulatory structures, which are highly challenged by acid-base disturbances. Thus, special emphasis is given to the development of branchial epithelia, by immunohistochemical methods to follow the structural differentiation of gill tissue as well as the occurrence and localization of the marker protein Na^+/K^+-ATPase. Additional information will be provided by the screening of the ion regulatory transcriptome (e.g. Na^+/H^+-exchangers, HCO_3^- transporters, Na^+/K^+-ATPase etc.) of whole embryos and various tissues such as gill, branchial heart and skin.

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AN OBSERVATIONAL AND MODELLING STUDY TO DEFINE THE CURRENT pH STATUS OF U.K. WATERS T23

Hydes, David[1], Eric Achterberg[1], Dorothee Bakker[2], Jerry Blackford[3], Nick Hardman-Mountford[3], Matt Mowlem[1], Ute Schuster[2], Carol Turley[3] Toby Tyrrell[1] and Andew Watson[2]

Although a number of serious potential impacts of marine acidification are recognised, little information exists on what present conditions are particularly in the complex environment of European shelf seas. The U.K. Government has funded two years of "baseline" observations. Relatively large natural changes occur in pH through a seasonal cycle. The measurement programme will determine the scale of these changes in a range of areas from eutrophic estuarine to open ocean. New measurements will be linked with on-going monitoring which will provide the information required to put the observations into their hydrodynamic and biogeochemical context. Existing time series data will be used along with the new measurements to quantify the likely degree of variation in pH over longer periods. A data set will be established of the new data and metadata describing its collection and validation. The carbonate system will be studied through measurements of discrete samples to determine DIC and Total Alkalinity, with continuous determination of pCO_2 on related cruises and ships of opportunity and direct measurements of pH. The newly available data will be used to evaluate and improve the ERSEM-POLCOMS full-shelf dynamic simulation model.

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A TOOL FOR EARLY DETECTION OF GLOBAL-SCALE CHANGES IN MARINE CALCIFICATION M24

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Ocean acidification is likely to impact calcification rates in many pelagic organisms, which may in turn cause significant changes in marine ecosystem structure. We examine effects of changes in marine $CaCO_3$ production on total alkalinity (TA) in the ocean using the global biogeochemical ocean model HAMOCC and a variety of future calcification scenarios. The model integrations start at a pre-industrial steady state in the year 1800 and run until the year 2300 forced with anthropogenic CO_2 emissions. Calculated trends in TA are evaluated taking into account the natural variability in ocean carbonate chemistry, as derived from repeat hydrographic transects. Using a synthesis of modeling and observational data, we address the following questions. (1) At what time does ocean acidification lead to a decline in marine calcification on a global scale that is detectable in the data? (2) Assuming different calcification scenarios, does the data presently available already allow discerning significant trends, given natural variability and data uncertainties? (3) If so, what is the magnitude and time scale of the decline? Our long-term goal is to help identifying target regions for future ocean chemistry surveys that are critical for early detection and determination of the exact magnitude of large-scale acidification effects from field data.

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EFFECTS OF ELEVATED CO_2 CONCENTRATIONS ON P-UTILIZATION OF THE DIAZOTROPHIC CYANOBACTERIUM *NODULARIA SPUMIGENA* AND A NATURAL SUMMER PHYTOPLANKTON COMMUNITY IN THE BALTIC SEA T24

Isensee, Kirsten[1], Henning Johansen[1], Maren Voss[1], Ulf Riebesell[2] and Monika Nausch[1]

The influence of elevated pCO_2 concentrations on cyanobacteria of the Baltic Sea was examined in two different approaches:
1. In free drifting mesocosms (60 m³) a gradient of different pCO_2 levels was adjusted by acidification with HCl. P-utilization ($[^{33}P]PO_4$ uptake) positively correlated with increasing pCO_2 for small coccoid cyanobacteria. In contrast, cyanobacteria in the size fraction >10 µm showed less P uptake under pCO_2 levels above 1000 ppm. Measurements of the inorganic and organic phosphorus pool (DIP, DOP) indicated no significant differences in consumption for the bulk phytoplankton along the CO_2 gradient.
2. In laboratory experiments with colony forming *Nodularia spumigena*, a representative Baltic Sea cyanobacterium, we investigated the kinetic response of P-utilization of DIP and DOP. We incubated *N. spumigena* under defined pCO_2 values which we obtained by directly injecting CO_2 gas to reach 450 ppm, 600 ppm and 900 ppm in 0.2 µm filtered natural seawater. DIP and DOP were added and their uptake and nitrogen fixation rates measured. The results suggested a lower P-utilization up to 64 % under present nutrient conditions and high pCO_2 levels, while additional DIP tends to favour the growth under high pCO_2. At pCO_2 of 900 ppm we detected 75 % higher P-utilization compared to present day conditions. In contrast, the amendment of DOP does not stimulate the P-utilization of *N. spumigena* under high pCO_2 levels.
Cyanobacteria with heterocysts and unicellular species may respond differently to elevated CO_2 concentrations which may results in possible changes in species composition with rising atmospheric pCO_2.

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IMPACT OF CLIMATE VARIABILITY ON SURFACE OCEAN CO_2 IN THE PACIFIC SIMULATED IN A 3-DIMENSIONAL MODEL M25

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Interannual to decadal variability of carbon cycle is diagnosed with a 3-dimensional physical-biogeochemical model to improve our understanding of physical and biological impact on the carbon cycle in the Pacific Ocean. We have performed the simulations with two boundary conditions for atmospheric pCO_2: one using the historical increase in atmospheric pCO_2 from year 1783 to 2002 (historical run), another with a constant pre-anthropogenic concentration of 278 ppmv (control run) in order to quantify the natural and anthropogenic carbon cycle. The modeled surface ocean at the Hawaiian Ocean Time-series (HOT) shows a long tern shift in carbonate equilibrium to lower pH and lower saturation states of the carbonate mineral aragonite, which are consistent with the observation. The model simulates two dominant climate variations; Pacific Decadal Oscillation (PDO) and El Niño/Southern Oscillation (ENSO). In the central North Pacific, primary production and biomass increase after the climate shift during the mid 1970s, and CO_2 flux also exhibits interannual-decadal variability. The variations of natural and anthropogenic CO_2 flux are in phase, i.e., both increase and decreases in the Central Pacific in interannual to decadal scale. The variations of natural and anthropogenic CO_2 flux are out of phase in the eastern Pacific, i.e., air-to-sea flux of anthropogenic CO_2 decreases when natural CO_2 flux increases and vice versa. This is explained with physical conditions such as upwelling and thermocline variability associated with El Niño and La Niña. Interannual variability of surface saturation states of the carbonate minerals associated with the climate variability is presented.

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IN SITU **ENCLOSURE EXPERIMENT DEVICE FOR ASSESSING DEEP-SEA ECOSYSTEMS WITH HIGH CO_2 CONCENTRATIONS T25**

Ishida, Hiroshi[1,2], Yuji Watanabe[1,2], Michimasa Magi[2] and Yoshihisa Shirayama[3]

It has been proposed to inject CO_2 into the ocean as a potentially effective method to mitigate global warming. Various methods such as seabed direct injection and dilution/dissolution techniques have been proposed, and their feasibility studies being carried out. However, the information on the impact of high CO_2 concentrations on deep ocean ecosystems is insufficient. In order to study the influence of CO_2 sequestration on the deep-sea ecosystem, it is necessary to investigate the ecosystem not only at the species level but also at the community level. To asses the influence of high CO_2 concentrations on deep-sea organisms precisely, it is necessary to carry out *in situ* experiments in deep-sea.
We here developed two types of experimental devices for evaluating on deep-sea ecosystems with elevated CO_2 concentration. One is a free fall type benthic chamber system on deep-sea benthic communities. The other is a water enclosure experiment system (pelagic chamber) in order to do the *in situ* experiment on plankton communities at 1,000 – 2,500 m in depth. Experiments with the benthic chamber system with elevated CO_2 concentrations (averages of 20,000μatm, 5,000μatm,

2,000µatm and control) were carried out in the Kumano Trough. The pelagic chamber system is under development and will consist of three chambers (250 L x 3), CO_2 control and water sampling apparatuses with several kinds of sensors. Results of the experiments using these systems and future planning of *in situ* experiments were reported.

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TREND OF OCEAN ACIDIFICATION IN THE WESTERN NORTH PACIFIC M26

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It is highly important to clarify the present status of ocean acidification by observations. Global Environment and Marine Department of JMA and MRI have been collaboratively continuing routine atmospheric/oceanic CO_2 measurements in the western North Pacific. These measurements in the tropical and subtropical zones along 137ºE include pCO_2 in air and in seawater in January-February since early 1980s and in June-July since 1990, DIC section by coulometry since 1994, pCO_2 and sections of DIC and pH by spectrophotometry four times per year since 2003.
While large meridional gradients and seasonal variations in these parameters and temperature have been observed in surface layer of the northern subtropical zone (ΔpCO_2sw = *ca.* 90 µatm, ΔNDIC (S=35) = *ca.* 35 µmol kg^{-1}, ΔpH at SST = *ca.* 0.10, and ΔSST = *ca.* 10 ºC), the range of temporal and spatial variations in NTA calculated from these parameters is smaller (*ca.* 10 µmol kg^{-1}). Increasing rates of pCO_2sw in January-February since 1983 and that in June-July since 1990 are both nearly equivalent to the increasing rate of atmospheric CO_2 during the same period. Such an increasing trend is also seen for NDIC in the water column above 26.8 σ_θ at around 30ºN, where increasing rate of NDIC ranges from +1.0 to +1.5 µmol kg^{-1} yr^{-1}. These results strongly suggest that pH in the upper layer of the western North Pacific tropical and subtropical zones is decreasing at a mean rate of *ca.* -0.015 per decade.

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EFFECTS OF HIGH CO_2 ON DEEP-SEA FISHES T26

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This study aims to evaluate the effects of CO_2 plumes created by deep-sea CO_2 injection on deep-sea fishes. Three species of deep-sea fishes have been obtained alive from the depth of 380 m at a deep-water withdrawal facility in Toyama, Japan. They can be kept in laboratory conditions for several months under the atmospheric pressure at 1-2°C, and used for in vivo CO_2 exposure experiments under the atmospheric and elevated pressures. We have developed an experimental setup to expose deep-sea organisms to high CO_2 conditions under pressures of up to 20 MPa at 1-2°C, which also allows us to record electrocardiogram to monitor heart rate.
Under the atmospheric pressure, a deep-sea fish *Careproctus trachysoma* (Liparididae) showed 100% mortality within 48 h at 30,000 □atm CO_2 conditions and 17% within 72 h at 20,000□atm. The other two species (*Allolepis hollandi* and *Malacocottus gibber*) showed mortalities similar to those we had

found for shallow-water fishes (mortality occurred mostly above 50,000 µatm). The ongoing high-pressure experiment indicates the possibility that the elevated pressure of 6 MPa could reduce CO_2 tolerance of *C. trachysoma*. Video recordings demonstrated depressed gill ventilatory frequency in hypercapnic conditions under the atmospheric and 6 MPa conditions, in contrast to hyperventilatory responses to CO_2 known for most shallow-water fishes. Preliminary electrocardiogram recordings under 10 MPa demonstrated a rapid decline in response to 20,000 µatm exposure (fish died at 13 h). Thus, some deep-sea fishes might be more sensitive to CO_2 than shallow-water species, particularly under high pressure conditions.

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IMPACTS OF OCEAN ACIDIFICATION ON BENTHIC PRIMARY PRODUCERS: LESSONS FROM A COLD CO_2 VENT SITE M27

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Benthic autotrophs represent a small yet important fraction of total aquatic primary productivity. Whilst ocean acidification has been projected to impact the viability of calcifying organisms, the effect on photosynthesis and the production of the climate relevant trace gas dimethyl sulphide (DMS) is poorly understood. Previous studies speculated that high-CO2 conditions will (1) release autotrophs from the need to divert photosynthetic energy to carbon-concentrating mechanisms and (2) reduce the overall production of DMS and its precursor dimethylsulphoniopropionate (DMSP). Here we present data from a field study conducted on the island of Ischia in the Bay of Naples in May 2008. This site is characterised by cold volcanic vents of 90% CO_2 that create a pH gradient of about 6.0 to 8.2 along 300 m of shoreline. Recent evidence suggests that natural CO_2 vents can be used to reveal ecosystem effects of ocean acidification. We deployed two *in situ* pH loggers to describe the spatio-temporal variation in pH and conducted a survey of DMSP and DMS production in seaweeds and benthic microalgae along the pH gradient. A characterisation of primary productivity and photosynthetic efficiency complements our data set. Our results address changes in marine benthic communities in a future ocean scenario and their possible effect on primary productivity and air-sea emissions of DMS.

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EFFECTS OF HIGH CO_2 CONCENTRATIONS ON THE *PHAEODACTYLUM TRICORNUTUM* (BACILLARIOPHYCEAE) AND *NODULARIA SPUMIGENA* (CYANOPHYTA) GROWTH AND ORGANIC MATTER PRODUCTION T27

Kosakowska, Alicja, and Janusz Pempkowiak

The coastal seas and estuaries are especially vulnerable to effects of increased CO_2 in the air. The extend by which production of organic matter is enhanced under increased CO_2 availability is of utmost importance for the areas. Also effects of chemical changes in the river run-off are important and require clarification.

In order to investigate the influence of increased CO_2 concentration in the atmosphere on the phytoplankton growth and organic matter production at three CO_2 concentrations, mimicking the present day (360ppm), the near future (600ppm), and a would be (1000ppm) conditions a series of experiments were performed. The influence was measured using two phytoplankton species, namely diatom *P.tricornutum* and Baltic cyanobacterium *N.spumigena*.

The growth rate and chlorophyll content were enhanced when *P.tricornutum* was grown at high CO_2 with respect to normal CO_2. The growth at 600 and 1000ppm CO_2 was 1,5 and 2 times higher as compare to 360ppm CO_2. On the other hands the production of chlorophyll and cells growth of *N.spumigena* were both negatively affected at 600 and 1000 CO_2 ppm during a 5 days long

incubations, and positively affected at 600ppm CO_2 after 7 days cultivation. Significant differences in chlorophyll content were observed between cells exposed to 600ppm CO_2 enriched air and the control, as were in the DOC concentrations in sea water used as culture medium.
The contrasting influence of the high CO_2 on the growth of these species suggests that CO_2 may alter algal community composition and species succession under actual high CO_2 stress.

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COCCOLITHOPHORE COMMUNITY RESPONSE TO OCEAN ACIDIFICATION M28

Krug, Sebastian A., Birte Matthiessen, Ulf Riebesell, and Ulrich Sommer

The effects of ocean acidification on the calcification and photosynthesis of coccolithophores has been a focus of research for more than a decade. So far most studies have relied on experiments with single species strains, indicating taxon-specific differences in the responses to rising atmospheric pCO_2. While environmental perturbations can have profound impacts on the diversity of an ecosystem and it has been hypothesised that diverse systems are able to compensate perturbations more efficiently than species poor systems. Hence, this experiment focuses on the capacity of a multispecies assemblage to absorb stress and re-organize while undergoing change. This has been addressed by exposing an artificial community consisting of *Emiliania huxleyi, Gephyrocapsa oceanica* and *Coccolithus pelagicus braarudii* to elevated CO_2 and comparing its response to that of the individual species in monocultures. Preliminary results of fully factorial tested effects of decreasing pH/increasing pCO_2 show significant treatment differences in the biomass production of monocultures compared to the coccolithophore assemblage. In terms of biomass production the community was able to compensate the CO_2/pH stress and underwent a shift from a *Gephyrocapsa oceanica* dominated assemblage at low pCO_2 towards an *Emiliania huxleyi* dominated system at a high pCO_2.

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REPRODUCTIVE PHYSIOLOGY OF SEA URCHIN IN A HIGH-CO_2 WORLD T28

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Calcifying marine organisms are the most vulnerable to reductions of calcium carbonate ($CaCO_3$) saturation state. Although previous studies revealed effects of high CO_2 seawater on calcification rate, growth rate and physiology of adult calcifiers, little is known about impacts on early development and reproduction, which is crucial to understand CO_2 effects in a population level, since these are usually the most sensitive stages of a life cycle and directly affect population size. Additionally, it is critical to understand their synergetic effects of high CO_2 and temperature on marine organisms.

We studied the reproductive physiology of sea urchin *Hemicentrotus pulcherrimus* reared under high CO_2 (1,000 ppm CO_2) and high CO_2 + high temperature (1,000 ppm CO_2 + 2° C) condition for 8 months. We found that both conditions impacted the physiology, GSI (gonad wet weight / wet weight) and gonad development of the sea urchin, although these conditions did not affect the survival and growth rate (size) of sea urchin. These results suggest that a future high-CO_2 world will potentially affect the reproductive success of sea urchin. Together with our previous findings of negative impacts of increased seawater CO_2 on the early development, we suggest that sea urchin populations will be threatened in a high-CO_2 world.

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EFFECTS OF INCREASED CO2 AND TEMPERATURE ON TRACE-ELEMENT BIOACCUMULATION IN EGGS OF THE COMMON CUTTLEFISH, *SEPIA OFFICINALIS* M29

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Cephalopods play a key role in many marine trophic networks and constitute alternative fisheries resources, especially given the ongoing decline in finfish stocks. Cephalopods die after mating, which means that their population dynamics are highly dependent on the hatching success of their eggs. Along the European coast, the eggs of the cuttlefish *Sepia officinalis* are characterized by an increasing permeability of the eggshell during development, which leads to selective accumulation of essential and non-essential elements in the embryo. Temperature and pH are two critical factors that affect the metabolism of marine organisms, but very few studies have considered the synergistic effect of both factors on trace-element bioaccumulation. In this study, we are testing the effects of pH and temperature through a crossed (3x2) laboratory experiment. Cuttlefish eggs are being reared at normal pH (8.10) and at two lower pH's (7.85 and 7.60); all three pH conditions are being studied at two temperatures (16°C and 19°C). Eggs are being exposed to ^{45}Ca, ^{54}Mn, ^{60}Co, ^{65}Zn, ^{109}Cd, ^{110m}Ag, ^{134}Cs, and ^{241}Am tracers that were dissolved in seawater in order to assess their uptake kinetics and spatial redistribution within the egg compartments and how that varies during the embryonic development time. Temperature and pH could affect embryo metabolic rates and chemical properties of eggshell components, which could lead to shifts in a) the accumulation of essential elements (Ca, Co, Mn, Zn) that are needed by the embryo and b) the capacity of the eggshell to shield against penetration of non-essential or toxic elements (Ag, Cd, ^{134}Cs, ^{241}Am).

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EFFECT OF HIGH CO_2 ON THE PHYSIOLOGY AND GROWTH OF THE HERMATYPIC CORAL *SERIATOPORA HYSTRIX* IN NANO-SIZED CHEMOSTAT T29

Leblud, J., A. Batigny and Ph. Grosjean

Growth of hermatypic coral *Seriatopora hystrix* was studied in a new original artificial chemostat. We succeed to maintain and growth small nubbins of 0.23±0.05g of the hermatypic coral *S. hystrix* in nano-sized chemostats (called "nanocultures") of 400 mL each during 3 weeks. Main physico-chemical parameters are monitored and controlled using microcomputers. This includes temperature, salinity, pH, alkalinity, omega aragonite and calcium concentration. Artificial light of 250±30 $\mu E.m^{-2}.s^{-1}$ on a 12h/12h light/dark cycle and a temperature of 27.0±0.1°C, salinity of 34±1, pH of 8.2±0.2, alkalinity of 2.9±0.3meq.kg^{-1} and [Ca^{++}] of 410±10 mg.kg^{-1} give a growth rate of 1.1±0.5% per day for the nubbins, i.e., an increase in weight of more than 25% during the experiment.

The study of variation of the physico-chemical parameters, including true duplicates or triplicates, are possible with our system. In the near future, we propose to investigate the effect of increasing CO_2 on growth and physiology of *S. hystrix*, his symbiotic zooxanthellae and his epibiontic bacterial colonies using these nanocultures. Relatively axenic conditions, measurement of the complete balance of inorganic/organic carbon in each chemostat, and concentration of the organic molecules released by the coral due to the extremely small volume potentially offer new insights on coral growth and physiology.

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REGULATION OF NITROGEN METABOLISM IN THE MARINE DIAZOTROPH *TRICHODESMIUM* IMS101 UNDER VARYING TEMPERATURES AND ATMOSPHERIC CO_2 CONCENTRATIONS. M30

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Trichodesmium spp., the dominant cyanobacterial nitrogen-fixer in the tropical and sub-tropical oligotrophic oceans, responds to elevated pCO_2 (from current to 900 μatm) with a 3-4 fold increase in nitrogen fixation rates. Here we examined regulation of N_2 fixation at the levels of transcript (*nifH* mRNA copies), protein, and activity (acetylene reduction) over ranges in both CO_2 and temperature [250 (low), 400 (ambient) and 900 (high) μatm CO_2 at 31 ^{0}C and 25 ^{0}C]. While the amount of nitrogenase protein remained comparable across all temperature and CO_2 combinations, both *nifH* transcription and activity levels were significantly influenced by CO_2 concentrations. *nifH* transcription in cultures acclimated to high CO_2 (at both temperatures) declined throughout the photoperiod, contrasting with the characteristic diel pattern of nitrogen-fixation which was markedly higher under elevated CO_2. Estimated catalytic rates for both nitrogenase and the subsequent nitrogen-assimilatory enzyme, glutamine synthetase, revealed a parallel diel pattern. At high CO_2 these enzymes operated at overall catalytic rates of over 60% of the *in-vitro* k_{cat} values while under ambient and low CO_2 these enzymes operated at only ~30% of k_{cat}. At elevated CO_2, the lower transcript levels combined with faster enzymatic catalytic rates may indicate enhanced stability and lower turnover of the protein. Thus, acclimation of *Trichodesmium* to elevated CO_2 lowers the energy costs for maintenance of the nitrogenase protein pool, while reallocation of energy and resources from competing pathways such as the Carbon Concentrating Mechanism and the Mehler reaction can stimulate the higher N_2 fixation and ultimately growth rates.

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CARBON CYCLE PERTURBATIONS DUE TO MODIFIED CARBON FLUX AND FUTURE CO_2 UPTAKE IN THE NORTHERN INDIAN OCEAN T30

Mahanta, Chandan

Large uncertainty exists concerning uptake of CO_2 by Indian Ocean due to insufficient knowledge of processes controlling carbonate chemistry. Settling of particulate organic carbon decreases total C and pCO_2 of surface layers, whereas removal of carbonate from surface waters aids in increasing atmospheric CO_2 by shifting carbonate equilibrium. The method in calculating sea-air CO_2 exchange was based on flux equation considering difference between partial pressure of atmosphere and sea surface that determine the direction of CO_2 exchange. While gas transfer velocity depends on wind velocity on sea surface, monsoonal episodic pulse of about 5% global particulate riverine C load received by Bay of Bengal shelf is important natural and human induced interactive forcing influencing future capacity of CO_2 assimilation. Bay of Bengal, a high productive area of the world oceans, has recorded high organic carbon fluxes of more than 3 g $m^{-2}y^{-1}$ in sediment trap experiments. Air-sea CO_2 flux variability impact due to variations in entrained terrestrial input could be more pronounced than surface temperature or wind speed. Result showed, in the past, release was around 2 moles CO_2 m^{-2} $year^{-1}$. Capacity of oceanic uptake continued to increase, and in recent times, the region absorbed up to 5 moles CO_2 m^{-2} $year^{-1}$. The prediction result based on the A2 scenario in the year of 2050 showed that BOB waters can optimally uptake up to 15 moles CO_2 m^{-2} $year^{-1}$, but would begin to drop due to decreasing of atmospheric CO_2 concentration until 2100. The B2 scenario showed a lower trend.

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DRASTIC DECREASE IN COLD WATER CORAL CALCIFICATION AS RESPONSE TO LOWER PH M31

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The cold-water coral *Lophelia pertusa* is one of the few species able to build reef-like structures and a 3-dimensional coral framework in the deep oceans. Such deep coral bioherms are likely among the first to be affected by ocean acidification i.e. decrease in pH due to an increase in pCO2. During a cruise in the Skagerrak, calcification rates and response to lowering pH has been studied directly onboard using cold-water corals that have been freshly collected with a video-equipped box corer. Calcification rates were assessed using $^{45}CaCl_2$. Experiments were conducted at ambient pH and pH lowered by 0.15 and 0.3 units. Calcification rates were higher than expected with an average of 0.05 % d^{-1} ±0.01 S.E. (normalised to initial skeletal weight) for bulk calcification of small branches. Highest calcification rates were found in youngest polyps, which had calcification rates of up to 1 % d^{-1} and average calcification rates of 0.11 % d^{-1} ± 0.02 S.E. (extremes removed). Lowering the pH by 0.15 and 0.3 pH units reduced coral calcification by 30 % and 56 %, respectively. Also, the effect of changes in pH (0.3 pH units lower than in ambient water) on calcification rate was stronger for fast growing, young polyps (59 % reduction) than for older polyps (40 % reduction). This first study on calcification rate and pH effects for *L. pertusa* implies that the young and fast calcifying corallites will be influenced most negatively by ocean acidification.

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EFFECTS OF OCEAN ACIDIFICATION ON EARLY LIFE STAGES OF SEA BREAM AND SEA BASS T31

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The gilthead sea bream, *Sparus aurata*, and the European sea bass, *Dicentrarchus labrax*, provide the largest economic sector for fish aquaculture along the Mediterranean and Eastern Atlantic coasts, with global production of 108,000 tons of sea bream ($595 million US) and 60,000 tons of sea bass ($386 million) in 2006. Despite their commercial interest and their wide geographic distribution, we do not understand how ocean acidification will affect these species and in particular their early developmental stages that could be particularly vulnerable to elevated CO_2 partial pressure (pCO_2). We investigated the consequences of ocean acidification on the embryonic and larval stages of *S. aurata* and *D. labrax*. Fish eggs and larvae were maintained in Mediterranean seawater at normal surface conditions (pH=8.1, pCO_2=380 ppm) and at three low-pH, high CO_2 conditions: pH=7.9 (650 ppm), pH=7.7 (1100 ppm), and pH=7.5 (1800 ppm). Eggs and larvae were exposed to ^{45}Ca, ^{54}Mn, ^{60}Co, ^{75}Se, ^{110m}Ag, ^{134}Cs, ^{241}Am, ^{65}Zn, and ^{109}Cd dissolved in seawater in order to assess the uptake kinetics of these elements from the spawning date to the end of the first week of larval development. Preliminary results reveal that ocean acidification may alter incorporation of trace elements in eggs and larvae. Both essential metals (Co and Zn) and non-essential metals (Ag and Cd) were taken up less efficiently by the eggs at reduced pH relative to normal pH, suggesting potential effects on fish physiological functions and on retention of toxic elements.

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HIGH CO_2 RETAINED FRACTION IN OCEAN SEQUESTRATION ESTIMATED BY A HIGH RESOLUTION MODEL M32

Masuda, Yoshio[1] and Yasuhiro Yamanaka[1,2]

In the CO_2 ocean sequestration, CO_2 retained fraction is one of the most important topics. It shows how long CO_2 injected into the ocean is isolated from the atmosphere. The retained fraction of the injected CO_2 calculated in previous studies are around 70% in average after 200 years (IPCC report) which are calculated by relatively coarse resolution models with the horizontal resolution larger than one degree. We considered that the retained fraction should be small, because 200 years are much shorter than the time scale (~2000 years) of deep ocean circulation. We estimated it using a high resolution model with the horizontal resolution of 0.1 degree. The fine grid mesh explicitly represent effects of mesoscale eddies on CO_2 transport and dilution. The injected CO_2 is kept in smaller ocean volume than that obtained from coarse resolution models. Only 0.4% of the injected CO_2 is released into the atmosphere after 200 years, although about half of the injected CO_2 is horizontally transported to the outside of the narrow model domain. We supposed that the difference in the retained fraction between high and coarse resolution models is caused by difference in horizontal CO_2 transport. Difference in simulated western boundary current regions also may effect on the difference.

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ENHANCED BIOLOGICAL CARBON CONSUMPTION IN A HIGH CO_2 OCEAN: A REVISED ESTIMATE OF THE EFFICIENCY OF THE OCEANIC CARBON UPTAKE T32

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Using recent empirical measurements of enhanced biological carbon consumption in a high CO_2 ocean (Riebesell et al., 2007), we have investigated the potential for this effect to increase the carbon uptake by the oceans in an ocean general circulation model (OGCM) and a data-calibrated two box model. Our results suggest an increased oceanic carbon uptake of 46 GtC up to the year 2100, which is less than half the value estimated by Riebesell et al., (2007). The reduced oceanic CO_2 uptake comes about through a more realistic parametrization of the re-supply of carbon from the interior ocean back to the surface than originally estimated from Riebesell et al., (2007) simple model. The OGCM simulations further reveals that the oceanic circulation modifies the distribution of carbon whereby some regions like the eastern equatorial Pacific and Southern Ocean experience reduced carbon uptake despite a local increase in biological carbon export. The pooling of the exported carbon in these regions allows the re-supply of carbon rich sub-surface waters to exceed the enhanced biological carbon export of the high CO_2 world.

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INCREASED CO2 UPTAKE IN THE ARCTIC OCEAN: HOW SEA ICE LOSS WILL IMPACT OCEAN ACIDIFICATION M33

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The Chukchi shelf is the site of some of the highest rates of primary production in the oceans. Rates of net community production over the shelf can be as high as 2,000 mg C m-2 d-1, and averaged 800 mg C m-2 d-1 across the entire shelf. Using conservative tracers to construct a carbon mass balance,

we found that 10% of the DIC consumed during net community production was converted to DOC and 15% was converted to suspended POC. The remaining 75% was exported from the mixed layer as sinking organic particles. At the termination of the bloom, most of the organic matter had been exported from the mixed layer, leaving surface waters undersaturated with respect to atmospheric CO2. Before reequilibration can occur with the atmosphere the surface waters are transported offshore, under the ice cap which further inhibits air-sea exchange and maintains low pCO2 levels in the surface waters of the deep Arctic Basin. However, in recent years, the extent of summer sea ice has retreated further into the Arctic Ocean with a 30% reduction observed in summer of 2007. This "opening" of the central Arctic has lead to an increased uptake of CO2 into the central basin, thus lowering the pH of surface waters in the region. Here, we show the distributions of pH over the Chukchi Sea and adjacent Canada Basin in 2002 and 2004 and discuss the impacts that future sea ice loss will have on ocean acidification in the Arctic.

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CO_2 VS. HCL FOR THE ADJUSTMENT OF SEAWATER pH T33

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The impact of acidification on the world's oceans is often predicted through the culture of marine organisms under controlled conditions. Physiological responses are monitored as seawater pH is adjusted by additions of HCl or bubbling of CO_2 gas. Both methods easily achieve target pH levels, but calculation of CO_2 equilibrium speciation shows that they have significantly different impacts on seawater chemistry and the concentration of dissolved inorganic carbon species. When CO_2 is used to lower the seawater pH, the total alkalinity (A_T) remains constant while the total inorganic carbon (C_T) increases. When HCl is used to lower the seawater pH, C_T remains constant while A_T decreases. Simulations show that the resulting differences in [CO_2(aq)], [CO_3^{2-}], and pCO_2 for these two methods of acidification are small. However, [HCO_3^-] is significantly higher for seawater adjusted with CO_2 compared to seawater adjusted with HCl. This difference in CO_2 speciation between the two methods of acidification may be significant for organisms that use HCO_3^- for photosynthesis. These results indicate that pH and CO_2 speciation must both be considered when designing culture experiments. In addition, the calculations show that seawater adjusted with CO_2 more closely mimics the changes in seawater carbon chemistry that are expected with rising atmospheric CO_2 levels.

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EARLIER SOUTHERN OCEAN ACIDIFICATION FROM SEASONAL AMPLIFICATION OF ANTHROPOGENIC CO_2 UPTAKE M34

McNeil, Ben I.[1] and Richard J. Matear[2]

Southern Ocean acidification via anthropogenic CO_2 uptake is expected to be detrimental to multiple calcifying plankton species by lowering the concentration of carbonate ion (CO_3^{2-}) to levels where calcium carbonate (both aragonite and calcite) shells begin to dissolve. Although seasonal variability has been suggested to hasten the onset of aragonite under-saturation (Orr et al., 2005), observational

evidence in the Southern Ocean has been lacking. We present a large-scale Southern Ocean observational analysis that examines the seasonal magnitude and variability of CO_3^{2-} and pH. Our analysis shows an intense winter-time minimum in CO_3^{2-} south of the Antarctic Polar Front and when combined with projected anthropogenic CO_2 uptake will induce aragonite under-saturation as early as the year 2030 and no later than 2038. Some prominent calcifying plankton, in particular the Pteropod species Limacina helicina, have important veliger larval development during winter and will have to experience detrimental carbonate conditions much earlier than previously thought, with possible deleterious flow-on impacts for the wider Southern Ocean marine ecosystem. Our results highlight the critical importance of understanding seasonal carbon dynamics within all important calcifying marine ecosystems such as continental shelves and coral reefs, since it may potentially hasten the onset of future ocean acidification.

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EVOLUTION OF PRE-ADAPTATION TO FUTURE OCEAN ACIDIFICATION: IDENTIFYING PHYSIOLOGICAL CHARACTERISTICS OF SURVIVORS T34

Melzner, Frank [1], Magdalena A. Gutowska[2], and Martina Langenbuch[1]

Several recent reviews have summarized potential dangers of future ocean acidification to marine animal survival and performance. However, we are still far from understanding the genetic and physiological mechanisms that provide certain groups of high-power animals (fish, cephalopods, some crustaceans) with a relative degree of tolerance towards simulated ocean acidification. Employing an evolutionary approach, this paper will synthesize information on how the development of high-power ecotypes resulted in the co-evolution of a relative acidification tolerance. High-power organisms experience high pCO_2s in their body fluids (1,000-8,000 ppm) under control conditions and during exercise already in today's ocean. Thus, contrary e.g. to unicellular ocean organisms, who are bathed in an extracellular fluid (the ocean) that has a pCO_2 of <400 ppm, high-power animals have already had a long time to evolve physiological mechanisms to live with high internal pCO_2s. Using the physiological literature of the last 40 years in combination with recent investigations on acid-base regulation in marine invertebrate animals in our laboratories, we will classify species groups (teleost fish, cephalopods, crustaceans, bivalves, echinoderms, cnidarians) according to key physiological parameters (ion exchange capacities and mechanisms, metabolic rate fluctuations, CO_2 exchange rates and body [CO_2] variations), to elaborate common patterns. We also will address the pressing question, whether the currently anticipated speeds of future acidification will leave enough time for evolution of such traits that promote tolerance to high ocean CO_2.

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ARE EASTERN BOUNDARY UPWELLING SYSTEMS GOOD ANALOGUES FOR A FUTURE HIGH CO2 OCEAN? M35

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Eastern boundary upwelling systems are characterized by waters with elevated pCO2 (500 – 1500ppm) and low pH (ranges?) which span the envisaged carbonate system characteristics resulting from future ocean acidification. This is especially the case where the shelf edge boundary conditions for the upwelled waters are derived from Equatorial OMZ thermocline waters. Advection of these waters over organic rich shelf sediments where aerobic and anaerobic respiration fluxes of CO2 prior to upwelling, create low pH (pH < 7.6) conditions in surface and sub-thermocline waters. Observational data from the Benguela upwelling system show direct effects of these conditions

through malformations of coccolithophorid shells in the surface layer (Giraudeau et al., 1993). The impacts of elevated CO2 may extend to other parts of the carbon and nitrogen biogeochemistry and possibly early life stages of calcifying and non calcifying organisms.
We have re-analyzed historical and more recent data with a view to establishing the extent and characteristics of variability of this natural acidification in the Benguela upwelling system.

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IMPACTS OF OCEAN ACIDIFICATION ON SCLERACTINIAN CORAL SKELETAL INTEGRITY T35

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Carbon dioxide emissions are well-documented to have risen exponentially since pre-industrial times. The rise of emissions has numerous effects on our environment, and coral reefs are emerging as one of the most susceptible ecosystems. Increasing emissions are resulting in warmer and more acidified seas that may compromise coral calcification and growth. Among many ecological and physiological effects, the ways in which the skeletal integrity of reef-building corals may be compromised by the rise of CO_2 must be addressed. The following study examines how the strength of the coral skeleton is affected by rising atmospheric CO_2. Samples from highly abundant corals representing differing skeletal characteristics were exposed to varying levels of CO_2 to represent future reef scenarios. Those corals exposed to high CO_2 levels grew similar amounts as the control corals; however, they broke with much less energy. This study sought to provide managers and policy-makers with quantifiable data regarding skeletal strength.

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LONG TERM NEUTRALIZATION OF ANTHROPOGENIC CO_2: THE ROLE OF CHANGING BASIN-TO-SHELF PARTITIONING OF CARBONATE BURIAL M36

Munhoven, Guy

The longterm implications of the ocean uptake of CO_2 released into the atmosphere by human activity on the partitioning of the global carbonate burial between shelf and pelagic sea-floor sediments is analyzed with MBM, a multi-box model of the carbon cycle in the ocean and atmosphere, fully coupled to the transient early diagenesis model MEDUSA. MBM-MEDUSA includes separate schemes for the accumulation of carbonate on the shelf (coral-reefs and banks) and in the deep-sea sediments; carbonate accumulation by coral-reefs is dependent on the saturation state of aragonite in the surface ocean. An emission scenario following a logistic function is adopted to prescribe the release of CO_2 from fossil fuel burning over the next centuries until depletion of resources (assumed to be 4240 GtC). Under that scenario, the net carbonate accumulation by coral-reefs rapidly decreases during the 21st century. Accumulation rates will be reduced by more than 90% in 2100 and almost completely vanish by the year 2200. Accumulation in coral-reef environments then slowly resumes, but even 20,000 years later, it only reaches 80% of the Holocene level. A complete feedback analysis regarding the role of the resulting change in the partitioning of carbonate burial between the shelf and deep-sea sediments for atmospheric CO_2 concentrations will be presented.

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AN EXPERIMENTAL STUDY SITE FOR OCEAN ACIDIFICATION AT THE UNIVERSITY OF WASHINGTON, FRIDAY HARBOR LABORATORIES. T36

Murray, James W.[1] and Terrie Klinger[2]

We are leading an effort at the University of Washington to design and construct an experimental study facility for ocean acidification at the Friday Harbor Laboratories (FHL). This facility will allow experimental studies of the response of marine organisms to changes in ocean pH and carbonate saturation in an environmentally-relevant setting. We anticipate that this facility will grow to become a site accessible for US and Canadian scientists to conduct experimentation on the biological and ecological impacts of ocean acidification. FHL is uniquely suited for this facility because it is an established center for research in marine biology, ecology and oceanography with a stellar international reputation. Its location allows experimentation on organisms native to the northeastern Pacific, which is predicted to show early, strong signs of acidification. This exciting new project brings together chemical and biological oceanographers from the Schools of Oceanography, Aquatic and Fisheries Sciences, Marine Affairs and The Friday Harbor Laboratories at the University of Washington. The initial centerpiece will be development of an experimental study site at the FHL that will incorporate both small scale lab based and larger scale mesocosm type experiments that will be used for studies of both ocean acidification and ocean warming. A planning workshop will be held at Friday Harbor Laboratories on 28, 29 August and the recommendations will be presented at this Symposium.

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MODELLING THE UPTAKE AND RELEASE OF CARBON DIOXIDE IN THE BALTIC SEA SURFACE WATER M37

Omstedt, A, Erik Gustafsson, and Karin Wesslander

The present work is the first attempts within GEWEX/BALTEX phase II to model the uptake and release of carbon dioxide in the Baltic Sea. The mathematical formulation is kept as simple as possible, but several aspects of the dynamics are included. The model system captures major physical-chemical and biological response patters as evaluated from observations from the central Baltic Sea and the modeling illustrates the need for fractional nutrient release in the photic zone for consistency with the CO_2 observations.
The carbon dioxide exchange between Baltic Sea and atmosphere are besides from carbon chemistry, strongly dependent on biologic production and mineralization. Modeling of long-term variations in partial pressure of carbon dioxide indicates stable conditions before industrialization and net release to the atmosphere. During modern industrialization era with eutrophication the modeling illustrates that the seasonal variability increased and the net release to the atmosphere decreased. The study illustrates that observed and modeled partial pressure of carbon dioxide gives important knowledge about time evolution and size of primary production. The modeling illustrates also the need for fully coupled physical-chemical-biological ecosystem models where the carbon chemistry is included. Improved knowledge about river and Skagerrak input of organic and inorganic carbon as well as alkalinity are needed.

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VOLATILE ORGANIC COMPOUNDS (VOCs) IN SEA WATER UNDER ELEVATED CO_2 LEVELS DURING AN OFF-SHORE MESOCOSM EXPERIMENT T37

Orlikowska, Anna and Detlef Schulz-Bull

Volatile organic compounds (VOCs) are known to play an important role in the global climate and are involved in a number of photochemically induced atmospheric reactions. The processes responsible for formation and degradation of VOCs are complex and are affected by various factors among them modifications in seawater chemistry.

In the current study water samples are analysed in order to investigate the influence of various parameters - especially elevated CO_2 levels, changes in irradiance and temperature - on concentration and composition of volatile hydrocarbons. Moreover stable carbon isotope analysis is performed to study δ13C values. While VOCs are ubiquitous trace gases released into the environment from natural and anthropogenic sources this technique can be used to make a distinction between their various origins as well as serving as valuable tool to distinguish biodegradation from physical, nondegradative processes. The seawater samples were taken during the SOPRAN off-shore mesocosm experiment in the central Baltic Sea in July 2007 and 2008. In an attempt to investigate CO_2 effects on marine ecosystem acid treatment is used to induce different pCO_2 environments in the mesocosms. The analysis is carried out by a purge and trap system coupled to a gas chromatograph interfaced with mass spectrometer and isotope ratio mass spectrometer. Twenty five low molecular weight volatile halogenated organic compounds (VHOCs) along with dimethylsulfide (DMS) and isoprene as well as monocyclic aromatic compounds are determined. Relations between the compounds as well as the influence of physicochemical factors are presented.

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ARCTIC ACIDIFICATION M38

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Climate change in the Arctic will be amplified, leading to reduced sea-ice cover, warming and freshening of surface waters, and changes in vertical stratification. The Arctic Ocean will also undergo acidification. Previous modeling studies suggest that the coldest surface waters of the Southern Ocean will be the first to become undersaturated with respect to aragonite, the metastable form of calcium carbonate ($CaCO_3$), i.e., within 50 years under the IS92a scenario. However, those studies did not discuss the potential for similarly dramatic changes in the Arctic Ocean, owing to lack of gridded baseline data in that region. To assess future $CaCO_3$ saturation in the Arctic Ocean, we used recent data along two trans-Arctic sections as a baseline, to which we added projected 21st-century perturbations in DIC, alkalinity, temperature, salinity, and nutrients from three coupled carbon-climate models forced under the IPCC SRES A2 scenario. In our projections, some Arctic Ocean surface waters become undersaturated with respect to aragonite within 10 years. On average, surface waters succumb to these conditions by 2050. By 2060, some surface waters become undersaturated with respect to calcite, the stable form of $CaCO_3$. At risk are pelagic and benthic marine calcifiers, including bivalve molluscs, a prominent species of the Arctic-shelf benthic community and a major food source for walruses, grey whales, and spectacled eiders. Owing to amplified Arctic climate change, which exacerbates effects from elevated CO_2, undersaturated conditions detrimental to ecosystems will develop first in the Arctic Ocean, 10 to 30 years sooner than in the Southern Ocean.

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CHANGES IN pH AND HYDROGRAPHIC PARAMETERS IN THE BALTIC SEA T38

Perttilä, Matti

The pH, alkalinity, salinity and calcium values in the Baltic Sea are affected by human activities, hydrographic processes, primary production, global CO_2 increase and acid rain in the drainage area. Distinguishing the effects of these pressures is one of the aims of the Baltic Sea monitoring programme.
The partial pressure of CO_2 shows large seasonal and geographical variations in the surface layer of the Baltic Sea. During winter, in the ice-free part of the sea it is generally close to atmospheric partial pressure, part indicating a pH equilibrium. Average pH for the winter period in the central Baltic Sea surface water has decreased from about 8.2 in 1985 to present value 8.1. The average summer pH, however, is rising, probably indicating an increasing primary production. Similar behaviour is found in the Gulf of Finland.
Alkalinity and calcium data in the Baltic Sea are discussed in view of carbonate processes, salinity variations and fresh water inputs. The development of calcium – salinity ratios in both Gulf of Finland and Gulf of Bothnia indicate enhanced calcium dissolution in both drainage areas, leading to a [Ca]/TA ratio higher than expected by the simple mixing of North Sea high salinity water with fresh water.
The investigation on alkalinity, calcium and salinity emphasize the potential use of their relations as water mass tracers in the Baltic Sea, and as tracers of environmental changes especially in the low salinity regions.

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EFFECTS OF OCEAN ACIDIFICATION ON THE BACTERIAL DEGRADATION OF ORGANIC MATTER M39

Piontek, Judith, Nicole Händel, Mirko Lunau, Corinna Borchard, and Anja Engel

The amount of CO_2 being sequestered from the atmosphere to the ocean is mainly controlled by the balance between autotrophic production, calcification and microbial decomposition of organic matter. In recent studies, rising CO_2 was shown to reduce the calcification of marine phytoplankton and to affect the photosynthetic carbon acquisition of single phytoplankton species and natural phytoplankton communities. However, effects of ocean acidification on microbial degradation processes and potential consequences for the remineralization of carbon are not yet considered, despite the fact that the largest proportion of organic matter is degraded in the upper water column, the zone primarily affected by rising CO_2. We tested the effect of decreasing pH on the degradation of organic matter in a series of chemostat- and batch-experiments with cultures of *Emiliania huxleyi* and with coccolithophore-dominated natural phytoplankton communities as source of degradable organic matter. Results show that decreasing pH affects the degradation of organic matter as derived from changes in the activities of polysaccharide- and protein-degrading extracellular enzymes (e.g. glucosidases, leucine-aminopeptidase). Variations in the microbial degradation activity during our experiments were related to changes in the biogeochemistry of organic matter. Our findings demonstrate the necessity to include the response of marine bacteria to ocean acidification when estimating the future carbon cycle.

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MACROALGAL COMMUNITY RESPONSE TO INCREASING CO_2 T39

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By 2100 the surface waters of our oceans are predicted to have decreased in pH by 0.5 units due to anthropogenic emissions of CO_2 into the atmosphere (IPCC report, 2007). Many studies are now trying to find out how this will affect marine systems, mainly by using short-term mesocosm and laboratory studies.
Here we show how the community composition of shallow-sublittoral macroalgae varies along a natural pH gradient at Castello Aragonese on the island of Ischia (Italy) where volcanic vents emit 90-95% CO_2 (together with 3-6% N_2 and small amounts of O_2, Ar and CH_4) at ambient temperature. The venting CO_2 acidifies seawater along a gradient from 8.17 down to 6.57 along a 300 m transect running parallel to the rocky shore (Hall-Spencer *et al*., 2008). We use this site to investigate which algae are tolerant of the long-term effects of increased CO_2 levels and how this affects macroalgal community structure.
Macroalgae were scraped from known areas of vertical rock faces to quantify the macroalgal community structure and their reproductive status. The most obvious effect was that both crustose and erect calcified algae (e.g. *Mesophyllum sp*., *Neogoniolithon brassica-florida*, *Jania rubens* and *Padina pavonica*) first decreased their reproductive potential then disappeared from the community. These calcifiers were being replaced by other crustose and erect algae (e.g. *Hildenbrandia rubra*, *Dictyota dichotoma* and *Osmundea truncata*). Brown algae were the high-biomass canopy forming species throughout the CO_2 gradient but *Cystoseira amentacea* var. *stricta* was dominant at normal CO_2 levels whereas *Sargassum vulgare* became dominant in the acidified zone.
We noted a 25% reduction in macroalgal biodiversity in the acidified zone. Ecophysiological analysis are now needed to determine what is special about the highly tolerant species and whether calcified species can adapt their mineralogy to cope with small increases in CO_2 levels.

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OCEAN ACIDIFICATION DUE TO MASSIVE CARBON DIOXIDE VENTING ALONG THE WAGNER FAULT, GULF OF CALIFORNIA, MEXICO. M40

Prol-Ledesma, Rosa Ma.[1], Carles Canet[1] and Paul R. Dando[2]

The Wagner Fault in the Northern Gulf of California, Mexico, is an area where CO_2 rises to the surface along deep faults in the 5 km-thick sedimentary column. There are an estimated 15, 000 gas vents in the area. The presence of bubbles, breaking the surface above the Wagner Fault vents, indicates CO_2 release to the atmosphere. Individual gas plumes can be 100 m or more across and bubbles reach the surface from 150 m depth resulting in acidification of the entire water column. Close to the outlets pH values can be as low as 6.3, with a full range of pH values up to 8.2 occurring in the water column and along the seabed. This makes the area a good study site for examining the effects of elevated CO_2 and low pH on the marine ecosystem. The gas venting has given rise to varied bottom topography with sorted, coarse-grained sediments and cemented deposits as well as the background silty-clays. This has resulted in a high diversity of bottom fauna, including groups with calcareous shells and skeletons. Since the water depths in the area do not exceed 210 m, these study sites are easily sampled using vessels with smaller ROVs.

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EFFECT OF ELEVATED PCO$_2$ ON THE BORON ISOTOPIC COMPOSITION AND B/CA RATIO INTO THE MEDITERRANEAN SCLERACTINIAN CORAL CLADOCORA CAESPITOSA T40

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It has been well established that ocean acidification negatively affects the calcification rate of calcifying organisms. However, how *p*H and the modified seawater chemistry act on the site of calcification is still debated. Because incorporation and fractionation of boron isotopes in carbonates are controlled by pH, boron is used as a proxy to understand coral calcification mechanisms.
The effect of the increase of CO_2 partial pressure (pCO_2) expected by 2100 was tested on the boron isotopic composition ($\delta^{11}B$) and the B/Ca ratio in the skeleton of the Mediterranean symbiotic coral, *Cladocora caespitosa*.
Colonies were collected in the Villefranche Bay (France) at 25 m depth. Corals were acclimated in aquaria under summer temperature (22°C) and irradiance (35 µmol photon m^{-2} s^{-1}) before being stained with alizarin. Colonies were split in two aquaria maintained at normal (400 ppm) and elevated pCO_2 (700 ppm). Temperature, light and photoperiod were changed according to natural yearly fluctuations at *ca*. 25 m depth in the Villefranche Bay. After one year of culture, the $\delta^{11}B$ and the B/Ca ratios were analyzed in the skeleton deposited above the alizarin line.
Preliminary results did not show any difference in $\delta^{11}B$ between the treatments: 27.3 ± 1.4 ‰ *vs*. 27.2 ± 2.3 ‰ respectively for 400 and 700 ppm. These values correspond to a pH of 8.75. The lack of difference between treatments has also been obtained with the B/Ca ratio (0.926 ± 0.063 and 0.929 ± 0.077 mmol/mol, respectively). We have concluded that on this range of seawater pH, the coral controls the pH at the calcification site.

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LIGHT-DEPENDENT TRANSCRIPTIONAL REGULATION OF GENES OF BIOGEOCHEMICAL INTEREST IN THE DIPLOID AND HAPLOID LIFE STAGES OF *EMILIANIA HUXLEYI* M41

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The cosmopolitan coccolithophorid *Emiliania huxleyi* is capable of carbon uptake by both photosynthesis for organic matter production and by intracellular calcification for coccolith production. The algal cells, generating huge blooms, photosynthetically produce a large quantity of organic matter and calcite crystals by fixing dissolved inorganic carbons (DIC), before sinking to the bottom of the ocean. Consequently, the regulation of photosynthesis and calcification by coccolithophorids is a key factor in the global carbon budget and constitutes one of the main targets of high-CO_2 condition in the near future. In order to follow both photosynthesis and calcification process in *E. huxleyi* CCMP1516 haploid and diploid stages, we decided to focus on the ribulose-bisphosphate carboxylase-oxygenase (rbcL) gene as candidate for photosynthesis and the calcium binding protein (gpa) for calcification. Transcripts regulation was monitored using quantitative RT-PCR method on a diel cycle. A similar diel regulation of *rbcL* mRNAs, with a peak of expression 2 h after the beginning of the light period, was observed in both haploid and diploid cells. Similarly, *gpa* mRNAs were up-regulated after 2 h of light but restricted to the haploid cells. However, *E. huxleyi* diploid cells, which precipitate calcium carbonate, exhibited a significantly larger abundance of *gpa* transcripts than the haploid, non-calcifiying cells, throughout the diel cycle. Comparative study has been conducted on *E. huxleyi* strain TQ26 and the analysis was extended to two more genes potentially involved in calcification such as the calmodulin and the carbonic anhydrase. The genes of interest are discussed as potential candidates for biogeochemical proxies.

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RISING SATURATION HORIZONS MAY OVERTAKE COLD, DEEP CORALLINE COMMUNITIES IN ANTARCTICA T41

Riddle, Martin J.[1], Bronte Tilbrook[2,3] Ian Snape , Kristina Paterson[2,3], and Katherine Berry[3]

A diverse, coral-based benthic community was recently discovered and recorded on video in a canyon system on the Antarctic continental slope off East Antarctica. The main structural components are heavily calcified branching hydrocorals and gorgonians creating habitat for the highest diversity of invertebrates and fish seen during a 20 day survey between 139°E and 145°E. The community was not seen at any of the ~60 shallower sites sampled on the continental shelf, possibly because it is slow growing and not competitive during early re-colonisation after ice-berg scour. The calcareous species were dominant at 600-850 m, well below the reach of modern ice-bergs, but were sparse at 900-1000 m and apparently absent at 1400 m. Water column CO_2 chemistry indicates that the aragonite saturation horizon was at about 900 m, with the calcite saturation state at this depth approximately 1.6. The canyon system drains cold, saline Antarctic Bottom Water generated during sea-ice formation in the permanently open waters of the Mertz Polyna, west of the 90 km long Mertz Glacier. Katabatic winds from the continent accelerate ice formation in the polynya and are likely to increase air-sea exchange of CO_2. The continued uptake of CO_2 will drive lower the saturation state of carbonate minerals and we predict that these coralline benthic communities will be among the first globally to show calcification effects due to the crossing of saturation thresholds. The narrow depth range currently occupied by this community suggests its continued existence may be threatened if acidification further reduces its range.

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COMPARISON OF *HALIMEDA* ARAGONITE FROM 40 YEARS OF ARCHIVED FIELD SAMPLES WITH SPECIMENS GROWN IN HIGH pCO_2 SEAWATER M42

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Ocean chemistry is changing more dramatically now than in the last 20 million years because of rising atmospheric pCO_2 levels. In fact, pH values of the open ocean have decreased by 0.1 since 1980 and are predicted to decrease 0.3-0.5 in the next 80 years. Ocean acidification will likely affect fundamental geochemical and biological processes including calcification and carbonate sediment production. The west Florida shelf has a natural gradient from temperate to subtropical carbonate sedimentation which provides natural laboratories to examine the effects of ocean acidification on aragonite production by calcareous green algae. Scanning electron microscopy (SEM) can reveal ultrastructural details of calcification that occurred at different saturation states. Comparison of *Halimeda* spp. from west Florida shelf archived samples collected more than 40 years ago, with specimens collected in ongoing studies, indicates the effect of increased pCO_2 and decreased saturation state over this time span. Laboratory experiments using living specimens of *Halimeda* in a range of pCO_2 environments are being used to constrain historical observations. *Halimeda* crystal data from apical sections indicate that increases in crystal density and decreased crystal width occurred over the last 40 years.

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PROJECTIONS OF VENTILATION IN A COUPLED CLIMATE MODEL: IMPLICATIONS FOR OCEANIC DISSOLVED OXYGEN T42

Russell, Joellen L. and Paul J. Goodman

Future circulation changes due to global warming are projected to have a dramatic impact on the concentration of dissolved oxygen in the global ocean. Warming of surface waters is likely to affect the concentration of dissolved oxygen in the ocean directly through solubility, as well as indirectly through stratification-driven changes to organic material export and remineralization rates. These changes are likely to lead to decreased oxygen in equatorial thermocline waters according to current climate model predictions. Results from the GFDL CM2.1 climate model indicate that the dissolved oxygen content of the Southern Ocean may increase temporarily during the transient into a high-CO2 world through increased wind-driven ventilation of cold, low-oxygen waters. Contrary to previous work, increased wind-forced upwelling associated with the poleward intensification of the Southern Hemisphere Westerlies leads to increases in Southern Ocean dissolved oxygen concentration over the next 100 years, not the decreases seen in models with poorly resolved Southern Hemisphere Westerly Winds.

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UPWELLING OF 'ACIDIFIED' WATER ONTO THE NORTH AMERICAN CONTINENTAL SHELF M43

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The absorption of atmospheric carbon dioxide into the ocean lowers the pH of the waters. This so-called ocean acidification could have important consequences for marine ecosystems. In order to better understand the extent of this ocean acidification in coastal waters, we surveyed 13 hydrographic sections perpendicular to the coast between Queen Charlotte Sound, Canada and the Mexican Baja Peninsula between May and June of 2007. Upwelling was observed from line 2 off central Vancouver Island to line 13 off Baja California, Mexico. Lines 2 and 3 to the north and lines 8 to 11 to the south experienced the weakest upwelling. Recent upwelling was observed on lines 5 and 6 near the Oregon-California border. Coincident with the upwelled waters we observed low pH seawater that was undersaturated with respect to aragonite covering large portions of the continental shelf. The undersaturated water reached depths of approximately 40-120 m along most transect lines and all the way to the surface on line 5. The aragonite saturation horizon closely followed the 26.2 potential density surface where the waters had a pH of about 7.75. This density surface shoaled from a depth of ~175 m in the offshore waters and breached the surface over the shelf near the 100 m bottom contour, approximately 40 km from the coast. While seasonal upwelling of the undersaturated waters onto the shelf is a natural phenomenon in this region, the ocean uptake of anthropogenic CO_2 has increased the areal extent of the affected area.

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ACIDIFICATION SENSITIVITY OF THE BLUE MUSSEL, *MYTILUS EDULIS*, IN THE BALTIC SEA: A HOLISTIC APPROACH T43

Saphörster, Julia, Jörn Thomsen, Agnes Heinemann, and Frank Melzner

Blue mussels of the genus *Mytilus* from the North Sea and the Mediterranean displayed decreased rates of calcification in combination with metabolic depression and uncompensated extracellular pH when exposed to low ocean pH. Baltic Sea *M. edulis* might even react more sensitively to acidified waters than populations from full-strength saline oceans, as the dilute Baltic is characterized by a low buffering capacity (TA <2.0 meq/l) and low calcium carbonate saturation (Ω_{arag}<1.5). Employing a holistic approach, we related acid base parameters, ion exchange capacity and extracellular ion composition to whole-animal performance indicators and shell isotopic composition.
Adult mussels were kept in flow through aquaria for 14 days at five different CO_2 concentrations ranging from 380 ppm to 1,400 ppm. During the experimental period, we determined heart rates and valve/siphon opening status at the lowest and highest CO_2 levels as measures for overall organismic performance. Following the incubation period, hemolymph samples were drawn from the posterior shell retractor muscle of all animals for extracellular pH measurements. Tissue samples were taken for determinations of intracellular pH and Na^+/K^+ ATPase activity. In addition, ion composition of hemolymph and extra-pallial fluid will be investigated by means of ion chromatography. All biochemical / physiological parameters will be correlated with whole animal performance indicators to gain a comprehensive understanding of the potential vulnerability of the species towards future ocean acidification. Since *Mytilus edulis* is one of the most important ecosystem engineers in northern seas, its acidification sensitivity might have significant ecological consequences.

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ANTHROPOGENIC GAS DISTRIBUTION IN THE SOUTHERN OCEAN: FORMATION AND SPREADING OF SAMW AND AAIW M44

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Chemical tracers are widely used to investigate the ocean circulation, water mass formation rate, and mixing and ventilation processes. Anthropogenic gas such as chlorofluorocarbon (CFC) is inert transit tracer in the ocean, similar in some ways to anthropogenic CO_2, and provides information on the ocean circulation and its variability on timescale of months to decade. We have carried out CFC-11 simulation to investigate the formation and spreading of Subantarctic mode water (SAMW) and Antarctic intermediate water (AAIW) using an eddy-resolving ocean general circulation model. The model has a horizontal grid scale of 0.1 degree and 54 vertical levels. A model is forced by a climatological data of NCEP/NCAR. The model exhibits considerable skill in reproducing the section along Greenwich Meridian (AJAX), 30E (WOCE I06SB), 115E (WOCE I09S), and 170W (WOCE P15S). The high CFC-11 water penetrates to 1000 m depth between 50S and 40S by the SAMW and AAIW ventilation for each section. In the distribution of CFC-11 inventory in 1994, the model is a good performance to observed distribution (GLODAP), especially between 60S and 30S. Distribution of CFC-11 inventory in 26.5-27.0 (SAMW) and 27.0-27.4 (AAIW) in the model is also close to observed. The eddy-resolving model explicitly simulates meso-scale eddies and improves the structure of upper ocean stratification in the Southern Ocean.

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EFFECTS OF HYPERCAPNIA AND HYPOXIA ON THE EMBRYONIC DEVELOPMENT OF RED SEA BREAM, *PAGRUS MAJOR* T44

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Because of the weak stress resistance of early stage aquatic animals, hypercapnic and hypoxic conditions are supposed to cause a mass mortality and/or teratogenic effects leading to a large adverse effect on their population dynamics. However, most of the effects of these conditions on their early development are less well understood. This paper demonstrates the effects of hypercapnia and hypoxia on the embryonic development of a teleost red sea bream (RSB), *Pagrus major*, which is an important constituent of neritic ecosystem and an important fisheries resource in the Far East.
RSB eggs were exposed to seawater of six dissolved oxygen concentrations (0, 10, 25, 50, 75, and 100%) and four dissolved carbon dioxide concentrations (0, 60, and 120 mg/L) for seven different periods (0-180 min.) during somitogenesis. Larvae hatched from these eggs were observed the condition of somites by microscopy. Isolated exposure to hypercapnia and hypoxia induced somitic disturbances at high incidence rates in newly hatched larvae. Combined condition of hypercapnia and hypoxia induced somitic disturbances in RSB larvae at the higher incidence rates than the isolated ones.
Our previous study demonstrated that the somitic disturbances in newly hatched larvae develop into centrum defects in the vertebral bone. The results of this study suggest that hypoxic and hypercapnic conditions in aquatic environment caused by the human-induced excess organic matter loading, red tides, and the planned carbon dioxide disposal into the sea are the possible causes of the reduction of wild fish population by the induction of developmental defects.

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PAST ANALOGUES FOR OCEAN ACIDIFICATON: INSIGHTS FROM THE PALEOCENE/EOCENE THERMAL MAXIMUM M45

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Continued absorption of fossil fuel CO_2 by the ocean may decrease surface ocean *p*H by up to 0.5-0.6 *p*H units over the next 250 years, pushing ocean geochemistry outside the range of values experienced during the last tens of millions of years. The Palaeocene-Eocene Thermal Maximum (PETM) has been suggested as an analogue for future global warming and ocean acidification, but *p*H and carbonate system changes at this time have not been well constrained.
We employed high-spatial resolution secondary ionization mass spectrometry (SIMS) of tests of the benthic foraminifer *Oridorsalis umbonatus* at Maud Rise (Site 690B, Weddell Sea, Southern Ocean, palaeodepth 1900 m) and *Lenticulina* sp. at Bass River (Leg 174X, New Jersey; shelf) to characterize B/Ca (carbonate saturation proxy) and Li/Ca (DIC proxy). Mg/Ca data indicate a total temperature increase from 12.7°C to 18.5°C at Maud Rise, in agreement with previous work, and a 4ºC temperature increase at Bass River to 36ºC during the PETM. The latter needs further evaluation because Mg/Ca for *Lenticulina* has not been calibrated. B/Ca show a transition from slightly over-saturated to under-saturated conditions going into the PETM $\delta^{13}C$ excursion at both sites and do not recover to pre-event values, even after recovery of $\delta^{13}C$ and temperature values. Li/Ca ratios show a minor reduction at both Sites, indicating little change in DIC, in contrast to what is expected in view of the magnitude of carbon release; we need more information on the behaviour of this proxy. Ba/Ca indicate an increase in productivity at Bass River but a decrease at Maud Rise, in agreement with micropalaeontological evidence.

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SENSITIVITY OF LYSOCLINE DEPTH AND AIR-SEA CO_2-EXCHANGE TO PARTICLE FLUXES IN THE WATER COLUMN T45

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An ocean biogeochemical model was applied to estimate the sensitivity of lysocline depth and air-sea CO_2-exchange to the vertical flux of particulate organic and inorganic carbon (POC, PIC). The results of four different perturbation experiments show that instaneously induced changes in the sinking of POC and PIC cause large scale reorganizations in the marine ecosystem that also result in shifts of the lysocline depth after 100 years of model integration. Although similar effects with a general deepening of the lysocline in the Atlantic and the Southern Ocean next to a shoaling in the North Pacific are observed in all simulations, the re-equilibration of air-sea CO_2-fluxes yields oceanic DIC inventories that are either higher or lower than in the reference simulation. Based on fluxes of POC and PIC, productivity and the distributions of nitrogen (NO_3), dissolved inorganic carbon (DIC) and alkalinity a number of indices defined to estimate the efficiency of carbon transport away from the atmosphere. The results show that the more efficient the vertical transport of organic carbon towards depth, the lower the surface ocean pCO_2, the higher the air-sea CO_2 flux and the stronger the increase in the oceanic inventory of dissolved in organic carbon (DIC). Along with POC flux it is important to consider variations in the flux of PIC, as the net effect of particle flux reorganizations on surface ocean pCO_2 is a combination of changes in DIC and alkalinity.

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COUPLED PHYSICAL BIOGEOCHEMICAL RESPONSE TO INCREASING CO_2 FROM AN EARTH SYSTEM MODEL M46

Segschneider, Joachim and E. Maier-Reimer

The recently intensified discussion about the impact of increasing uptake of CO_2 by the oceans and the subsequent acidification on the marine biota has mainly been focusing on the biogeochemical system. Here, by using results from a fully coupled Earth System Model driven with A2 CO_2 emissions, it will be shown that the physical response of the ocean to climate change induced by increasing atmospheric CO_2 may be of equal importance as the biogeochemistry:
The slowdown of the meridional overturning circulation in response to climate warming causes reduced upwelling of nutrients. This effect is more pronounced for silicate than for nitrate, since biogenic opal remineralizes at greater depth than particulate organic carbon. Hence, silicate concentrations in the surface waters decrease more rapidly than for phosphate and nitrate. Diatoms, which currently outcompete coccolithophores in the request for nitrate and phosphate provided that sufficient silicate is available, are thus having a relative disadvantage. In our model study, this results in an increase of global calcium carbonate export of 20% by the year 2100. Since this is quite contrary to what one would expect from a purely biogeochemical view (namely the decrease of calcite formation in more acid waters) it should be noted that our model computes enhanced dissolution of calcium carbonate (with an predicted drop in pH of about 0.3 units in surface water, which are still supersaturated), but no impact of acidification on the calcite formation is included.

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DISSOLVED INORGANIC CARBON IN THE CANADIAN ARCHIPELAGO OF THE ARCTIC OCEAN: THE EXPORT OF PACIFIC CARBON TO THE NORTH ATLANTIC VIA BAFFIN BAY T46

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The Arctic Ocean appears to be particularly sensitive to climatic changes, and is thought to be an area where such changes might be detected. The Arctic hydrological cycle is influenced by: runoff and precipitation, sea ice formation/melting, and the inflow of saline waters from the Bering and Fram Strait and the Barents Sea Shelf. Pacific water is recognizable as low salinity water, with high concentrations of dissolved inorganic carbon (DIC), flowing from the Arctic Ocean to the North Atlantic via the Canadian Archipelago. We present DIC data from an east-west section through the Archipelago, as part of the Canadian IPY initiatives. The fractions of Pacific and Arctic Ocean waters leaving the Archipelago and entering Baffin Bay and subsequently the North Atlantic are computed. The transport of carbon from the Pacific, via the Arctic, to the North Atlantic is estimated.
Fluctuations in water mass transport out off the Arctic have been linked to the North Atlantic Oscillation (NAO). During NAO induced Great Salinity Anomalies (GSA), large amounts of fresher water, with relatively higher concentrations of DIC, are released to the North Atlantic. The contribution of Pacific-origin carbon exported to the North Atlantic during such an anomaly is estimated. The reorganization of the Arctic circulation during the recent decades has led to an altered transport of Pacific waters to the North Atlantic Ocean. This in turn is deemed to modulate CO_2 uptake and acidification in the temperate and subpolar North Atlantic.

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EFFECT OF THE HIGH CO_2 ON GROWTH OF PHYTOPLANKTON SPECIES: LABORATORY STUDY M47

Shin, Kyoungsoon, Bong-Gil Hyun, and Kitack Lee

Cultured phytoplankton, *Cylindrotheca closterium*, *Melosira nummuloides*, *Nitzschia* sp., *Phaeodictylum triconutum, Prorocentrum minimum* were subjected to test the growth rates under the different conditions of CO_2 concentration. Two different CO_2 concentrations were defined as 'normal condition' (pCO_2: 200ppm) and 'high condition' (pCO_2: 980ppm). The experiment was performed under the nutrient enriched-condition. The temperature was maintained 25±1 □ under the equally lit light cycle (12 hr. light : 12 hr. dark). *Nitzschia* sp. and *M. nummuloides* showed higher chlorophyll-a concentration under the high condition than under the normal condition. However, higher chlorophyll-a concentration was measured for *P. minimum* under the normal condition than under the high condition. These results may reflect that the highly concentrated CO_2 environment increased the growth rate of *Nitzschia* sp. and *M. nummuloides*, while the growth rate of *P. minimum* was retarded under the high condition. There was no a clear difference of growth rate between high and normal conditions in the case of *C. closterium* and *P. triconutum*. The researches are in progress and will argue on the matter of the rapid variations of phytoplankton community structure and primary productivity which is induced by the increase of global CO_2 level.

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NATURAL ANALOGUE FOR OCEAN ACIDIFICATION T47

Shitashima, Kiminori

Large amounts of CO2 are being supplied to the ocean from the seafloor as a natural phenomenon at seafloor hydrothermal systems. Hydrothermal fluids are highly enriched with CO2 and show low pH (around pH 2 to 3) relative to seawater. This CO2 is taken up from the basalt by the fluid during high temperature seawater-magma interaction. In the Okinawa Trough and Mariana Trough, liquid CO2 is emitted from hydrothermal vents at about 1500m depth, and CO2 gas bubbles are erupted from seafloor at 100-200m depth in the Kagoshima Bay.
Dissolution of CO2 during ascent of CO2 droplet and diffusion of low pH seawater were observed at the Hatoma Knoll in the Okinawa Trough. The CO2 droplets emitted from the seafloor dissolve slowly into the ambient seawater while ascending, but changes in pH and pCO2 near the rising CO2 droplets are small. The in-situ pH mapping revealed that the discharged liquid CO2 does not cause widespread pH depression in the ambient environment. The result of CO2 gas bubbles mapping survey at the Wakamiko Caldera in the Kagoshima Bay showed only localized pH depression below 120m depth. At the NW Eifuku submarine volcano in the Mariana Trough, the low pH plume derived from hydrothermal liquid CO2 was detected in 100m high and 200m wide area above the summit of the volcano.
Natural analogue of the hydrothermal liquid CO2 would provide an opportunity for understanding the mechanism, influence and recovery of ocean acidification.

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EFFECTS OF OCEAN ACIDIFICATION ON DEVELOPMENT AND GROWTH OF *S. DROEBACHIENSIS* LARVAE AND ADULTS M48

Stumpp, Meike, Katja Trübenbach, and Frank Melzner

Previous work has shown that larval stages of sea urchins react highly sensitive towards ocean acidification, displaying dramatically reduced growth rates. However, nothing is known so far about the underlying physiological mechanisms leading to growth depression. Within the current study, we use the sea urchin *Strongylocentrotus droebachiensis*, a temperate to polar sea urchin that occurs commonly in all northern regions of the world oceans, as a model organism to study the effects of ocean acidification and global warming on key physiological processes.
Currently, basic experiments estimate the effects these environmental changes have on the development, morphology and survival of *S. droebachiensis* larvae and on the growth rate of adults. First results showed a significant reduction in larval growth rates at 1,400 ppm CO_2. Using quantitative PCR and the sequenced genome of the congener *S. purpuratus*, we will subsequently target gene products responsible for ion homeostasis, pH regulation and calcification, as these might be processes most relevant for the observed changes in larval morphology. Furthermore we will define tissue specific gene expressions responsible for ion homeostasis in adults. Additional non-hypothesis driven approaches, employing 454 pyrosequencing of control vs. stressed phenotype transcriptomes, will help us develop new hypotheses regarding what physiological processes might define sensitivity towards elevated CO_2 and temperature.

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REGULATION OF PHOTOSYNTHESIS OF A COCCOLITHOPHORID LIVING IN A HIGH CO2 WORLD T48

Suggett, David J., Richard Webster, Tracy Lawson, Stephane Lefebvre, Christine Raines, and Richard J. Geider

Growth of calcifying unicellular coccolithophorids contributes significantly to export of both organic carbon and calcium carbonate ($CaCO_3$) from surface waters. Previous research has demonstrated that calcification by these organisms will be negatively affected as the pH of the oceans decreases with rising atmospheric CO_2; however, the simultaneous response of photosynthesis and therefore growth is less clear. As with these previous studies we examined the globally important coccolithophorid *Emiliania Huxleyi*. A calcifying strain (PML-B11) was grown in pH stats at each of two CO_2 (180 and 750 ppm) and light (30 and 300 µmol photons m-2 s-1) growth conditions. In addition to calcification, we examined the response of the light harvesting antennae, photosynthetic reaction centers and photosynthesis rates (electron transfer rates, gross and net O_2 evolution, respiration). Calcification rates changed with CO2; however, most photosynthetic parameters were largely altered by light availability and not CO2. Only cell size significantly increased at higher CO2 levels. Similarly, light and not CO2 altered the expression of a subset of FCP genes at the RNA and protein levels. Our results further suggest that acidification will have limited effect on the photosynthetic capacity of coccoltihophorids but that combing calcification and cell size may have important ecological and biogeochemical implications. Our results are somewhat inconsistent with other similar studies highlighting that such fundamental responses must be better placed within the context of the genetic diversity for *E. huxleyi* that exists in nature.

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A NEW APPROACH TO STUDY THE EFFECTS OF CO_2 IN DEEP-SEA ORGANSIMS M49

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The deep ocean is one of the last of the planet's major frontiers. The ocean floor beyond the edge of the continental shelf covers some 50 percent or more of the entire Earth's surface. Deep-sea biology has traditionally been rather descriptive and dependent on the availability of organisms obtained by means of trawls or grabs. Research over the past decades has revealed high levels of biodiversity and endemism associated with many deep-sea ecosystems. Global warming and associated euthropication will have tremendous impact on deep-sea faunas that are assumed to be highly sensitive to changes in pH and temperature. Increased acidosis of the deep sea may lead to metabolic suppression, reduced protein synthesis, respiratory stress, reduced metabolic scope, and ultimately death of the organisms exposed to it. Only in recent years the increased use of underwater video systems and ROVs has allowed *in situ* studies of deep-sea organisms in their environment. Here, we advocate that the study of deep-sea organisms under controlled lab conditions (monitored experimental parameters) is still essential to elucidating ecological and physiological life history adaptations of deep-sea organisms to their environment, complementing field observations. We present an infrastructure for work on living deep-sea organisms under controlled laboratory conditions: The IPOCAMP$_{(TM)}$ system, allows the study of organisms under deep-sea conditions including controlled conditions of temperature, pressure and carbon dioxide, in a closed seawater circulation system. We present first results of this newly established system in the CO_2 context.

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CO_2-DRIVEN ACIDIFICATION RADICALLY AFFECTS LARVAL SURVIVAL AND DEVELOPMENT IN MARINE ORGANISMS – II. ECHINODERMS T49

Thorndyke, Michael[1], Jon Havenhand[2], and Sam Dupont[1]

Perhaps one of the key marine groups most likely to be impacted by predicted OA is the echinoderms. Echinoderms are a vital component of the marine environment with representatives in virtually every ecosystem; where they are often keystone ecosystem engineers. In addition, many are indirect developers (e.g. urchins, brittlestars) where both larva and adult have critical (and quite different) episodes of skeletogenic calcification. In contrast others (Asteroids) exhibit adult but not larval skeletogenesis. In this way echinoderms offer a valuable and tractable experimental system for exploring the impacts of OA on marine biota. We have used our CO_2 – based sea water acidification system to investigate the affects of increasing acidity on early developmental success in the brittlestars *Amphiura filiformis* and *Ophiothrix fragilis*, the sea star *Asterias rubens* and the sea urchin *Strongylocentrotus droebachiensis*. Our data show that the impact of acidification on larval development is species-specific and highlight the danger of extrapolation from just a few key species, even within closely related taxa. For example, in *O. fragilis*, low pH induces dramatic mortality after one week due to larval and skeletal malformations while more subtle effects were observed in *A. filiformis* where some individuals survive to the juvenile stage. Urchins and asteroids on the other hand seem relatively unaffected. These results are interpreted in the context of adaptive potential to these rapid environmental changes.

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THE MEDITERRANEAN SEA: A VERY HIGH ANTHROPOGENIC CO_2 AND ACIDIFIED ENVIRONMENT. M50

Touratier, F. and C. Goyet.

The Mediterranean Sea ecosystems suffer from a very intense anthropogenic pressure that strongly affects most biogeochemical cycles. During the last century, the impact on the carbon cycle and especially on the carbonate system has been poorly understood given the scarce data available for total alkalinity (A_T), total dissolved inorganic (C_T), and/or pH. Since almost a decade however, several national and international programs were designed to increase the amount of high quality data in the region.
Using this recent database we first describe the distributions for C_T and A_T for the whole Mediterranean Sea. The concentration of anthropogenic CO_2 (C_{ant}) accumulated since the pre-industrial era and consequently the level of acidification are also estimated. It is shown that all waters (even the deepest ones in both the western and eastern basins) are contaminated by C_{ant}. This trend is confirmed by the distribution of other anthropogenic tracers like CFCs and tritium. We show that the C_{ant} averaged inventories in the Mediterranean Sea are approximately twice as those estimated in the North Atlantic Ocean, resulting in a much larger acidification of this semi-enclosed sea. Consequently, at depths, the Mediterranean Sea acts as a significant source of anthropogenic carbon for the Atlantic Ocean.
The analysis of the temporal trends clearly reveals the impact of the EMT (Eastern Mediterranean Transient) which resulted in an intense sequestration of anthropogenic carbon into the deep waters of the eastern basin. The recent observation that C_{ant} in the intermediate and deep waters of the DYFAMED site (western Mediterranean) is decreasing since the 1990's is also discussed in the light of the EMT event.

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THE EFFECTS OF ELEVATED CO_2 AND REDUCED pH ON THE INTERTIDAL SEA ANEMONE *ANTHOPLEURA ELEGANTISSIMA* AND ITS ALGAL SYMBIONTS T50

Towanda, Trisha and Erik V. Thuesen

Anthopleura elegantissima (Brandt) is a non-calcifying anthozoan with symbiotic algae similar to that of hermatypic corals. It is locally abundant in the intertidal zone along the Pacific coast of North America. To better understand the impacts of ocean acidification on photosynthetic symbioses, the effects of elevated carbon dioxide (hypercapnia) and reduced pH were investigated on *A. elegantissima*. The anemone forms aggregations of clones through fission, and experiments were designed to examine effects of hypercapnic acidification with paired experiments using couplets of clones. Couplet individuals were maintained in the laboratory at pH values of 8.1 (ambient) or 7.3 (CO_2-induced) for a period of 10 weeks. Individuals were compared for differences in respiratory rate, photosynthetic rate, growth rate and the contribution of zooxanthellae to the animal's respiration (CZAR). Chlorophyll content and density of algal cells in anemones as well as algal cell size and mitotic index were also measured for comparisons.

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TESTING THE SENSITIVITY OF THE CARBON CYCLE IN THE EASTERN MEDITERRANEAN SEA IN RESPONSE TO ANTHROPOGENIC INFLUENCE. M51

Triantafyllou, G., V. Avgoustidi, E. Krasakopoulou, K. Tsiaras, and A. Pollani

A seawater carbon cycle model adopted from Chuck et al (2005) has been implemented in the area of the Eastern Mediterranean Sea in an attempt to test the behavior of an ultra oligotrophic system, in view of the ongoing ecosystem changes. More specifically, we are aiming to asses the behavior of the seawater carbon cycle in the area under investigation, through the response of a number of biotic and

abiotic processes to climate change and anthropogenic influence. The studied area is considered to be highly sensitive to climate change and forms a system characterized by extreme phosphorous limitation all year round.
The model describes phytoplankton standing stocks and growth in the euphotic zone (120 m), seawater concentrations as well as riverine inputs of nitrate, phosphate and silicate, TCO_2, alkalinity, the air sea gas exchange of CO2, calcite production and remineralisation. Phytoplankton and phosphorous dynamics are provided by the ERSEM (European regional seas ecosystem model) in the carbon cycle model. Sensitivity experiments are being carried out through a series of perturbation tests; increased usage of fertilizers, increasing temperature, increased air sea gas exchange of CO_2 according to a number of different emissions scenarios, changes in the abundance of calcite/coccolithophores, changes in the action of the biological pump.
Such sensitivity analysis in the area of the Eastern Mediterranean Sea will allow a first investigation on the possible biogeochemical feedbacks that might arise in response to the current anthropogenic forcing.

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DISTRIBUTION OF PELAGIC BIOGENIC CARBONATES ACROSS THE SOUTHERN OCEAN SOUTH OF AUSTRALIA T51

Trull, Tom[1], Tim Smit[2], and Diana Davies[1]

Developing an understanding of the impact of ocean acidification on pelagic microbial biogenic carbonate forming organisms requires knowledge of their abundance. As a first step in this assessment for Southern Ocean waters south of Australia, surface water PIC was measured from March 22, 2008 through April 19, 2008 at 60 sites along the WOCE/CLIVAR SR3 transect between Tasmania and Antarctica. PIC was determined on bulk samples collected from the underway clean seawater supply with a continuous flow centrifuge size-fractionated samples obtained by sequential filtration through a 1000 um pre-screen followed by 200 and 55 um nylon screens, and 1 um glass-fibre filters. Bulk PIC values ranged between <1 ug/L and 20 ug/L. PIC values were low (1-2 ug/L) close to the Antarctic continent and increased (2-6 ug/L) in the AZ (Antarctic Zone) and PFZ (Polar Frontal Zone). Highest values were observed across the SAZ (Subantarctic Zone) with a peak of 16-20 ug/L between 51°S and 47°S. Results from the size-fractionated PIC measurements suggest that coccolithophores (the 1-55 um size fraction) made up the largest fraction (65-95%), with foraminifera (55-200 um fraction) contributing 15-30%, and the remaining small fraction of PIC came from other larger calcifying organisms like pteropods (200-1000 um fraction). The PIC distributions will be compared to carbonate saturation indices, and to particulate organic carbon and particulate biogenic silica distributions to provide a perspective on the relative importance of these carbonate forming taxa in comparison to other phytoplankton functional groups.

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RESPONSES OF MARINE COMMUNITIES TO PH CHANGE. A FIELD BASED EXPERIMENTAL APPROACH. M52

Vance, Thomas

Without field based experimentation, accurately gauging the effect of increasing atmospheric pCO_2 on multi species community processes such as recruitment, succession, trophic interactions, biogeochemical cycling and ecosystem functioning is challenging.
Obtaining such data is difficult in the lab, and due to the inherent pH buffering potential of seawater, has largely been rejected as not practical for a field based experimental approach.

This current study presents a novel field based method where settlement panels are exposed to experimentally manipulated CO_2 induced reduced pH environments. The pH conditions are manipulated to simulate future global ocean carbonate states. Microbial, algal and invertebrate communities were measured to provide benthic ecosystem responses. This approach allows a balanced and replicated field based experimental approach to be applied to answer fundamental questions about biological responses of communities to ocean acidification.

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DECREASING OF AGGREGATE SIZE OF MARINE SUSPENDED PARTICLES UNDER HIGH CO_2 CONDITIONS T52

Watanabe, Yuji[1,2], Nobuhiro Maeda[1,2], and Koh Harada[3]

Suspended particles flocculate and form larger sinking particles in the ocean. Such large particles have an important role on the biological pump transporting organic carbon from the surface ocean to the deep layer, and the aggregates also provide the suitable habitat for bacteria and nano-flagellates. As the process of aggregation is affected by the surrounding pH conditions, we investigated the aggregation ability of marine particles by exposing them to lowered pH controlled with elevated CO_2. Suspended particles, which were collected from near the sea bottom (100 m depth) in Toyama bay and from about 1500 m depth in the western north Pacific, were stirred in seawater with various pH (6.0 - 8.0) conditions. The larger aggregates were formed in normal pH condition, but lowered pH condition inhibited the aggregation of suspended particles. Such decreasing the aggregate size causes decreasing in the sinking rate of that, consequently the available abundance of food source for planktonic organisms will be affected. And also the microhabitat for the attached microorganisms will decrease.

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A WHOLE ORGANISM APPROACH TO THE PHYSIOLOGICAL IMPACTS OF OCEAN ACIDIFICATION. M53

Wood, Hannah L.[1], Stephen Widdicombe[1], and John I. Spicer[2]

Investigations into the impact of ocean acidification on an organism can be achieved by studying physiological processes. Currently, calcification and growth are popular proxies to quantify a species response because of their vulnerability to the changing carbonate chemistry predicted in a high CO_2 world. However, hypercapnia and acidosis have the potential to affect many other physiological processes within an organism. Moreover, these processes are frequently interdependent and by focussing on just one area (e.g. growth/calcification) there is a high possibility of overlooking sub-lethal impacts of ocean acidification. A series of mesocosm experiments have been conducted to investigate how key survival processes are affected by ocean acidification. These experiments have been conducted using the ophiuroid brittlestar *Amphiura filiformis*, a calcifying species which is an ecosystem engineer widespread across European temperate waters. Investigating how pH affects metabolism, ecosystem function (nutrient flux), reproduction, muscle maintenance, arm regeneration and differentiation, in addition to growth and calcification, gives a clear picture of how this organism is affected by, and potentially copes with ocean acidification. The results for *A. filiformis* show metabolic up-regulation and increased calcification, which result in a trade off with other physiological processes. While the results of the study indicate an increase in growth and calcification, and therefore suggest no detrimental effect of increase pH, the whole organism approach reveals a different picture; the trade offs and prioritisation reveal the survival of this species in a high CO_2 ocean could be at risk.

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RESPONSES OF PHYTOPLANKTON ASSEMBLAGE AND ORGANC CARBON DYNAMICS TO CO_2 INCREASE T53

Yoshimura, Takeshi[1], Jun Nishioka[2], Koji Suzuki[3], Hiroshi Hattori[4], Hiroshi Kiyosawa[5], Daisuke Tsumune[1], Kazuhiro Misumi[1] and Takeshi Nakatsuka[2]

To investigate the responses of phytoplankton and organic carbon dynamics to CO_2 increase, a CO_2 manipulation experiment was conducted in the Okhotsk Sea in summer 2006. Surface water with a natural phytoplankton assemblage was incubated with bubbling air containing different CO_2 concentrations (180, 380, 750, and 1000 ppm). Temporal changes in phytoplankton pigments and particulate and dissolved organic carbon (POC and DOC) were observed for 14 days. The surface water was depleted in nutrients, so phytoplankton in the bottles remained at a low biomass under a regenerated system. If the values at the end of the experiment were compared in each treatment, the fucoxanthin/Chl-*a* ratios decreased with increasing CO_2, indicating the relative abundance of fucoxanthin-containing phytoplankton such as diatoms would be sensitive to a change in CO_2. Since no cells of coccolithophores were detected using a scanning electron microscope, we could not determine the response of them to the CO_2 gradient. The amount of DOC accumulation decreased with increasing CO_2, while no significant difference was observed for change in POC between treatments. The increase in atmospheric CO_2 is concluded to potentially affect the phytoplankton community structure and organic carbon flow in the nutrient-depleted subpolar surface water.

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