S2.1 Marine carbon cycling and other biogeochemical cycles

20 May, 09:15 (S2.1-4797) Plenary

Recent trend in the global oceanic CO_2 sink

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In spite of the large increase in atmospheric CO_2 in recent decades, numerous studies have reported that long-term observations of seawater pCO_2 and sea-air pCO_2 difference are not always consistent with an increasing global oceanic sink for CO_2. We analysed observations and models over the 1981-2007 time period to set constrains on the rate of increase of the global oceanic sink for CO_2. Our analysis includes repeat surveys of oceanic pCO_2, inversions of atmospheric CO_2 observations, and a process model forced by different combinations of observed atmospheric surface conditions. The observations and models show large temporal and spatial variability in the mean annual rate of change of seawater pCO_2, including periods where it increases faster than atmospheric CO_2. We show coherence between data and models that suggest a steady increase in the air-to-sea CO_2 flux in large sectors of the North and South Pacific oceans, and no change or a decrease in air-to-sea CO_2 flux in the sub-tropical North Atlantic, equatorial Pacific and Southern Oceans. Globally, the process model shows no increase in the oceanic CO_2 sink between 1981 and 2007 because of wind-driven changes in the physical transport, but this result remains only partly constrained by observations.

20 May, 10:35 (S2.1-4817) Invited

Decadal changes in the Atlantic, Pacific and Indian Ocean inorganic carbon inventories

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Discrete high-quality dissolved inorganic carbon and total alkalinity data were acquired as part of the international WOCE/JGOFS global CO_2 survey cruises in the early 1990s. These data provided a baseline global ocean carbon inventory. In 2003, the US CLIVAR/CO_2 Repeat Hydrography Program began reoccupying a subset of the WOCE/JGOFS lines on a ten year rotating schedule with the goal of quantifying the ocean uptake of anthropogenic CO_2 and the effects of natural variability and climate change on marine ecosystems and biogeochemistry. Although the survey is only half completed, cruises have been run in the Atlantic, Pacific and Indian Oceans allowing an initial comparison. We will discuss approaches for separating the anthropogenic CO_2 signal from variations in local circulation and biology using an extended multiple linear regression (eMLR) analysis. Anthropogenic CO_2 column inventory changes range from 0.25 to 0.75 mol m^{-2} yr^{-1} with some unexpected patterns. The largest inventory changes over the last 10 years were not found in the North Atlantic as suggested from changes since the preindustrial. Substantial DIC changes were observed in the North Pacific over the last decade, but as much as 80% of the change can be attributed to variations in circulation. The southern hemisphere oceans experienced the largest anthropogenic CO_2 inventory changes since the WOCE/JGOFS survey. We will examine the inventory change patterns and discuss the mechanisms leading to these changes. We also will discuss the total alkalinity results but find that there is insufficient evidence to conclude that there have been any measurable anthropogenic changes over the last 10-15 years.

20 May, 11:00 (S2.1-4954) Invited

The changing uptake of CO_2 by the North Atlantic Ocean

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The growing number of measurements over the last 10 years, both of surface pCO_2 and of subsurface parameters from repeat oceanographic sections, has begun to update our previously static "climatological" view of the ocean sink for CO_2. In the North Atlantic we see that the uptake is very variable, changing coherently from year to year and by a factor of two from the mid-1990s to the early 2000s. The changes are due to altered rates of formation of sub-surface water masses such as the Labrador sea water. In transatlantic sections of calculated anthropogenic CO_2 we can see how its distribution is changing rapidly in the upper water column and the southward travelling deep western boundary current. These changes are in turn forced by climate variability, in particular, the North Atlantic Oscillation. Our conclusion that the uptake in the North Atlantic at least partly correlates with the NAO, is similar to our understanding of the equatorial Pacific, the other region where the time variability of air-sea flux is well-studied, and where it correlates closely with the ENSO. Most models of the sink for CO_2 in the North Atlantic do not reproduce the variability in uptake that we see, so it is difficult to forecast how it will evolve in the future. In particular, we cannot tell how much of the observed weakening of the sink is a response to anthropogenic climate change, and how much is due to natural variability – only a longer time series of measurements will answer this.

20 May, 11:25 (S2.1-4670)

What can surface fCO_2 measurements tell us about the evolution of the Southern Ocean CO_2 sink?

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In this study trends of surface ocean CO_2 fugacity (fCO_2) are estimated from observations conducted in 1991-2007 in the south-western Indian and Southern Oceans. These observed trends are also compared with recent ocean modelling and atmospheric inverse approaches that suggest that the Southern Ocean has experienced a reduction in carbon uptake over recent decades. In the latitudes 20°S-60°S we see that over the observational record the annually-averaged oceanic fCO_2 increased at a rate of 2.11 (±0.07) µatm/yr, i.e. about 0.4 µatm/yr faster than in the atmosphere. We also analyse the decadal variability in different regions (20-35°S, 35-40°S, 40-42°S and 50-55°S) and in different seasons. During the austral summer oceanic fCO_2 was seen to increase between +2.2 and +2.4 µatm/yr and was homogeneous across all regions. Conversely, during the austral winter, the growth rate is lower north of 40°S (+1.5 to +1.7 µatm/yr) in comparison to higher latitudes (+2.2 µatm/yr), broadly consistent with a Southern Annular Mode response. Our results show that *in situ* observations do suggest a reduction or near-stabilisation of the CO_2 sink in the Southern Ocean. To conclude we explore how well the trends can be simulated using an ocean biogeochemical model and how representative are these regional results of the greater Southern Ocean, over both the present and historical periods.

20 May, 11:40 (S2.1-4701)

Negative feedback of poleward intensifying southern hemisphere winds on atmospheric CO_2 in the 21st century

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An Earth System model is used to explore the response of the oceanic and terrestrial carbon sinks to strengthening and poleward shifting of the extratropical southern hemisphere winds, which is a robust feature of climate models' response to greenhouse gas forcing through the 20th and 21st centuries. We find that poleward intensifying southern hemisphere winds have an opposite effect on the uptake of natural and anthropogenic CO_2 in the Southern Ocean (90°S-40°S): altered winds lead to anomalous outgassing of natural CO_2 and anomalous uptake of anthropogenic CO_2. As a result, uptake of total CO_2 (natural + anthropogenic) initially decreases and, from the end of the 20th century on, increases relative to the pre-industrial flux. On land, changing winds also lead to an enhanced efficacy

of the CO_2 sink. We therefore suggest that poleward intensification of the southern hemisphere winds will likely provide for a negative feedback on atmospheric CO_2 in the 21st century. This feedback is found to be in the order of a few percent in 2100.

20 May, 11:55 (S2.1-4708)

The combined effects of rising atmospheric CO_2 and declining stratospheric ozone on the past and future uptake of CO_2 by the Southern Ocean

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Recent observations suggest that the Southern Ocean is a decreasing sink of atmospheric CO_2. This trend is linked to the Southern Annular Mode (SAM), the leading mode of climate variability in the Southern Ocean. The SAM in its positive phase increases wind speeds over the Southern Ocean decreasing the uptake of atmospheric CO_2. The SAM is driven in equal parts by changes in both greenhouse gases (GHGs) and the Antarctic ozone hole. Coupled climate carbon models used to project the future response of the Southern Ocean have not been able capture this decreasing trend in CO_2 uptake, nor the increasing wind speed. In this work we use the French IPSL coupled climate carbon model and prescribe an ozone hole in conjunction with GHGs, to reproduce the observed wind speed changes and hence the observed trend in CO_2 uptake over the historical period and thus project how under a higher wind speed regime the Southern CO_2 sink will respond in the future.

20 May, 12:10 (S2.1-4854)

Natural and anthropogenic carbon changes in mode waters of the south west Indian Ocean

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The CO_2 content in the present ocean is affected by both climate variability and anthropogenic CO_2 emissions. In an attempt to isolate the climate component in ocean carbon trends we evaluated jointly the change in total carbon (C_T) and the accumulation of anthropogenic CO_2 (C_{ant}). Mode waters are of particular interest here, both because they provide a privileged pathway for the transport of C_{ant} into the ocean interior and because they are most sensitive to climate variability and change. Observations collected 15 years apart in the south-west Indian Ocean, a region where Subantarctic Mode Water is formed, show a small increase in mode waters C_T (around 5 µmol/kg). The change in C_{ant} estimated using three different methods is significantly higher (>10 µmol/kg over the 15-year period). The difference between changes in total and anthropogenic carbon must be explained by natural or climate change induced variability. We found that interannual variability has a relatively small impact on mode waters C_T. Instead the small increase observed in C_T as compared to the accumulation of C_{ant} could result from a reduction in the biological activity as suggested by satellite data and/or decadal changes in ocean circulation. These different hypotheses will be discussed based on global ocean-carbon simulations.

20 May, 12:25 (S2.1-4861)

Advective impacts on North Atlantic carbon sink variability

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Using a physical-biogeochemical model that is able to capture much of the seasonal variability in surface ocean pCO_2 across the North Atlantic and the interannual variability observed at Bermuda, we examine the impacts of changing horizontal advection on carbon sink variability across the basin. At Bermuda, preliminary results

suggest that carbon sink variability that would be driven by the local atmospheric forcing is damped by anomalous advection of heat from the South Atlantic. Basin-wide, the net flux variability is small, but spatio-temporal variability in the carbon sink is due to decadal trends in the strength of gyre circulations. These results suggest that changes in the carbon cycle due to horizontal advection have first-order impacts on decadal variability in surface ocean pCO_2, and thus on the spatial distribution of the North Atlantic carbon sink.

20 May, 12:40 (S2.1-4928)

Altimetry helps to explain patchy changes in repeat hydrography carbon measurements

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Observations and models have been used to evaluate the relative amplitudes of natural variability and the anthropogenic perturbation in dissolved inorganic carbon (DIC) over the upper ocean. There are three main results: first, the amplitude of the natural variability of column inventories of DIC on seasonal to interannual timescales is of the same order of magnitude as the anthropogenic transient signal as it changes over a decade. Second, the latitude/longitude pattern of natural variability is distinct from what is found for the decadal changes in anthropogenic DIC inventories. Third, that dynamically-driven variability constitutes at least a first-order component of the total background variability for DIC inventories. In particular, we focus here on the impact of local variability in circulation acting on background gradients in tracer concentrations in the ocean interior. Importantly, it is shown that natural DIC inventory variations are closely related to sea surface height variations over much of the ocean, with the North Atlantic being a notable exception. The underlying mechanisms and the implications for the detection of anthropogenic DIC using repeat hydrography measurements is presented.

20 May, 12:55 (S2.1-4832)

Understanding the impact of physical forcing on Southern Ocean phytoplankton and primary production

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Phytoplankton in the Southern Ocean exist in a high nutrient, low chlorophyll regime where primary production rates and accumulation of large phytoplankton are often limited by seasonally and spatially heterogeneous interactions among light, iron and silicic acid. Uncertainty in the current controls of Southern Ocean phytoplankton impacts our understanding of how assemblages will respond under climate change scenarios. For instance, warmer temperatures and increased stratification will tend to favour higher rates of primary production while changes in windstress may alter upwelling of macro and micronutrients influencing regional patterns of primary production in complex ways. We regressed monthly mean climatology-corrected anomalies over time (1997-2007) in remotely-sensed and calculated fields of natural log-transformed chlorophyll *a* ($ln_{chl\ a}$), sea surface temperature, wind stress and primary production. Preliminary results indicate that the zonal mean $ln_{chl\ a}$ has increased in the Antarctic and Subantarctic Zones while phytoplankton biomass has decreased markedly in the Polar Front Zone and weakly in the Subtropical Zone. When zonal means are further decomposed by ocean basin or month (November-March), further complexity is introduced. In order to facilitate our understanding of Southern Ocean phytoplankton and the physical mechanisms that have significantly influenced them over the past decade, we will use self organising maps (SOM), a type of artificial neural network adept at pattern extraction from large and often non-linear data sets. Furthermore, we will compare our results with model output from a hindcast simulation with multiple phytoplankton functional groups (NCAR CCSM) coupled to the Parallel Ocean Program (POP) general ocean circulation model.

20 May, 14:30 (S2.1-4601)

An increase of silicic acid and nitrate concentrations along the pathway of Lower Circumpolar Deep Water in the Pacific Ocean: results of snapshot comparisons

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Changes of nutrient concentrations and other hydrographic parameters such as temperature and dissolved oxygen concentration were observed when we compared WOCE revisited cruises in the 2000s and WOCE cruises in the 1980s and 1990s in the Pacific Ocean. A typical future of changes in nutrient concentrations are silicic acid concentration increased 1-2 μmol kg^{-1} per decade, about 1% change per decade, if we can assume the changes are linear, along the pathway of Lower Circumpolar Deep Water (LCDW) in the North Pacific. We also found good positive correlation between silicic acid concentration and nitrate concentration, and negative correlation between silicic acid concentration and dissolved oxygen concentration. Since independent chemical measurements for nutrients and dissolved oxygen indicate the same direction of changes as water properties, these changes can be thought to be much more reliable, although it is believed that there is less comparability of nutrient measurements at the present time. In the deeper layers in the eastern North Pacific, silicic acid concentration decreased in contrast with the areas of LCDW pathway. These findings showed that nutrient concentrations in the deeper layers might change systematically. These findings also suggest that northward LCDW and southward NPDW transport has decreased which is consistent with the previously reported warming of a few mK in the deep waters in the North Pacific Ocean by Fukasawa *et al*., 2004 and Kawano *et al*., 2006.

20 May, 14:45 (S2.1-4643)

Recent decrease of summer time nutrients in the mixed layer of the North Pacific HNLC region

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Multi-decadal deceases of summer time nutrients in the mixed layer have been observed in various locations in the subarctic North Pacific, known as the third largest HNLC region in the world oceans. In this study we demonstrate, for the first time, that the decreasing trend is detectable over the entire subarctic North Pacific. We corrected 351 and 278 phosphate and silicate data, respectively, and these data were divided into two time groups before and after 1990 to investigate temporal changes. Area-averaged concentration decreased by 0.07±0.05 μM and 1.55±1.55 μM for phosphate and silicate, respectively, from the period 1975-1990 to 1991-2002. Close inspection of the time series data reveals that the differences are not the result of short-scale temporal variations such as *El Niño*/*La Niña* events. Instead, the decreasing trends are consistent with the linear trends observed in various time series stations, resulting from a multi-decadal SST increase. Our analysis indicates that the recent decrease of upward nutrient transport is larger than that of downward export production in the North Pacific HNLC region. This imbalance may have generated an oceanic carbon sink of 12 x 10^6 ton C for the recent 30 years in the region. If we assume that this trend continues until the end of this century, 48% of the present sub-arctic North Pacific-HNLC region will change to a non-HNLC region as the result of nutrient decrease. This change may cause a considerable shift in the ocean ecosystem leading to significant changes in both the carbon cycle and fisheries of this region.

20 May, 15:00 (S2.1-4820)

Possible mechanism of decadal-scale variation in PO_4 concentration in the western north Pacific, and the influence on ocean productivity

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Recent studies based on analyses of comprehensive ocean data sets have revealed decadal-scale variation in oceanographic conditions. Such variation has been attributed to trends associated with anthropogenically induced greenhouse warming and natural climate–oceanographic oscillations such as Pacific Decadal Oscillation. Variation in actual oceanographic conditions could be caused by a combination of both of these factors. Here, we suggest mechanisms of decadal-scale variation in PO_4 concentration induced by these effects in the western North Pacific. Significant decreasing and increasing trends in PO_4 have occurred in the surface and subsurface layers, respectively. Synchronous bidecadal-scale oscillations in PO_4 were also found between the two layers. The differing relationships of the trend and oscillation between two layers suggests that these are driven by separate process. The trend component might be induced by attenuation of water exchange between the two layers due to a decrease in surface salinity in the North Pacific Ocean. On the other hand, the influence of the 18.6-year period nodal tidal cycle may cause the bidecadal-scale oscillation. The present process may be related to decadal-scale variation in nutrient supply in a broad area of the North Pacific. *Neocalanus plumchrus* is a dominant mesozooplankton in the North Pacific. The biomass had a significant positive relationship with surface PO_4 in both waters. Variations in PO_4 supply might affect the biomass of *N. plumchrus* due to changes in primarily productivity.

20 May, 15:15 (S2.1-4711)

Seasonal and interannual variation of ocean carbon cycling in the western and eastern tropical-subtropical Pacific: a physical-biogeochemical modelling study

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A 3D physical-biogeochemical model is used to investigate spatiotemporal variations of the physical environment and oceanic carbon cycling in the tropical-subtropical Pacific. The physical model is based on the Regional Ocean Model System (ROMS) and the biogeochemical model is the Carbon Silicon Nitrogen Ecosystem (CoSiNE) model. The coupled physical-biogeochemical model is forced with the daily air-sea fluxes derived from the National Centers for Environmental Prediction (NCEP) reanalysis for the period of 1994 to 2004. The model results, of which performance was verified by two observations along 137ºE and 155ºW, show significant differences in seasonal and interannual variations of the water temperature, dissolved inorganic carbon (DIC), partial pressure of CO_2 in seawater (pCO_{2sea}), and air-sea CO_2 flux, both longitudinally and latitudinally. The interannual variations, driven by various factors such as the global warming, ENSO and PDO, are more significant in the tropical regions than in the subtropical regions, and along 155ºW than along 137ºE, but the relative effect of each factor differs substantially with space. We identify a major cause of annual and interannual change in the pCO_{2sea}, by estimating the relative contribution of the water temperature, salinity, DIC and total alkalinity to the pCO_{2sea} change. The model results show that the cause of the interannual pCO_{2sea} increase is also different among the oceanic regions, and that the increase is primarily resulting from increase in the DIC along 155ºW and the subtropical region of 137ºE, and is mainly due to an increase in the water temperature in the tropical region along 137ºE.

20 May, 15:30 (S2.1-4777)

The impact of rising sea surface temperature on the cycling of organic matter: an indoor mesocosm study

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Recent climate models (e.g. the 4th IPCC report) predict an increase in global sea surface temperature of up to 6°C by the end of this century. Biological processes will respond differently to this, depending on their temperature-sensitivity. For instance, heterotrophic processes (e.g. bacterial degradation of organic matter) are expected to be more sensitive to temperature than autotrophic ones (e.g. photosynthesis), which are typically rate-limited by light or nutrient availability. As a consequence, global warming may affect the balance between production (source) and consumption (sink) of organic matter with possible feedbacks to climate change. To investigate the effect of rising temperature on the cycling and stoichiometry of organic matter during a phytoplankton spring bloom, we performed indoor mesocosm experiments using a natural Baltic Sea plankton community, and followed the build-up and decline of the bloom at four different temperature regimes. We observed significant temperature related effects on the uptake of dissolved inorganic carbon and on the production and fate of organic matter. Rising temperatures lead to an enhanced accumulation of dissolved organic matter and to a change in its C:N:P stoichiometry. In contrast, the concentration and elemental composition of particulate organic matter was less affected by changes in temperature. A sharp increase in transparent exopolymer particles was observed at elevated temperatures, potentially supporting the aggregation of organic matter. Based on these findings, the potential consequences of global warming for the cycling of organic matter in the surface ocean and the functioning of the biological pump will be discussed.

20 May, 15:45 (S2.1-4965)

Microbial dynamics and response to a changing polar ocean climate

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Marine heterotrophic microbes (i.e. prokaryotic bacteria and eukaryotic protozoa) dominate the fluxes of organic carbon in the upper ocean, where they typically remineralise >75% of primary production back to CO_2. Although these small organisms and their interactions are well studied in low latitudes, there is far less known about their distribution, community structure, activity and food web interactions, and their impact on upper open biogeochemistry in high latitudes. Despite the low temperatures, microbial processes are highly active and the rates of growth and elemental transformations are similar to those in lower latitudes. Profound climate changes are predicted for high latitude regions. These include altered temperatures, ice cover, mixing, and nutrient supply. These changes will influence the distribution of ice, physiochemical, biological and food web properties. In the present study, we report on a meta-analysis of a large database on heterotrophic microbes from the polar oceans. Using the results of database analyses, and conceptual and analytical models, we examine the influence of predicted changes in the climate in polar regions on microbial activity, their mediation of upper ocean biogeochemistry, and potential feedbacks on the cycling and flux of climate active properties.

20 May, 16:00 (S2.1-4938)

Climate mediated changes in phytoplankton productivity and air-sea CO_2 exchange on the western shelf of the Antarctic Peninsula over the last 30 years

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Air temperatures along the Western Antarctic Peninsula have increased dramatically over the last 50 years which also corresponds with major retreats in the glaciers and disappearance of perennial sea ice. These changes will directly impact the phytoplankton productivity and associated elemental cycling, therefore we have been studying

the time series changes in phytoplankton community composition and atmosphere-ocean differences in the CO_2 partial pressure ($\Delta pCO_2 = pCO_2$sea - pCO_2air) over the western shelf of the Antarctic Peninsula (WAP) using ship and satellite data from 1978-2006. Satellite data shows the enhanced primary productivity (>2 mg Chl *a* m^{-2}) in the southern sectors and declines in the offshore waters and in northern coastal waters. The satellite results were compared to an 18 year time series of phytoplankton pigments and discrete pCO_2. The January average (1993-2006) of ΔpCO_2 suggested a net 'sink' of CO_2 over the whole sampling grid however the size of the sink appeared to increase after the year 2000. Fucoxanthin (diatoms) explained >80% of the ΔpCO_2 variability, especially closer to the coast and in the southern part of the study area. A greater net 'sink' of atmospheric CO_2 during 2001-2006 with respect to 1997-2006 corresponded to increases in the contribution of larger diatom cells which presumably increased the efficiency of the carbon export flux. These results suggest that as the ice along the Western Antarctic Peninsula declined, the overall productivity and size of the biological CO_2 'sink' has increased to the south.

20 May, 16:15 (S2.1-4816)

Characterisation of phytoplankton blooms and their contribution to export production

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The oceans absorb one quarter of the fossil fuel CO_2 emitted to the atmosphere every year. Air-sea CO_2 flux is controlled by CO_2 solubility, physical processes and biological processes. One biological pathway that controls the draw down of CO_2 is the sinking of organic material following intense phytoplankton blooms. The current assumption is that plankton blooms will continue into the future with the same level of activity as today. To estimate the contribution of phytoplankton blooms to export production, we used satellite chlorophyll data from the SeaWiFS sensor and the results of chlorophyll, primary production (PP) and export production (EP) from our global biogeochemistry model PlankTOM-5 that includes five plankton functional types. Phytoplankton blooms are characterised by their initiation dates, amplitudes and durations. Bloom initiation occurs earlier in the subtropics and propagates over a period of 10 weeks towards higher latitudes. Amplitudes of the bloom show increasing chlorophyll concentrations towards the north up to 2.5 mg Chl/m^3 in the northern hemisphere. In the Southern Ocean, maximum concentrations oscillate around 0.5 mg Chl/m^3. Bloom durations range between 10-15 weeks in the subtropics to less than seven weeks at high-latitudes. In the northern hemisphere, between 30-60ºN, cumulative PP during the bloom period is high compared to the southern hemisphere where PP values decrease towards the pole. Interestingly, the PP latitudinal trends observed in each hemisphere are coupled with both the variations in bloom amplitudes and durations. Spatial variations in PP and EP are shown to be associated with particular bloom characteristics.

20 May, 16:30 (S2.1-4686)

Formation of POC through interactions between TEP and mineral ballast

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The reasons for the fairly constant ratio between particulate organic carbon and dry weight (POC: DW = 5%) observed globally in sinking matter below 1000 m are unclear. Possibly, these 5% POC represent a coating of organic carbon covering inorganic particles. We investigated the formation of POC from dissolved compounds in the presence of minerals during four 24-hour aggregation experiments. Exudates of diatom cultures (1.2 µm pre-filtered) were incubated with biogenic silica, smectite (clay) or $CaCO_3$ dust at concentrations ranging from 0 to 50 mg L^{-1}. POC, DW and transparent exopolymer particles, TEP, which form abiotically from dissolved precursors, were measured. Microscopic aggregates formed everywhere, whereas macroscopic aggregates (> 0.5 mm) formed only in the smectite treatments. After 24 h, the POC: DW ratios of aggregates decreased exponentially with increasing biogenic silica, smectite and $CaCO_3$ concentrations, reaching minimum values of, 0.62%; 0.95% and 1.08%, respectively at a mineral concentration of 50 mg L^{-1}. POC and TEP both increased with mineral concentration and were appreciably higher in smectite treatments compared to those with biogenic

minerals. Microscopic observations revealed different attachment patterns between TEP and minerals, depending on the mineral. Our results show that the amount of organic matter coating minerals is ≤ 1%, too small to explain the 5% POC: DW found in traps. The carrying capacity of minerals for organic matter appears to depend on the mineral type and especially clays may enhance the transformation of dissolved material to POC.

20 May, 16:45 (S2.1-4909)

Comparing the carbon cycle response of two ocean ecosystem models to climate change

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The uncertainty due to model structure in future ocean CO_2 uptake is examined. The natural carbon cycle in the ocean is strongly influenced by the "biological pump": phytoplankton remove CO_2 from the surface waters for growth, some of which is exported to depth before returning to solution. This keeps the atmospheric CO_2 concentration much lower than it would be if it equilibrated with the high concentration in the deep ocean. The biological pump's strength is determined by a number of factors, any or all of which may be affected by climate change, and it is expected to be a significant feedback on global warming. The size of this feedback is very uncertain however. In this study, two ocean ecosystem models of different complexities are used: the HadOCC model (a simple nutrient-phytoplankton-zooplankton-detritus model) and the Diat-HadOCC model (which additionally features two types of phytoplankton and the cycles of silicate and iron). Historical-future global warming scenario simulations are run with both models, and their climate change responses are compared in terms of the change in pattern and magnitude of CO_2 uptake from the atmosphere by the ocean, and in terms of the export flux of carbon. The inter-annual variabilities of these quantities in each model are compared to data and to each other. The effect of the additional processes in the Diat-HadOCC model (for example, those involving silicate and iron) is examined. Finally, a lower limit on our uncertainty in future ocean CO_2 uptake is deduced.

S2.1 Posters

Poster S2.1-4531

Input of 'new' nitrogen by *Trichodesmium* in the Arabian Sea

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Trichodesmium, an N_2-fixer, provides 'new' nitrogen to the ocean waters and plays an important role in regulating marine productivity of the oceans which have traditionally been recognised as nitrogen limited. A *Trichodesmium* bloom occurs every year in the north-eastern Arabian Sea during the spring intermonsoon when winds are predominantly from the Arabian Peninsula and other parts of the Middle East. The wind-blown dust supplies bioavailable Fe which is the key element controlling the distribution and abundance of N_2-fixers in ocean waters. The Arabian Sea is also known for intense denitrification, contributing ~60 TgN to the atmosphere annually. Therefore *Trichodesmium* plays a dominant role in nitrogen cycling, by supplying 'new' nitrogen in the Arabian Sea. Here we present an estimate of input of 'new' nitrogen by *Trichodesmium* during spring 2006 in the Arabian Sea. A cruise was undertaken in the northeastern Arabian Sea during April 2006 onboard FORV *Sagar Sampada*, (cruise #SS-244) where *Trichodesmium* presence was observed along the west coast of India. A bloom of *Trichodesmium* was ascertained at 20°31'N, 70°36'E. We detected excess nitrate (~35 mmol N m^{-2}) in the top 20 m surface water at the bloom station. Nitrification of NH_4 released from the remineralisation of *Trichodesmium* could be the source of this excess nitrate. Our preliminary results show that the 'new' nitrogen input into the Arabian Sea in the form of excess nitrate (*Trichodesmium*-derived) appears to be comparable in magnitude to the estimated loss of nitrogen through denitrification.

Poster S2.1-4568

Phytoplankton influence on atmospheric carbon dioxide under global climate change

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The carbon cycle dynamics in the atmosphere-ocean system are examined using a mathematical model consisting of ordinary differential equations. In the model, the oceanic CO_2 turnover is divided into 28 latitudinal belts with 5º width. The vertical ocean stratification includes the upper quasi-uniform layer (UQL), the thermocline layer, and the deep-sea layer (DL). The vertically uniform atmosphere is divided into the same zones as the ocean. The model variables are the molar concentration of non-organic carbon in each ocean block and carbon content as CO_2 in each atmospheric zone. The model considers the phytoplankton activity as both the rate of organic substance production in the UQL and the rate of organic substance decay in the UQL, thermocline, and DL. Our main results are the following. First, the maximal partial pressure of carbon dioxide dissolved in the UQL is registered at the equator whereas the minimal values of this variable are observed at the polar ocean. Another essential distinction of the polar ocean is that the largest differences between the results were obtained with and without taking into account the phytoplankton. Next, the tropical ocean is the CO_2 source for the atmosphere, whereas the carbon dioxide flows from the atmosphere into the ocean at high latitudes. Finally, the model outcomes for the adaptation time of the global climate system on the human economic activities show that if the ocean biota is taken into account then the adaptation time may be significantly decreased.

Poster S2.1-4639

The distribution of CO_2 surface partial pressure and air-sea CO_2 flux in El Mex Bay Alexandria, Egypt

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The partial pressure of CO_2 and air-sea fluxes were determined monthly during 2003-2004 in El-Mex Bay which is a shallow sheltered estuary west of Alexandria. Surface water partial pressure of CO_2 varied largely between 0.6 - 9464.2 µatm. Its distribution was controlled by complex combinations of different factors such as volume and water quality of discharged waste water from different land based sources, biological activity, physical mixing processes, and fresh water residence time. El-Mex Bay surface water was found in most cases to be oversaturated with respect to the atmosphere and saturation percentages ranged between 0.16-2487.85%. The calculated water-atmosphere CO_2 flux showed a clear dependence on salinity. Water type L (brackish water with S<10) showed an annual average CO_2 flux to the atmosphere 148.54 mmol $m^{-2}day^{-1}$, while the flux in water type M (mixed sea water with land drainage water type with salinity ranges 10<S<30) was 19.2 mmol m^{-2} day^{-1}. The more saline zone which is water type D (diluted sea water with salinity 30<S<35) had the lowest annual average flux to the atmosphere of 2.94 mmol m^{-2} day^{-1}. Different statistical studies, correlations and step wise regression analysis, were applied to evaluate the effect of phytoplankton standing stock, salinity, sea surface temperature, dissolved oxygen, and pH on sea water pCO_2 distribution. These studies reflect the great effect of the El-Umum Drain and other land based sources on the carbon cycle in the bay.

Poster S2.1-4648

A higher storage of anthropogenic carbon in the Indian Ocean?

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For the first time in March-April 2002 a full-depth high-resolution 32ºS trans-Indian Ocean section was sampled for CO_2 variables: pH, alkalinity (TA) and some total inorganic carbon (TIC) for internal consistency control. The main goal of this project was to measure the meridional overturning circulation in the southern boundary of the Indian Ocean. On the other hand, the 2002 CO_2 data will allow the first direct estimation of anthropogenic carbon (CANT) in the subtropical Indian Ocean and eventually enable us to close the CANT budget in this ocean. In this work we present, compare and discuss the CANT inventory along 32ºS following different techniques: three back-calculation techniques, Sabine *et al*. (1999), Lo Monaco *et al*. (2005) and the TrOCA method (Touratier *et al*, 2007). We present two modifications to the Sabine *et al*. (1999) method which improved the preformed TA and the preindustrial preformed TIC estimation. The Lo Monaco *et al*. method yields higher CANT specific inventories than the Sabine *et al*., and finally the TrOCA method. The inventories will be discussed by water masses, as deep waters with a southern origin could have some CANT signal as pointed out by tracers. The discrepancies arise from the assumptions in each method to estimate the biological contribution and the preindustrial preformed TIC or in the case of Sabine *et al*., the so called disequilibrium. We will be comparing the transient time distribution (TTD) method applied to CFC-11, 12 and CCl_4 and the results from a general circulation ocean model to estimate CANT. One of the main questions is whether the CANT inventory in the Indian Ocean has been previously underestimated and what are the strengths and drawbacks of each method.

Poster S2.1-4660

Trichodesmium sp. population structure along the North Atlantic subtropical gyre

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The role of *Trichodesmium* sp. in the cycle of nitrogen remains one of the main objectives on the climate change research agenda. Because of its potential to fix atmospheric N_2, these species play an important role in the patterns of marine primary productivity in the subtropical zones and thus, also in the global carbon cycle. In this work, building on data collected along a transect in the North Atlantic subtropical gyre during the CARPOS cruise (planktonic carbon fluxes in subtropical oligotrophic environments: a lagrangian approach, October-November 2006), we describe population level patterns of abundance and size structure for this important organism. Samples were obtained using 53 μm mesh triple WP2 nets towed vertically from 200 m to the surface. In the laboratory, *Trichodesmium* trichomes were counted and measured. We differentiate between free trichomes and those forming colonies (puffs and tufts). Strong spatial variation was detected; previous abundance patterns were confirmed and variation in size-structure was also detected. These changes were related to physical variation as well as to community wide patterns like chlorophyll *a* and zooplankton biomass. Finally, we assessed the implications of population heterogeneity on nitrogen fixation rates obtained from existing size-based, physiological relationships, in order to disentangle the contribution of such patterns to nutrient cycles.

Poster S2.1-4673

Dissolved oxygen and nutrient export by new Antarctic Bottom Water in the Ross Sea

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The Ross Sea is one of the major contributors to the Antarctic Bottom Water (AABW). Two shelf waters (SW) participate in the formation of AABW: the High Salinity Shelf Water (HSSW), characterised by salinities between 34.75 and 34.85, and the Deep Ice Shelf Water (DISW), defined by temperatures below the freezing point. Circumpolar Deep Water (CDW) is a relatively warm (θ>1°C), low oxygen and nutrient rich water mass, transported onto the shelf in a pulsing but persistent way at specific locations. Intense tidal vertical mixing of SW with the local CDW intrusion near the shelf break produces new AABW. Dissolved oxygen and nutrient data were collected across the shelf break off Cape Adare (Victoria Land) and off the Glomar Challenger Basin during the 2005-2006 austral summer by the CLIMA (Climatic Long-term Interaction for the Mass-balance in Antarctica) and PolarDOVE (Polar Deep Ocean VEntilation) projects within the XXI Italian Antarctic Expedition. The thermohaline measurements were performed using a SBE 9/11 plus CTD and water samples for chemical analyses were collected from 12 litre Niskin bottles. Dissolved oxygen was measured by the Winkler method, while nutrients were determined using an Autoanalyser Technicon II. Two separate 300 kHz RDI Workhorse ADCP heads were used as a lowered ADCP system to measure the dynamical field. In this work we estimated and compared the export of nutrients and oxygen ventilating the bottom layers at the two areas. A comparison with data collected in the 1998-2003 surveys is also presented to evaluate the variability of the properties of the new AABW.

Poster S2.1-4688

Marine system sensitivity to iron speciation and organic complexation

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A number of recent studies have elucidated some of the complicated reactions of marine iron biogeochemistry. The present study uses one dimensional models to investigate and parameterise a series of different model representations based on these recent studies and data sets. The one-dimensional models will investigate the role

of iron speciation and organic complexation with respect to biogeochemical modelling. The one dimensional models also allow us to investigate parameter sensitivity and are used as an initial step for inclusion into a three dimensional model. Here we show results that address questions concerning the role of different iron species and the role of iron complexing with differing organic compounds. The iron representation is embedded in a NEMO-PISCES, physical-biogeochemical coupled model. This allows the investigation of questions concerning iron chemistry, biological iron availability, and in particular marine system sensitivity due to changes in iron biogeochemistry.

Poster S2.1-4690

Nitrogen fixation and nitrogen cycles in a Plankton Functional Type model

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A number of approaches are being developed to address ocean nutrient dynamics in terms of chemistry, ocean physics and biology. One such approach is to use models based on the representation of Plankton Functional Types (PFT's) and the associated geochemistry, coupled to a physical ocean model. These PFT based models, in addition to enabling us to more adequately evaluate biogeochemical responses of marine systems, allow the investigation of multi-nutrient limitation (light, nitrogen (N), phosphorus (P), iron, silicon), the response of external N:P concentrations, and changes in community structure due to changing nutrient and physical conditions. The focus of this presentation is on results from present studies evaluating the response of N_2 fixation to the changing community structure, fluxes of N_2 fixation and denitrification (including aspects of anammox), subsequent implications for N:P concentrations, and responses in air-sea gas exchange. Of particular relevance is the response of the nitrogen cycle, community structure, primary productivity and export to changing physical conditions (such as warming, stratification and changes in circulation) that are used to evaluate marine system sensitivity and potential feedbacks on climate.

Poster S2.1-4693

Macrozooplankton in the global ocean biogeochemical model PlankTOM10

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Macrozooplankton play an important part in the removal of carbon from the surface layers of the ocean to the deep ocean. Their role in the export of large particulate organic carbon distinguishes them from other types of zooplankton. The explicit representation of macrozooplankton in a Plankton Functional Type (PFT) model is essential to capture the effect they have on the natural carbon cycle. Especially synthesised data sets for process rate measurements allow macrozooplankton to be represented in such a biogeochemical model - PlankTOM10. This model has been developed to include 10 PFTs. Process rate data are used to constrain macrozooplankton parameters. Preliminary runs show realistic values for primary production, export, air-sea CO_2 flux, and phytoplankton biomass. However, the group is overly abundant when compared to an independent validation data set of macrozooplankton biomass. Sensitivity analysis on well-populated data sets will allow these rates to be better constrained. The more poorly constrained parameters such as food preference will be investigated using the model. Little is known about the influence of macrozooplankton on the carbon cycle. PlankTOM10 will allow investigations into their interannual variability, links between macrozooplankton and fisheries and *vice versa*, and their vulnerability to climate change.

Poster S2.1-4700

Importance of organic matter in nutrient cycles and carbon dioxide sequestration in the oligotrophic waters of the Gulf of Aqaba: open water versus fish farms

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Three years of observations (2004-2007) on inorganic and organic nutrients in the open water column and recent observations (1 year) at a floating cages on a fish farm site are discussed. Three distinctive dissolved inorganic nutrient (DIN) pools are observed in the open water column. First is the shallow DIN pool (photic zone), where DIN concentrations rise during winter mixing, and drop to undetectable levels during summer stratification. Second is the deep water pool, where the DIN inventory is generally steady except for sharp variations as a direct response to water column stability alteration. Third is an intermediate water pool, where an extensive decrease in the DIN reservoir is observed during mixing, similar to deep water, however the recovery is relatively slow and can last throughout the whole period of stratification. Net decomposition of organic matter in the case of the open water column occurs in two major areas, on the sediment and in intermediate water (200-400 m). After the winter and spring productivity bloom, the Particulate Organic Matter (POM) either sinks to the bottom or suspends in the water column and recycles back to DIN through dissolved organic compounds (DON). The rate of POM remineralisation is dependant on the persistence of the DON produced in this process. While labile DON molecules are oxidized on a scale of days, semi-labile DON has a half life of months. Thus the more labile DON forms the faster DIN concentration boost after stratification; and the more semi labile DON forms the more carbon is sequestered and driven to the bottom. Fish farms are a major source of POM and DON. A detailed budget of organic and inorganic nutrients in the water column under fish cages (20 m-40 m) and in the bottom sediments has been generated; and DON persistence compared to that naturally produced in the open water column. This is to assess floating cage fish farms effects on carbon dioxide recycling in waters of the Gulf of Aqaba as a model of oceanic water.

Poster S2.1-4722

Mesozooplankton respiration in the North Atlantic subtropical gyre and its implications for the carbon cycle

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Nowadays one of the most challenging tasks in environmental sciences is the quantification of the ocean's role in the carbon cycle, because of its potential impact in the cycle and in climate change. The biological pump could be an important factor in the withdrawal capacity of the ocean, especially in regions where zooplankton cover hundreds of metres in their diel vertical migration (DVM). In this work, we build on data taken during the CARPOS cruise (Planktonic carbon fluxes in subtropical oligotrophic environments: a lagrangian approach, October-November 2006), and describe the mesozooplankton community and its diel vertical migration. Samples were obtained with LHPR (200 μm mesh size) hauls from 700 m, where the deep scattering layer was found, to surface. Finally we estimate the whole community respiration rate using the existing size-based physiological relationships for the different zooplankton groups, in order to assess the amount of carbon removed and transported by the mesozooplankton community.

Poster S2.1-4724

Estimation of the seasonal pattern of carbon dioxide in a coastal lagoon

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A carbonate system model was applied to investigate the seasonal pattern of carbon dioxide in the Lagoon of Venice, Italy, as a function of the temporal evolution of photosynthesis and respiration. Carbonate speciation was estimated on the basis of hourly pH data, collected by a real-time monitoring network, and of alkalinity

data. The model was applied to estimate the hourly evolution of the inorganic carbon species at different lagoon sites characterised by the presence of different communities of primary producers at different time windows in the period 2002-2005. The model outputs are consistent with the short-term evolution of the dissolved oxygen time series observed at the same sites. The statistical analysis of the simulated time series shows that the fluctuations of the carbon species can be explained by circadian cycles and are strongly influenced by climate forcing, e.g. temperature and solar radiation, and the community being considered. Carbon budgets based upon the model outputs obtained at different time windows highlighted that the lagoon may act as a carbon source for the atmosphere, depending upon the season and the site. Because our analysis can be easily implemented and applied to other case studies, we think that it could represent a straightforward way to extract valuable information about marine ecosystem functioning and to compute carbon budgets on the basis of data being collected in many estuaries as part of routine monitoring programmes.

Poster S2.1-4736

Evaluation of carbon anhydrase importance in carbon concentration in marine autotrophic organisms

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By using specific inhibitors of several pathways of carbon acquisition in marine cyanobacteria, the response evidenced that the anhydrase activity is not the preferred way to incorporate carbon. Three mechanisms were alternatively used by *Microcoleus cthonoplastes* colonies (cyanobacterial mats). One is based on the ATPase activity. The second is the most important in terms of carbon percentage incorporated into the cell. It is based on the specific ionic pumps, which presented at least two different kinetics. Other alternatives, less important, are suggested and argued as possible. On the other hand, the internal carbonic anhydrase (CA) activity is not enough to transform all the incoming bicarbonate in the cell and a pool of this cation is suggested to be included in some vacuole-like compartment. The activity of internal carbon anhydrase related to RuBisco capacity is discussed in order to understand the fate of CO_2 in the cell in case of uncoupling between the two systems, Internal CA and RuBisco. Several evolutive comments supported the frame in which future observation of carbon acquisition and assimilation of the aquatic plants must be focussed on.

Poster S2.1-4738

Spatial distribution of phytoplankton production and biomass in the Hudson Bay Complex during summers 2004 to 2006

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The spatial distribution of phytoplankton production and chlorophyll *a* (chl *a*) biomass in the Hudson Bay Complex is investigated for the months of August and September between 2004 and 2006. Sampling was conducted at 6 stations along a longitudinal transect in the northern Hudson Bay (ca. 60°N) and at 4 to 6 stations in the Foxe Basin and Hudson Strait (FBHS). Samples from the euphotic zone were size-fractionated to determine the contribution of small (0.7-5 µm) and large cells (>5 µm) to total phytoplankton production and biomass. During the three sampling years, total production and chl *a* biomass were significantly higher in the FBHS area than in the Bay (243 to 3444 *vs* 54 to 929 mg C m^{-2} d^{-1} and 29 to 87 *vs* 6 to 51 mg chl *a* m^{-2}, respectively). Primary production was generally dominated by small cells, except in the Hudson Strait in 2004. Chl *a* biomass, however, was dominated by large cells, except in the bay in 2005. Small cells generally account for a higher proportion of the production than their contribution to the chl *a* biomass. These results suggest that small phytoplankton cells were grazed intensively by microzooplankton whereas large cells accumulated within the euphotic zone. During this study, total production was inversely correlated with density stratification of the water column. This suggests that vertical mixing controls the phytoplankton production distribution, through its effect on nutrient supply. Future enhancement of the upper water column stratification by warming and freshwater input from precipitation may affect the phytoplankton production of the Hudson Bay complex.

Poster S2.1-4744

Effects of two different iron sources on the iron cycle in the subarctic North Pacific

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Dissolved iron concentrations in the subarctic North Pacific (SNP) are higher in the western region (WSNP) than in the eastern region (ESNP) at intermediate depths. The higher concentrations in the WSNP are considered to be due to 1) higher aeolian iron inputs in WSNP and/or 2) horizontal transport of iron from the continental shelf of the Sea of Okhotsk. By conducting numerical experiments, we examine which process more reasonably accounts for the iron distribution in the SNP. We used a Parallel Ocean Program combined with the Ocean Carbon Model Intercomparison Project biotic carbon model which was modified by addition of a prognostic equation for productivity and inclusion of iron as a co-limiting nutrient. Three cases of experiments (CTL, DST and OKH) were conducted changing the way of iron input to the WSNP. In CTL, the model was forced with aeolian iron input. In DST, the input fluxes in the WSNP were increased by factor of 10. In OKH, iron flux was considered to intermediate water of WSNP from the area of Kuril Islands. The additional flux in OKH was similar to the one in DST. The higher iron concentrations in intermediate water of WSNP are simulated in DST and OKH. In DST, however, the concentrations in surface water largely exceed those shown in observational data. The results suggest that the iron transport from the continental shelf of the Sea of Okhotsk is playing an important role in the iron cycle in SNP.

Poster S2.1-4749

Invasion of anthropogenic CO_2 recorded in stable isotopes of planktonic foraminifera from the northern Gulf of Aqaba, Red Sea

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The stable carbon isotopic composition of the planktonic foraminifera *Globigerinoides sacculifer* and *Globigerinoides ruber* (white) and sedimentary organic matter from the northern Gulf of Aqaba have been investigated to estimate changes in $\delta^{13}C_{DIC}$ in surface waters during the last 1000 years. The high sedimentation rates at the core sites (about 54 cm/ky) provide high temporal resolution (~10 years). Recent sediments at the top of the cores reflect conditions earlier than 1950. The $\delta^{13}C$ records of the planktonic foraminifera from three multicores display similar trends, showing a uniform and consistent pattern before the 1750s, and a gradual decrease of approximately 0.63‰ over the last two centuries. This decrease seems to track the decrease of $\delta^{13}C_{DIC}$ in surface waters, which is mainly caused by the increase of anthropogenic input of ^{13}C-depleted CO_2 into the atmosphere. Similarly, a trend toward lighter values of the carbon isotopic composition of sedimentary organic matter ($\delta^{13}C_{org}$) during the last 200 years supports the interpretation obtained from the planktonic foraminiferal $\delta^{13}C$. Furthermore, direct measurements of seawater show that $\delta^{13}C$ of the dissolved inorganic carbon (DIC) in the northern Gulf of Aqaba has decreased by about 0.44‰ during the period 1979-2000. The average annual decrease is 0.021‰, which is similar to that observed globally. The $\delta^{13}C$ values of planktonic foraminifera combined with organic matter $\delta^{13}C$ from marine sediments are good indicators for reconstructing past changes in atmospheric CO_2 concentrations from the northern Gulf of Aqaba.

Poster S2.1-4764

Mechanisms underlying coastal waters CO_2 emissions

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In the CO_2 context, assessment of the role played by coastal waters adjacent to the Tagus and Sado estuaries (Portugal) was done based on data from May 2000, 2002 and 2003, periods representative of spring conditions. The estimated CO_2 fluxes reached, respectively, mean values of 6, 14 and 29 mmol CO_2 m^{-2} d^{-1}. In May 2000 the absence of upwelling and the moderate river flow (190 m^3 s^{-1}) favoured the generation of a pronounced Tagus river plume enriched in nutrients, which induced significant phytoplankton growth (chlorophyll *a* up to 9.5 mg m^{-3}), and the consequent uptake of CO_2. Therefore, a decrease in surface water CO_2 partial pressure (pCO_2) lowered the CO_2 emissions. In May 2002, a moderate upwelling event induced an increase of pCO_2, and the development of phytoplanktonic *Coccolithus braarudii* species constituted an additional source of CO_2 to the water. Actually, the presence of such a phytoplanktonic bloom led to production of about 5 tons of calcite, which resulted in the release of 7.4 mmol CO_2 m^{-2} d^{-1}. During the more intense upwelling event, in May 2003, CO_2 emissions exhibited higher values, most likely, attributed to the upwelled waters enriched in dissolved inorganic carbon, and to the occurrence of a considerable river discharge (280 m^3 s^{-1}). Despite the different conditions and processes responsible for the CO_2 emissions one may conclude that the respective coastal area functions as a source of CO_2 to the atmosphere, contributing to the global warming process.

Poster S2.1-4781

The Australian SAZ-SENSE study of the sensitivity of the Sub-Antarctic Zone to climate change: an introduction

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Sub-Antarctic Zone (SAZ) waters east of Tasmania (ET) exhibit higher levels of satellite chl *a* in than west of Tasmania (WT). The ET waters are affected by the input of sub-tropical waters from eddies of the East Australia Current, with some westward flow occurring south of Tasmania in summer. This flow forms part of the southern hemisphere super-gyre, which connects the Pacific and Indian oceans. That circulation contributes much of the variability in the total east-west transport between Australia and Antarctica, and is likely to be subject to climate changes such as southward movement and/or intensification of the westerly winds. The Tasman Sea to the east of Tasmania has experienced rapid warming over the past few decades. In summer 2007, the ACE CRC undertook an ET *vs*. WT comparison of biogeochemistry and microbial ecosystem function, with the overall objective to assess what changes might be expected in the circumpolar SAZ if it evolves from the cold low biomass WT to the warmer higher biomass ET state. Preliminary results suggest ET waters had a greater fraction of production from >20 µm phytoplankton, suggesting a more efficient transfer to higher trophic levels. Higher ET iron levels contributed to the enhanced production, but the pathways of iron delivery are not yet clear, nor are their possible responses to climate change. These results and previous work in the Southern Ocean suggest that ecosystem change may be driven by changes in iron supply from the ocean margins as much as it is from physico-chemical changes within the ocean.

Poster S2.1-4787

Uncertainties in the global carbon budget: the contribution of echinoderms to the shelf/neritic export at present

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The available estimates of carbon production, export, and accumulation in the neritic, shelf, and deep-sea areas are a limited representation of the global carbon budget. It has been assumed that the pelagic contribution of calcium carbonate is dominated by planktonic organisms yet the contribution of large calcium carbonate producing animals

has been overlooked. Among these animals, echinoderms colonise environments ranging from the continental shelf down to the deep-sea. The reported values for neritic carbon export carry uncertainties of up to 100% in shelf and neritic environments. At present, the content of inorganic carbon carried by these organisms and that in the sediment remains an open question. We present the contribution of inorganic and organic carbon in a subset of ecologically relevant echinoderm species. We discuss the results in a biogeochemical context both in present-day and in future climate scenarios.

Poster S2.1-4811

Long-term nutrient changes in the southern Benguela: intensified upwelling due to global climate change?

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A predicted result of climate change on upwelling systems, is that an increasing thermal gradient between land and sea will result in greater equatorward winds driving greater upwelling intensity. Notable ecosystem changes have been documented in eastern boundary upwelling regions in recent decades, including the southern Benguela, where dominance shifts in pelagic fish and striking changes in zooplankton, demersal fish, linefish, squid, rock lobster and seabird abundances have been shown. Nutrient availability has undeniable bottom-up influences on upwelling systems, ultimately determining food web pathways by mediating phytoplankton competition and succession. We have compiled a long-term study of nutrient variability, including hydrographic data, for St Helena Bay in the southern Benguela upwelling region. Using subsurface measurements to avoid an uptake signal from phytoplankton and general linear models (GLMs) to remove seasonal effects, pronounced interannual variation was observed. Nitrate and phosphate concentrations both increased significantly between 1983 and 2004, by ~40% and ~50% respectively. Silicate shows no similar trend over this period. Oxygen concentrations showed a significant (~30%) downward trend between 1960 and 2004. Increased primary productivity is the most likely cause of elevated organic matter regeneration and oxygen utilisation. Neither complementary wind or chlorophyll data sets were obtainable for purpose of comparison with results. The increase in nutrients and decrease in oxygen have important implications for biogeochemical cycles, ecosystems and commercial fisheries. Due to its retention of upwelled water and organic material, St Helena Bay could provide an effective early warning system to detect and study changes in upwelling intensity and their consequences.

Poster S2.1-4844

Net metabolic balance in the eastern and central North Atlantic subtropical gyre in October-November 2006

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The contribution of the marine biota to oceanic carbon budgets remains a debated issue, partly because of the uncertainties in the net balance between the processes of production, export and oxidation of organic matter. These uncertainties make it difficult to elucidate the role of the ocean on climate change, and to anticipate the effect of climate change on the marine biota. While the magnitude and variation of primary production (PP) in the ocean is relatively well known, the reason for this lack of knowledge is the paucity of measurements of respiration (R), which impede constraining net metabolic balance estimations. Such paucity is particularly important in the oligotrophic areas of the open ocean, representing 80% of the world ocean surface. We present here concurrent measurements of PP, R and net community metabolism in the photic layer made during a cruise that traversed from the eastern side to the centre of the North Atlantic subtropical gyre in October-November 2006. A zonal transect of 7 stations was initially sampled from 14ºW-34ºN to 26ºW-36ºN, with the aim of verifying the existence of a gradient in the net metabolism of the plankton communities from the periphery to the central region of the gyre. This sampling was followed by two lagrangian experiments, in the central, and NE marginal areas of the North Atlantic subtropical gyre. The results show the disparities on the net metabolic balance between different oligotrophic areas of the open ocean.

Poster S2.1-4847

The dynamics of dimethylsulphide and dimethylsulphoniopropionate in a global prognostic model

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Dimethylsulphide (DMS) is a climate relevant trace gas involved in cloud formation. DMS emission is also the most important pathway by which sulphur is recycled from the ocean to the land. DMS is produced from its marine precursor dimethylsulphoniopropionate (DMSP) in interactions within marine ecosystems. Here, we study the dynamics of DMS and DMSP using the global ocean biogeochemistry model PlankTOM5, which includes 3 phytoplankton and 2 zooplankton functional types. A fully prognostic DMS module describes intracellular particulate DMSP production, concentrations of dissolved DMSP and DMS production and consumption. The model produces annual mean DMS fields that compare reasonably well with observations, and predicts emissions of 23 TgS/yr for the present period. The interannual variability of DMS is low in temperate and tropical region and increases towards the high latitudes, where highest values for DMS are found. While the absolute values for the interannual variabilities of DMS and chlorophyll *a* are predicted to be similar by the model, their spatial distributions are different. The model can reproduce the summer paradox in parts of the low latitudes, but underpredicts DMS at the Bermuda Atlantic Time series station (BATS). We use the model to study the impact of ecosystem composition on DMS concentration patterns and fluxes. We find that while plankton distribution matters, bacterial parameters are also important for DMS concentration patterns. The introduction of strong light dependencies in the model improves the results for the summer paradox, but decreases the importance of ecosystem composition.

Poster S2.1-4872

Testing potential impacts of changes in precipitation temporal patterns on biogeochemical properties of a coastal marine ecosystem

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A downscaling approach has been used to assess potential effects of variations in nutrient loads induced by climate changes on the water quality of the Lagoon of Venice (Italy). The analysis is based on a hierarchy of dynamic and statistical models for linking climatic changes to effects on biogeochemical processes. The outputs of the regional climate model for present day scenario (1961-1990) are compared with local climatological observations as well as reanalyses of observations. Results showed a good agreement in terms of both monthly area averages and seasonal spatial distribution of precipitation data and mean frequency of rainy events is also satisfactorily reproduced. Moreover, outputs of regional climate model simulations for present day and future (A2 and B2 IPCC emission scenarios) conditions are used to force two statistical models that provide forcing and boundary conditions for a 3D coupled transport biogeochemical model of the lagoon. Under both A2 and B2 IPCC scenarios we observe a strengthening of seasonal precipitation patterns (drier summer and rainier winter), which affect timing of nutrient inputs to the lagoon. In particular, results in terms of future spatio-temporal dynamics of biogeochemical properties evidenced that nutrient loads are, with respect to the reference scenario, higher in wintertime and lower in summertime. In winter nutrients are not used by phytoplankton, whose growth is limited by temperature, and are mainly exported from the system. Conversely, reduced nutrient inputs in summer strengthen their limiting effect for primary production. This causes a reduction of the planktonic productivity of the ecosystem.

Poster S2.1-4875

Interannual to decadal variability of the carbon cycle in the Pacific simulated in a 3-dimensional model

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To improve our understanding of physical and biological impact on the carbon cycle in the Pacific Ocean, interannual to decadal variability of the carbon cycle is diagnosed with a 3-dimensional physical-biogeochemical model. The simulations have been performed with two boundary conditions for atmospheric pCO_2: one using the historical increase in atmospheric pCO_2 from year 1837 to 2002 (historical run), another with a constant pre-anthropogenic concentration of 278 ppmv (control run) in order to quantify the anthropogenic carbon cycle. The modelled surface ocean at the Hawaiian Ocean Time series (HOT) shows a long term 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 interannual to decadal scales. In contrast to the phase relation in the central Pacific, 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*.

Poster S2.1-4880

Estimation of ocean carbon uptake with an Earth system model under CO_2 stabilisation scenario projection

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For mitigation of global warming, the CO_2 concentration must be stabilised at some level, and the amount of the permissible emission of CO_2 for the stabilisation should be estimated. The CO_2 stabilisation means that anthropogenic CO_2 emission is balanced by nature uptake. Therefore, using an integrated Earth system model, we calculated the carbon fluxes in and out of the natural terrestrial and oceanic carbon cycle under prescribed CO_2 stabilisation concentration scenarios from year 1850 to 2300. What we found is that the land carbon cycle would relatively quickly adjust to equilibrium within the 21st century under stabilising CO_2 level. Furthermore, the global warming could change the terrestrial environment from a carbon sink to source by enhanced respiration. Thus the land would not be a reliable CO_2 sink in the long term. On the other hand, the ocean would remain as sink beyond the year 2300 because the ocean needs a long time to equilibrate. CO_2 uptake would gradually decrease during the adjustment to the stabilised CO_2 concentration. Although the feedback by climate change is relatively small compared with the land, the warmer sea temperature would reduce carbon uptake by the ocean. Under the 550 ppm stabilisation scenario, the ocean carbon uptake accumulated from the year 1850 to 2300 amounts to 600 PgC while the uptake reduction by climate change feedback is estimated as 108 PgC.

Poster S2.1-4893

A coupled approach data/model to infer the decadal changes of the surface carbon dioxide and related parameters in the Mediterranean Sea

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A coupled approach based on available data sets of temperature, salinity, oxygen, nutrients and chlorophyll (from Medatlas, 2002), and a model previously developed (Louanchi *et al.*, 1996) and modified for the present work, allows a reconstruction of dissolved inorganic carbon (DIC) and total alkalinity (TA) mixed-layer fields in the Mediterranean Sea. The modelled carbonate system parameters are validated using available data sets for this region. The errors do not exceed 10% of the modelled fields. From pre-anthropogenic conditions to the 1990s, the Mediterranean Sea has been a sink for atmospheric CO_2, the amplitude of this sink being the weakest in the 1980s. Decadal variations of the carbonate system parameters are analysed considering the changes in physical and biological conditions over the decades. According to the model results, the atmospheric CO_2 increase since the pre-anthropogenic period is responsible for a DIC increase of about 70 µmol/kg, and a pH decrease of about 0.08 in surface waters. As a consequence, the carbonate saturation state has decreased by about 0.5 and 0.7 in aragonite and calcite, respectively. Future changes in pH and carbonate saturation are investigated according to several IPCC scenarios.

Poster S2.1-4939

Evaluation of DMS concentrations under global warming conditions by means of a mechanistic global ocean biogeochemistry model (PlankTOM5)

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Dimethylsulfide (DMS) emissions from the oceans and subsequent conversion to sulphate aerosols in the atmosphere is believed to affect the optical properties of low-height clouds through its influence on the number and density of cloud condensation nuclei (CCN). Higher number of CCN (e.g. from DMS oxidation to sulfates) imply more optically dense (whiter) and more persistent clouds, thus increasing albedo and therefore cooling the Earth's surface. This natural mechanism of increasing the Earth's albedo and reducing global temperature through the oceanic production and emission of DMS has been suggested to partially compensate human-driven global warming. In order to test the hypothesis that under global warming conditions oceanic DMS production will be enhanced (negative feedback) we have run a state-of-the-art global ocean biogeochemistry model (PlankTOM5) with atmospheric forcing(s) corresponding to a global warming IPCC scenario (SRES98-A2). PlankTOM5 comprises of 29 biogeochemical tracers and includes 3 phytoplankton (silicifiers, calcifiers and mixed phytoplankton) and 2 zooplankton (micro- and mesozooplankton) functional types as well as an explicit characterisation of DMS dynamics, a prognostic formulation for DMS and its oceanic precursors. PlankTOM5 is coupled to the General Circulation Model (NEMO2). Although still very preliminary, our results point towards a non-significant and spatially inhomogeneous change of global surface DMS concentrations under global warming conditions, that is probably not enough to offset the anthropogenically-driven temperature increase.

S2.2 Ocean acidification and coral reef bleaching

21 May, 08:30 (S2.2-4953) Plenary

Coral reef ecosystems as casualties of rapid climate change

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Coral reefs occupy less than 1% of the world's ocean yet are exquisite storehouses of biodiversity. They also underpin billion-dollar industries and are critically important to over 100 million people that forage on them daily for food. Rapid changes to the temperature and carbonate ion concentration of tropical/sub-tropical oceans in response to anthropogenic greenhouse gas emissions have already produced major changes to coral reef ecosystems. These changes have affected reef-building corals by slowing their growth and eliminating them in large numbers during mass bleaching and mortality events. These impacts have had secondary effects on the estimated million species that live on and around reef-building corals, and have begun to affect the resources and ecological functions available to associated human societies. Most of the evidence suggests that this damage is likely to escalate under further changes to atmospheric CO_2, and even under the most optimistic projections where atmospheric carbon dioxide stabilises at 450 ppm, carbonate coral reef ecosystems appear unviable. While corals may persist as minor members of tropical reef communities, tropical near-shore ecosystems will be vastly different to what they are today. The question of how we respond to this crisis in tropical/sub-tropical ecosystems (less than 30 years away at current rates of increase of atmospheric CO_2) needs to drive the next set of research and management questions. Only by understanding the associated impacts on tropical fisheries, tourism and coastal protection, will we have a chance as a society to find ways to adapt to these major changes.

21 May, 10:35 (S2.2-4800) Invited

Ecosystem effects of ocean acidification in times of ocean warming: a physiologist's view

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Ocean warming and acidification occur at global scales and, in the case of temperature, have already caused shifts in marine ecosystem composition and functioning whereas, in the case of CO_2, effects may still be so small that evidence for changes in the field is lacking. However, depending on ecosystem characteristics, future scenarios indicate a threatening of marine life forms through the specific or synergistic effects of both factors. This paper builds on the view that development of a cause and effect understanding is required beyond empirical observations, for a secure projection of ecosystem effects and for the development of quantitative scenarios. Identification of the mechanisms through which temperature and CO_2 related ocean physicochemistry affect organism fitness, survival and success, is crucial in this research strategy. From present evidence I suggest that the operation of unifying physiological principles, not only of temperature but also CO_2 effects, across animal groups and phyla. Thermal windows of optimised performance emerge as a basic character defining species success and survival, including their capacity to interact with other species. Through effects on performance at levels of reproduction, behaviour and growth, ocean acidification acts especially on lower marine invertebrates characterised by a low capacity to compensate for disturbances in extracellular ion and acid-base status. The key consequence is a narrowing of thermal tolerance windows, of the scope for performance at ecosystem level and of associated ranges of geographical distribution.

21 May, 11:00 (S2.2-4860) Invited

Acidification of the Arctic Ocean

James C. **Orr**[1], Sara Jutterström[2], Laurent Bopp[3], Leif G. Anderson[2], Victoria J. Fabry[4], Thomas Frölicher[5], Peter Jones[6], Fortunat Joos[5], Ernst Maier-Reimer[7], Joachim Segschneider[7], Marco Steinacher[5] and Didier Swingedouw[8]

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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 modelling 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 a lack of gridded baseline data in the region. To assess $CaCO_3$ saturation in the Arctic Ocean, we used recent data along trans-Arctic sections as a baseline, to which we added 21st century perturbations in DIC, alkalinity, temperature, salinity, and nutrients from three coupled carbon-climate models forced under the SRES A2 scenario. In our projections by the year 2020, some Arctic Ocean surface waters become undersaturated with respect to aragonite and all surface waters succumb to these conditions by 2050. By 2100, all 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 which serve as a major food source for walruses, grey whales, and spectacled eiders. Our findings indicate that 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, not in the Southern Ocean as suggested previously.

21 May, 11:25 (S2.2-4786)

Detecting climate change impacts in coral reef calcification

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Ocean acidification can cause a significant reduction in coral reef calcification. Extrapolation of experimental results suggests that rates may fall below threshold levels required to offset erosive processes. Detecting climate change effects on coral reef calcification will require significant improvement of current measurement techniques to broaden the spatial scale of measurements so that whole reef systems are represented; not just lagoons or reef flats. Such new measurements must yield average rates over weeks to months rather than currently reported hourly rates and must be applied widely and long term. The key to detecting net climate change effects will be evidence that observed changes are globally distributed and varying temporarily in concert with observed climate parameters. To this end, four innovative methods are being tested at La Parguera, Puerto Rico. The first is based on locating current meters, pCO_2, pH and O_2 sensors along the predominant axis of flow of a reef and measuring change in total alkalinity (TA) allowing Eulerian measurement of calcification from the change in water properties as water flows past sensors located 1.5 km apart. The second involves measuring spatial distribution of TA drawdown relative to offshore source water and using hydrodynamic circulation and model-derived water residence time to estimate effective drawdown across the whole reef system. The third, a profile flux technique, entails measuring vertical eddy diffusivity from highly resolved water velocity profiles and mean concentration gradients of oxygen and TA measured with sensors and/or discrete measurements. The fourth involves using a geochemical tracer ^{7}Be to estimate water residence time.

21 May, 11:40 (S2.2-4961)

Potential effects of ocean acidification on deep-sea coral ecosystems

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Ocean pH and the calcium carbonate saturation state of the world's oceans are decreasing at an alarming rate due to an influx of anthropogenic CO_2 to the atmosphere. Experimental evidence has shown declining carbonate saturation inhibits the ability of marine organisms to build calcium carbonate skeletons, shells, and tests. We put forward a hypothesis suggesting the global distribution of deep-sea scleractinian corals could be limited in part by the depth of the aragonite saturation horizon (ASH). Aragonite is the metastable form of calcium carbonate used by scleractinian corals to build their skeletons and the ASH is the limit between saturated and undersaturated water. The hypothesis is tested by reviewing the distribution of deep-sea, bioherm-forming scleractinian corals with respect to the depth of the ASH. Results indicate that > 95% of coral locations occurred in saturated waters during pre-industrial times. Projections indicate that approximately 70% of these locations will be in undersaturated waters by 2100. If this hypothesis is true, then decreasing carbonate saturation state will probably impact scleractinian cold water corals earlier than shallow water reef builders. Decreases in calcification rates could occur well before corals experience undersaturated conditions as aragonite saturation state decreases progressively over time. Indirect negative effects on fishes, including commercially important species and other deep-sea organisms which rely on deep-sea coral ecosystems for protection and nutritional requirements are possible. Manipulative CO_2 experiments to determine cold water coral sensitivity and calcification response to decreasing carbonate saturation states should be a top priority for future research.

21 May, 11:55 (S2.2-4834)

More effective time grid reconstruction in the calibration of geochemical proxies from coral skeletons

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The extraction of paleoclimate signals from the aragonitic skeletons of scleractinian shallow-water corals and to a lesser extent deep-water corals using stable isotopes, trace and minor element compositions represents a significant scientific advance, although coral physiology (i.e. "vital effects") plays an important role in modulating the environmental signals preserved within the growing carbonate skeleton. Typically, a geochemical proxy analysed along the coral growth axis is empirically calibrated against an environmental parameter (e.g. sea surface temperature) through the anchor-point method, considering common features in the two time series as fixed points and assuming a constant growth-rate between these points. This assumption is often at best a poor approximation since the growth rate can vary on a sub-annual (e.g. monthly) time scale. Here, we present an alternative method to obtain a growth-rate modulated time grid following a more rigorous approach, based on the spectral analysis. This method can reconstruct sub-annual variations in growth-rate and accretion stops, with the final aim being to derive better calibration functions to be used for paleoclimate reconstructions.

21 May, 12:10 (S2.2-4794)

Near-future levels of ocean acidification impair fertilisation and development in a sea urchin

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CO_2-induced increases in the solubility of biogenic calcareous structures threaten 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 of the gametes and larvae of the sea urchin *Heliocidaris erythrogramma* to CO_2-induced acidification by -0.4 pH units (the upper limits of predictions for the year 2100, IPCC AR4 2007). Unlike most urchin species, larvae of *H. erythrogramma* lack a calcareous skeleton. We found statistically significant reductions in sperm swimming performance, fertilisation success, and post-metamorphic juvenile morphology in acidified treatments. We discuss the implications of these findings for fertilisation success and development of the larvae of both non-calcified and calcified taxa, and for the population viability of marine invertebrates.

21 May, 12:25 (S2.2-4570)

Decadal changes in the carbonate system of the North Pacific Ocean

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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 and coastal cruises in the North Pacific show direct evidence of 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 over large sections of the northeastern Pacific. These dramatic changes can be attributed, in most part, to anthropogenic CO_2 uptake by the ocean over the past decade. 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 North Pacific. Such shoaling is due to the effects of anthropogenic CO_2, ventilation and biological respiration processes in the surface and intermediate waters.

21 May, 12:40 (S2.2-4671)

Marine calcification in a high CO_2 world: changes in coccolithophore calcification since pre-industrial times

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Ocean acidification occurs as a direct consequence of increasing carbon dioxide (CO_2) partial pressure caused by the absorption of CO_2 by the ocean, which lowers surface ocean carbonate, reduces surface water pH and the degree of supersaturation of calcium carbonate ($CaCO_3$). It has been hypothesized that marine calcification is directly affected by the increasing CO_2 partial pressure that drives a decrease in pH and the saturation state of $CaCO_3$. However, some of these studies have, at least in part, manipulated the carbonate system by the addition of acid or base to the growth medium. One problem with this approach is that it alters the total alkalinity, which is not the case when fossil fuel-derived CO_2 dissolves in the ocean. Here we show that calcification and

photosynthetic carbon fixation in the coccolithophore species *Emiliania huxleyi* are significantly increased by high CO_2 and these calcification trends are consistent with those seen in the geological record. Our findings have significant implications for biogeochemical modelling of future oceans, and highlight acclimation and evolutionary adaptation of a major calcareous group to past and future ocean acidification.

21 May, 12:55 (S2.2-4718)

Effects of CO_2 induced acidification on diatom food quality and copepod reproduction

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Increasing dissolved CO_2 concentrations and the associated decrease in ocean pH affect phytoplankton cell physiology, biochemical and elemental composition and community structure. Since the physiological condition and, particularly, the biochemical composition of phytoplankton can control zooplankton growth and reproduction, trophic transfer efficiency and secondary production might change in correspondence with the alteration of CO_2 and/or pH. Experiments were conducted to test whether the reproductive success of copepods is related to the CO_2 concentration and the pH of the growth medium of the diatom *Thalassiosira weissflogii*. The alga was grown in turbidostats under either ambient air or enhanced CO_2 concentrations of 500 or 1000 ppm. In 6 day laboratory experiments, food uptake, egg production, hatching success and faeces production of the copepod *Temora longicornis* were determined, accompanied by measurements of carbon, nitrogen and lipid contents of the food. While no differences were observed in feeding, faeces production and egg hatching success, egg production was lower in copepods fed with diatoms grown at 500 and 1000 ppm than those fed with food grown at ambient conditions. Accordingly, the gross efficiency of egg production was reduced by ~10% at 500 and 1000 ppm. Because no direct effect of the increased CO_2 and reduced pH on copepods was observed when the diatoms grown at ambient conditions were fed to copepods under 1000 ppm, the reduced efficiency in the utilisation of the ingested food for egg production is attributed to indirect changes in food quality.

21 May, 13:10 (S2.2-4779)

Responses of phytoplankton assemblages and organic carbon dynamics to CO_2 increase

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To investigate the responses of phytoplankton assemblages and organic carbon dynamics to CO_2 increase, a CO_2 manipulation experiment was conducted in the Sea of Okhotsk in summer 2006. Surface water with a natural phytoplankton assemblage was incubated in 8 L bottles with bubbling air containing different concentrations of CO_2 (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 of the sampling site was depleted in nutrients, so phytoplankton abundance in the bottles remained at a low biomass of 0.1-0.4 µg chlorophyll *a* L^{-1} during the course of the experiment. If the values at the end of the experiment were compared in each treatment, the fucoxanthin/chlorophyll *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. This result may have been due to the higher efficiency of C-fixation by Rubisco in diatoms than other algal groups. Since no cells of coccolithophores were detected using a scanning electron microscope, we could not determine the response of coccolithophores to the CO_2 gradient. The amount of DOC accumulation decreased with increasing CO_2, while no significant difference was observed for changes in POC between treatments. The continuing increase in atmospheric CO_2 is concluded to potentially affect the phytoplankton assemblage composition and organic carbon flow in the nutrient-depleted surface water in the subarctic regions.

21 May, 13:25 (S2.2-4547)

The effect of ocean acidification and temperature on the fertilisation and development of the Sydney rock oyster, *Saccostrea glomerata* (Gould, 1850)

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There has been global concern regarding the elevation in atmospheric CO_2 and the subsequent impact of this on natural ecosystems. It is expected that by 2065, the atmospheric CO_2 may be double that of preindustrial levels. Such an increase in greenhouse gases may cause a substantial rise in sea temperature, increase the partial pressure of CO_2 (pCO_2) in the surface ocean and subsequently have impacts on the fertilisation, development, survival and growth of marine organisms. While studies have investigated the effect of elevated pCO_2 on the calcification of marine organisms, less is known about the effect of elevated pCO_2 on the early stages of development. Furthermore, there has been limited investigation on the synergistic effects of elevated pCO_2 and temperature. Here, we examine the synergistic effects 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). The results of this study showed that pCO_2 and temperature interacted significantly to affect the fertilisation and embryonic development of *S. glomerata*. There was reduced fertilisation, embryonic growth and development and increased abnormality at elevated pCO_2 and temperatures that were above and below 26°C. This affect was most noticeable when embryos were exposed to the pCO_2 and temperature treatments for both the fertilisation and embryonic stages of their development.

21 May, 13:40 (S2.2-4698)

Increased CO_2 levels in the ecosphere may modify the structure of marine plankton

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Stoikiometry of marine plankton vary only within limited ranges. Recently it has been showed that the average C:N ratio of phytoplankton may increase in a high CO_2 world. Increased availability of organic carbon may in principle stimulate heterotrophy, but heterotrophic prokaryotes are not only dependent on dissolved organic carbon (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 and nutrients in pelagic plankton, using both laboratory culture experiments and field work including mesocosm perturbation methodology. Although the concentration of labile marine DOC greatly exceeds the concentration of microbial biomass, bacteria do respond to increases in available organic carbon. Some of our results suggest that tipping points exists in the competition between heterotrophs and autotrophs, and that increased levels of CO_2 in the biosphere may induce the passage of such tipping points.

S2.2 Posters

Poster S2.2-4541

Implications of the potential removal of a keystone sub-Antarctic species due to ocean acidification

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It has been predicted that by 2050 the acidity of the high latitude oceans will be so high that many shell-forming organisms, including euthecosome pteropods, will not be able to survive. Results of the present study suggest that the euthecosome pteropod, *Limacina retroversa*, can be considered a keystone species in the sub-Antarctic Polar Frontal Zone. The implications of the removal a keystone species are likely to be far reaching, but as yet, cannot be predicted due to a paucity of relevant data. Our findings suggest that *L. retroversa* generally exhibits relatively low abundances, contributing approximately 5.2% to total mesozooplankton numbers. Estimates of *L. retroversa* grazing rates, however, show that the pteropod plays a considerable role in the food web of the Polar Frontal Zone. *L. retroversa* exhibited ingestion rates of approximately 4137.6 ng (pigm) ind^{-1} day^{-1}, far exceeding those of any of the dominant copepods, as well as many of the larger grazers, including euphausiids. *L. retroversa* were responsible for removing up to 89.1% of the available phytoplankton biomass during the study, contributing to up to 84.4% of the total mesozooplankton grazing impact. This finding suggests that the species has the potential to reduce phytoplankton standing stocks and thus significantly contribute to the functioning of the Polar Frontal Zone ecosystem. It is clear that if *L. retroversa* disappears from the sub-Antarctic waters, the way in which the community functions at present will be greatly altered.

Poster S2.2-4593

Ocean-atmosphere heat flux estimates over the Great Barrier Reef and Coral Sea: implications for recent mass coral bleaching events

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A regional scale estimate of the surface heat budget of the Great Barrier Reef (GBR) and Coral Sea (10ºS-26ºS, 142ºE-155ºE) has been developed for the period 1995-2005 in the hope of understanding the trends of sea surface temperatures (SST) and the surface heat balance. This study describes the methodology to acquire input parameters from satellite observations, the resultant individual components of the surface heat budget and their validation with existing data sets and surface measurements. These improved estimates allow a higher confidence in studies which examine recent SST trends and observed mass coral bleaching for the region. It is proposed that the greatest uptake of heat occurs over the spring/summer period in the central and southern regions of the Great Barrier Reef, agreeing well with areas where anomalously high sea surface temperatures are observed and where the most significant coral bleaching has occurred, and not in the most northern more tropical region as one may expect. The surface heat budget climatology was used to examine the mass bleaching episode that occurred in 2002. Results show that areas of maximum and minimum bleaching are better discriminated by the anomaly from mean seasonal values in $Q_{NET\neg}$, with an accuracy of 86 and 79 percent, respectively, than by absolute $Q_{NET\neg}$, absolute SST or SST anomaly. Influences of the net surface heat flux and oceanic processes have also been investigated with respect to the observed changes in SST and mixed layer depth temperatures, uncovering some interesting features of the GBR and Coral Sea such as seasonal upwelling and "geostrophic pumping".

Poster S2.2-4615

CO_2-driven acidification radically affects larval survival and development in marine organisms

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The world's ocean are slowly becoming more acidic. In the last 150 years, the pH of the oceans has dropped by ~ 0.1 units. Estimates of future levels of atmospheric CO_2 vary, but modelling shows that the pH in the ocean is likely to fall by 0.2-0.4 pH units by the year 2100. These changes will have significant effects on marine organisms, especially those with calcareous skeletons such as echinoderms. Alarmingly little is known about the long term impact of predicted pH changes on marine invertebrate larval development. We used computerised monitoring and control of pH in natural sea water by controlled injection of CO_2. This system permits the manipulation of pH to an accuracy of 0.04 units with dynamic stability. We will present results detailing the quantitative (survival, growth, etc.) and qualitative (skeleton formation, phenotype, etc.) impacts of acidification (pH range from 8.1 to 7.7) on the long term development of six key marine species from fertilisation to juvenile/adult stages: the pelagic copepod *Acartia tonsa*, the brittlestars *Amphiura filiformis* and *Ophiothrix fragilis*, the sea star *Asterias rubens* and the tunicates *Ciona intestinalis* and *Ascidiella aspersa*.

Poster S2.2-4629

Mass bleaching of a soft coral, *Sarcophyton* sp., in Thailand: is this related to climate change?

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During June to October 2006 and 2007, mass bleaching of a soft coral, *Sarcophyton* sp. was found in the upper Gulf of Thailand at the Royal Thai Marine Corps, Chonburi Province, eastern Thailand. Approximately 90% of the populations experienced extensive bleaching, and almost 95% of the colony was bleached. It was the first time that mass bleaching of *Sarcophyton* was observed in Thailand. The bleaching of soft corals was found between 1-2 metre depths below the mean seawater level. The results from the laboratory experiments showed that heat stress and low salinity were the main factors contributing to the bleaching of this soft coral species. During the months of the bleaching period, there were extremely low tides and unusually high rainfall, which had an effect on the salinity in the area. The field observations during 2006 and 2007 showed that one month after the phenomenon each year, fragmentation of *Sarcophyton* was observed. By the end of July, some colonies started recovering partially. At the beginning of October, 95% of the population of *Sarcophyton* recovered and survived the bleaching. Some hard coral species in the area such as *Favites halicora, Porites lutea, Hydnophora microconos, Goniastrea retiformis, Platygyra daedalea,* and *Turbinaria frondens* were also bleached, but only 10% of the populations were affected.

Poster S2.2-4669

Effect of changes in carbonate chemistry on larval development of echinoderms

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The increasing levels of CO_2, as a result of anthropogenic activity cause a decrease in pH and the saturation of calcium carbonate. These changes from the industrial revolution are the highest reported for the last hundreds of thousands of years. There is an urgent need for a wider understanding of the effects that these changes will have on marine organisms, particularly calcium carbonate-producing organisms. Among these organisms, those with a free-swimming larval stage, may be particularly vulnerable to changes in carbonate chemistry. Echinoderm larvae

are among the most susceptible to ocean acidification since calcification occurs at the very early developmental stages. Additionally, agreement on experimental approaches to test the relationships between climate change and biotic responses are fundamental to make robust projections to the future. There are a few studies testing the impact of increasing carbon dioxide partial pressure on marine organisms, especially at the early stages of development. We tested this by using echinoderm larvae as a model organism representing ecologically important benthic calcified animals. We used present-day and future projections for CO_2 partial pressure to the years 2050 (~560 p.p.m.v. CO_2) and 2100 (~700 p.p.m.v. CO_2). Additionally, we tested the effect of saturation state of calcium carbonate by using artificial seawater simulating values of present-day and three projections for future climate scenarios. We report the effects of carbonate chemistry on larval physiology including calcification and discuss the results in an evolutionary context.

Poster S2.2-4675

Reconstructing past seawater pH from boron isotopes in carbonates

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Marine absorption of CO_2 results in the progressive acidification of the oceans, which has detrimental and possibly devastating effects for marine organisms, particularly those that construct a skeleton of calcium carbonate (corals, mussels, clams, etc.). To better understand the magnitude of this environmental problem it is crucial to know how seawater pH has oscillated in the past. Because instrumental records of seawater pH exceeding a couple of decades are not yet available, past variations of pH need to be reconstructed using proxies in suitable archives. A very promising geochemical proxy is the isotopic composition of boron in fossil biogenic carbonates which, so far, is the only practical method to quantitatively determine seawater pH variations back through time. This proxy has provided some important reconstructions of pH using fossils of foraminifera found in deep sea sediments. More recently, the method has been proved to be successful by means of corals, and a first reconstruction from a massive *Porites* species coral from Flinders Reef, in the Coral Sea, has been produced. This reconstruction, that covers the last 300 years, displayed an interesting and surprising ~50 year cyclicity of ~0.3 units of change in marine pH. In this presentation, we will review the theoretical grounds of the boron isotope proxy, show the empirical calibrations performed so far, briefly comment on some aspects of the analysis of boron isotopes, and we will present and discuss some of the most relevant results on paleo-pH reconstructions published so far.

Poster S2.2-4810

A multi-temporal approach to tackle the ocean acidification problem: insights from coral cultures and instrumental time series of pH

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The increasing CO_2 levels in the atmosphere and their high uptake by the oceans are lowering the pH of the oceans. Predictions indicate decreases of approximately 0.3 to 0.5 pH units by year 2100 and of nearly 0.8 pH units by year 2300, a scenario for which there is no obvious precedent over the last hundreds of millions of years. Such pH reduction could have major effects on marine biota, especially on calcareous plankton and coral reef communities, which may be unable to calcify effectively under these conditions. In the specific case of the Mediterranean Sea, it is still not clear how rapidly it is absorbing anthropogenic CO_2 and thus lowering its pH but, owing to its smaller size, there is the possibility that the lowering of pH may be more severe and abrupt than in the world oceans. In the context of a recently started PhD, we aim to tackle this environmental issue from different perspectives: first, we plan to investigate the consequences of ocean acidification for marine organisms by means of manipulative experiments in aquaria, particularly targeting representative species of the Mediterranean coralligenous concretions such as the aragonitic corals *Leptosammia pruvoti* and *Cladocora caespitosa*. And second, we wish to characterise the modern temporal variability of pH in different environments by deploying

a SAMI-pH that, using specific dyes and spectrophotometry, provides unattended measurements of pH at high precision (~0.0007 pH units). In this presentation we will outline the aims of this project and show the very first preliminary results.

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Calcified marine invertebrates: latitudinal variation and ocean acidification

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Heavily calcified marine animals such as molluscs, brachiopods and echinoderms have vital roles in ocean ecosystems and are major elements of Antarctic benthic communities. How will these heavily calcified animals cope in a changing 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 Southern Ocean 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 in these calcareous invertebrates, we present data from polar, temperate and tropical latitudes on shell and skeleton size, $CaCO_3$ crystal form and elemental composition. Results show Antarctic invertebrates have thinner shells and less shell per unit body mass than closely related temperate and tropical species. In buccinid gastropods, shell accounts for only 35% of the total dry mass of the Antarctic snail, *Neobuccinum eatoni*, compared to 81% in the temperate snail, *Buccinum undatum*, and 90% in the tropical snails, *Cantharus fumosus* and *Phos senticosus*. The Antarctic sea urchin, *Sterechinus neumayeri*, has 15% less skeleton than the temperate urchin, *Psammechinus miliaris*. Scanning electron microscope imaging of crystal type shows the Antarctic brachiopod, *Liothyrella uva,* has a calcite shell whereas shells of Antarctic gastropods and bivalves are composed predominately of aragonite. Wavelength dispersive spectroscopy determined variation in shell chemical composition at different latitudes. Having a smaller, more soluble shell raises particular concern for these aragonite based animals from Antarctica.