Abstracts

Investigating the Role of Nitrogen Fixation in Exporting Particulate Carbon to Depth

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Understanding the mechanisms that facilitate carbon export from oceanic surface waters to depth remains a critical gap in our understanding of global ocean carbon biogeochemistry. Several studies have suggested that the magnitude of the biological pump is highly dependent on episodic processes that can be both physical (e.g. nutrient injection) and biological (senescence) in nature. Here, we investigate the role that nitrogen (N2) fixation may play in not only the quantity of particle export, but also in the efficiency of downward transport of particulate organic carbon and nitrogen to depth. Water samples were collected at high vertical resolution in the eastern tropical North Pacific during summer 2008. Data include 238U:234Th and 210Po:210Pb disequilibria as tracers of particle export combined with a suite of N2 fixation and biomarker analyses. Preliminary results from this study will allow an evaluation of the relevance of N2 fixation in facilitating downward transport of carbon and nitrogen from the euphotic zone.

Quantifying the Biogeochemical Impact of Zooplankton Daily Vertical Migrations.

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Global biogeochemical models typically assume that the respiration of organic matter is accomplished by bacteria dipersed throughout the ocean. However, a growing body of research highlights the role of active transport due to diel vertical migration (DVM) of interzonal zooplankton and nekton. DVM takes place between the surface layers, where interzonal migrants feed at night, and the mesopelagic zone, where they excrete organic matter and respire oxygen by day. Whereas DVM appears to be a widespread phenomenon, relatively high uncertainty exists over its significance from a biogeochemical prospective. Furthermore, state of the art Earth System Models used to understand and project changes in the ocean carbon cycle, generally ignore the active fluxes mediated by DVM. We developed a simplified NPZ-type one-

dimensional ecosystem model which includes explicit DVM. The one-dimensional model is used to characterize and quantify: (1) the partitioning between passive and active transport of nutrients from the surface to the mesopelagic zone, (2) the deep oxygen consumption due to zooplankton activity versus detritus remineralization mediated by bacteria, (3) the interaction between zooplankton and open ocean oxygen minimum zones. The one-dimensional framework allows extensive exploration of the biogeochemical response to model aspects such as migration behavior, zooplankton metabolic parameters and particle dynamics. In addition we explore possible way of parameterizing the effects of zooplankton DVM in biogeochemical models coupled to three dimensional general circulation models.

Carbon Export and Natural Iron Fertilization in the Southern Ocean, Large Uncertainties Subsist.

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The impact of natural iron fertilization on carbon export was investigated in waters surrounding the two islands Kerguelen (KEOPS) and Crozet (CROZEX) in the Southern Ocean. In both fertilized environments, the enhancement of the carbon export was demonstrated compared to the carbon export in the HNCL region. The ratio of the excess of carbon export versus the excess of iron supply was calculated for different time scales. Short-term carbon and iron budgets established for the duration of the cruise, and using similar methodologies, lead to consistent estimates at both sites (70,000 and 40,000 mol/mol for KEOPS and CROZEX, respectively). However, when extrapolations were made at the seasonal scale, large discrepancies (2 orders of magnitude) emerged which are equally due to differences in the iron budget and the carbon export. Several explanations of the differences can be proposed. Some of them can be rejected on the basis of the existing data sets but others need further field investigations with new strategiesand methodologies.

Stimulating the Biological Pump to Mitigate Climate Change by Means of Iron Fertilization and Enhanced Vertical Mixing: A Review of Modeling Estimates

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The biological pump is one important process by which the ocean can take up atmospheric CO_2 and results from the surface water fixation of CO_2 into organic matter during photosynthesis and subsequent sinking and remineralisation at depth. Accordingly, some geo-engineering proposals seek to mitigate for rising atmospheric CO_2 by increasing the efficiency of the biological pump and hence also the oceanic sink for atmospheric CO_2. In the past, such proposals tended to focus on the artificial fertilization of ocean productivity by the micronutrient iron. More recent proposals to increase the strength of the ocean's biological pump concern the artificial mixing of nutrient-rich deep waters with nutrient-poor surface waters via mechanical pipes. Testing and quantifying the net effect of such methods (iron fertilization and ocean pipes) on atmosphere-ocean fluxes of CO_2, as well as the additional perturbations to ocean ecosystems and other climatic gases, in the field remains a significant challenge. Mechanistic models of ocean biogeochemistry that represent the requisite processes can provide a valuable framework within which to address these questions when evaluated against data. In this presentation, we review some of the recent modeling results that have estimated the impacts of ocean Fe fertilization and/or enhanced vertical mixing on the biological pump and atmospheric CO_2. We also explore how these artificial perturbations would impact other climatic-relevant gases such as dimethylsulfide and nitrous oxide.

Putting the 'Bio' Into Modelling the Biogeochemistry of the Twilight Zone

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Prior modeling studies of particulate export flux into the deep ocean have seldom incorporated any biological detail. However, the recent focus on the Twilight Zone (defined here as the base of the euphotic zone to 1000 m depth) provides an opportunity to ensure that modeling studies focus on both key geochemical and biological processes in this stratum. This zone is characterized by particle supply from the overlying waters, particle destruction (heterotrophic bacteria and zooplankton) and particle transfer (vertically migrating zooplankton). Furthermore, these processes take place in different zones, each with different depth ranges, and with regional variations, within the Twilight Zone. This poster will step through the various components of a new biological model which links particle production from the base of the euphotic zone to particle transformations within the Twilight Zone (Buesseler & Boyd, (2009) Limnol. Oceanogr., 54, 1210-1232). Examples of a range of depth-dependent biological particle transformations from sites including the NE Atlantic (NABE) and NE subarctic Pacific (Papa) will be employed to demonstrate the utility of this model.

Can Optical Sensors "See" Sinking Particles? - Interpreting in-Situ Spikes in Fluorescence, Backscatter and Attenuation as Sinking Aggregates.

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The 2008 spring bloom in the subpolar North Atlantic southwest of Iceland was studied using a combination of optical and other sensors on multiple platforms including ships, Seagliders and Lagrangian floats. The floats and gliders were deployed before the onset of the spring bloom and remained in the water for up to three months, as part of the NAB08 project. Measurements of chlorophyll fluorescence, optical backscatter and beam attenuation served as proxies for phytoplankton biomass and particulate organic carbon concentration (POC). Initially phytoplankton biomass was low and uniformly distributed within the mixed layer; the bloom began in mid-April as the mixed layer shoaled. At the height of the bloom in mid-May, 'spikes' in chlorophyll fluorescence, optical backscatter and beam attenuation began to appear at depths below the mixed layer, eventually extending to 900 m, our deepest observations. The 'spikes' were observed from all platforms, although with some differences. We interpret the 'spikes' as sinking aggregates of phytoplankton and other organic particles. Their appearance coincided with depletion of silicate in the mixed layer and the observation of a massive diatom flux event as documented by material from PELAGRA sediment traps (Lampitt and Martin, this conference). Several different methods were used to identify and quantify the magnitude of the optical 'spikes'. We compared 'spikes' from different optical sensors, from sensors on the same platform separated by known distances, and from sensors on different platforms at different locations in order to produce estimates of frequency, magnitude, spatial distribution, and chlorophyll and carbon content of these 'spikes'. Although 'spikes' in optical backscatter were observed through the end of June (the end of the experiment), their frequency and magnitude decreased. The relative magnitude of chlorophyll fluorescence associated with the 'spikes' also decreased with time, suggesting a change in the nature and composition of the sinking particles.

Shedding Light on the Ocean's Biological Pump and Twilight Zone Processes

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In this talk, a brief history of marine studies of the biological pump will be presented followed by a reanalysis of selected twilight zone data as presented in Buesseler and Boyd, L&O, v54(4), 2009, 1210-1232. This reanalysis leads to a new conceptual framework and ecosystem model with which to compare the strength and efficiency of the biological pump between different settings and seasons. We confirm the need to be more careful in our consideration of variability in euphotic zone depths as we compare biological pump efficiencies. To include this, we compare the ratio of POC flux at the base of the euphotic zone (Ez) to net primary production, called the Ez-ratio, to distinguish it from depth normalized flux export ratios (e-ratios). Conventional curve fitting of particle flux data can skew our interpretation of twilight zone processes, and thus attenuation below Ez is parameterized by the ratio of POC flux 100 m below Ez to the flux at Ez. This transfer efficiency, T100, varies from <20% to 100%. These new metrics are used to classify the ocean into regions and times of high and low surface export and subsurface attenuation. We will expand the analyses presented in Buesseler and Boyd (2009) to other sites and using other flux methods. Future twilight zone research will benefit from combined studies of geochemical properties and biological processes that consider variability in these new metrics within a unified sampling strategy and model framework.

Biomarkers and Their δ13C Signature in Suspended Particles in the Open Ocean Water Column: the Case of BONUS-GoodHope Expedition (Southern Ocean)

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Improving our understanding about the functioning of the biological carbon pump is necessary for a proper assessment of the ocean's CO2 sequestration capacity. The biological pump efficiency depends on the phytoplankton community structure and its activity in the upper mixed layer as well as on the composition and activity of zooplankton and prokaryotes consuming the sinking flux of organic matter. The relative importance of different microbial and zooplankton components, as well as the variable composition of the C-export flux in the water column can be resolved by studying the occurrence and spatial variability (depth and latitude) of specific compounds or biomarkers, such as lipids, in suspended matter. During the BONUS-GOODHOPE expedition (Feb.-March 2008, R/V Marion Dufresne), particulate organic matter was sampled along the Greenwich Meridian using large volume in-situ filtration systems. Five stations were selected on the basis of their zonal characteristics: S1 (36°S, 13°E) and S2 (42°S, 8°E) in the Subtropical Zone, S3 (47°S, 4°E) in the

Subantarctic Zone, S4 (51°S, °E) in the Polar Front Zone and S5 (57°S, 0°E) in the Weddell Gyre (Antarctic Zone). For surface waters, two size fractions were separated (Ø1 > 53 µm and 53 > Ø2 >1 µm), while from the mesopelagic layer to the deep ocean we sampled the 53 > Ø2 >1 µm particles. We applied an extraction procedure based on a modified Bligh and Dyer method, followed by separation of neutral, polar lipids and glycolipids and silica gel columns. Neutral lipids (containing sterols and alkenones) were sylilated, while polar lipids were methylated prior to analysis. Samples (at present only the neutral and polar lipid fractions) were analyzed by GC-MS for compound identification and GC-c-IRMS for carbon isotopic composition and relative quantification. We discuss the depth distribution as well as the zonal distribution of individual compounds and their carbon between the Cape Basin and the northern Weddell Gyre.

The Biological Pump in the Enhanced Greenhouse: Simulations with the Canadian Earth System Model CanESM1

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Ocean uptake of anthropogenic carbon dioxide has substantially mitigated the effect anthropogenic emissions on climate. Climate change and ocean acidification will affect future rates of ocean carbon dioxide uptake, and have likely already begun to do so. Both positive and negative feedbacks are possible, but the overall effect is likely to be reduced ocean uptake and therefore a greater airborne fraction of future emissions. The Canadian Earth System Model CanESM1 is a fully coupled climate/carbon-cycle model with prognostic ocean and terrestrial carbon cycle models; the model has been used to simulate the historical climate using known emissions, and future climates, using IPCC emission scenarios. Future ocean carbon dioxide uptake depends on changes in ocean stratification that affect the biological pump, and on climate-induced changes in surface temperature and salinity. Substantial declines in export from the euphotic zone are expected over the 20th century, particularly in the North Pacific. Declining export production due to increased stratification is partially mitigated by increasing dinitrogen fixation, while an increased inorganic/organic carbon 'rain ratio' has the opposite effect, reducing ocean carbon dioxide uptake for a given rate of export production. Changes in the flux of terrestrial mineral dust may also affect future uptake of carbon dioxide by determining the extent of photic zone nutrient utilization. Improved process models of dinitrogen fixation, calcification and calcite dissolution, iron supply and dust dissolution are required to confirm or falsify our model projections.

The Biological Pump in the Eastern Tropical Pacific Oxygen Minimum Zone

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Large regions of the world's oceans have persistent oxygen minimum zones (OMZs), which appear to be sensitive to climate variability. OMZs have varied significantly in extent over geological time, potentially influencing oxygen,

carbon, and nutrient cycles. These regions are typically characterized by relatively high surface productivity, often the presence of commercially important fisheries, reduced ventilation of intermediate depth waters, and non-linear nutrient cycling. Strong vertical oxygen gradients exert a considerable influence on the biogeochemical properties and organism distributions. Remineralization of sinking or suspended particles may be reduced, allowing a greater particle flux to depth. Standing stocks and rate measurements associated with the biological carbon pump were obtained during two cruises to the eastern tropical north Pacific, 18 October – 17 November 2007 and 8 December 2008 to 6 January 2009. Stations were located between the Tehuantepec Bowl (13ºN 105ºW) and the Costa Rica Dome (9ºN 90ºW), having variable physical features (e.g., gyre, eddies, upwelling) and nutrient, oxygen, and productivity gradients (Rhizosolenia and radiolarian blooms). There was significant spatial and interannual variability in abundance and depth distributions of particles and grazers. In general, the highest concentrations of POC, detrital particles, and zooplankton occurred in the surface layer, or coincident with chlorophyll maxima, and decreased in the OMZ. Some zooplankton, fish, and squid were residents or migrators into the OMZ, depending on oxygen tolerances. Concentrations increased again at the lower oxycline. Trophic interactions within chemoclines will be discussed.

Impact of Minerals on Degradation of Sinking Aggregates Over the Course of Several Weeks

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One recent question concerning the export of particulate organic carbon (POC) to depth within the ocean, is whether or not POC is more likely to reach great depths in association with minerals such as calcium carbonate and biogenic silica than without. The proportion of the originally produced POC reaching great depths depends on the balance struck between POC sinking velocity and degradation rate. Thus minerals could enhance export by either enhancing sinnking velocities or diminishing degradation rates.

We chose to test the latter case over the course of four weeks, roughly the time it would take a particle sinking at 150 m per day to reach 3000 m. Diatom aggregates were deployed into a series of rolling tanks containing either no minerals or a high concentration of suspended minerals and allowed to decompose in the dark. Over the course of the four weeks, the high mineral tanks showed some differences to the no mineral tanks in terms of aggregate number and shape: In the former aggregate abundance per tank was higher but they were smaller and more compact while in the latter aggregate numbers were lower and their shape somewhat more fluffy.

Determining the Net Annual Biological Carbon Pump and the CaCO3: Organic Carbon Production Ratio using in situ Measurements of O2, N2, pCO2 and pH

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To predict feedback of the ocean to increasing atmospheric pCO2 and the effects of ocean acidification, one must first know the value of the natural upper-ocean organic and inorganic carbon fluxes and mechanisms controlling them. We use in situ measurements of oxygen, gas tension, pCO2 and pH in a simple upper ocean model to determine the net annual biological oxygen production, the net annual production of organic matter and the production ratio of CaCO3 to Organic Carbon. Measurements were made on surface moorings at the subarctic and subtropical Pacific Ocean time series stations Papa (145W, 50N) and HOT (158W, 23N), respectively. Results of these studies suggest that the net annual biological organic matter production in the subtropical Pacific is at least as great as that in the subarctic Pacific, which is contrary to the images of the ocean's carbon pump produced from both satellite color and ocean general circulation models. There is no compelling experimental evidence that the annual carbon export flux from the subtropical Pacific is lower that that in the subarctic. Possible reasons for the discrepancy will be discussed. In the summer of 2007 the molar production ratio of CaCO3 to organic carbon in the subarctic Pacific at Stn. P was near ~1.0 based on the response of the ocean's carbonate system (pCO2 and pH) to the measured net oxygen production. This value is very high and suggests that the inorganic carbon to organic carbon ratio of the biological pump is much more variable both regionally and seasonally than model estimates which derive a relatively uniform global value of between 1:10 – 1:20. Our message is that globally distributed measurements of the seasonal variations in the biological carbon pump are essential to ground truth paradigms that have grown mainly from model studies and remote sensing observations.

Using In-situ pCO2 Observations to Evaluate and Improve Ocean Carbon Models: A North Atlantic Case Study

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Due to its complex and variable temporal and spatial scales, it is unclear how the North Atlantic carbon sink responds to climate variability and how it will respond to future climate change. Recent studies of the subpolar North Atlantic carbon cycle suggest different patterns of interannual variability in surface ocean pCO2, and it is difficult to distinguish trends in the net carbon sink (Schuster & Watson, 2007; Thomas et al. 2008; Ullman et al. 2009). In order to resolve this carbon uptake debate, further analysis is needed. Furthermore, despite the current push to develop IPCC AR5 climate models with interactive carbon cycling, data-based metrics for these models are sorely lacking.

Using the vast, newly released, in-situ dataset provided by Takahashi et al. (2009), analysis of trends in the subpolar North Atlantic carbon sink over recent decades can be considered. We compare the observed trends to a North Atlantic regional ocean biogeochemical model (Bennington et al. 2009; Ullman et al. 2009; Koch et al. 2009), and highlight regions where the model is performing well and where it needs improvement. We also use the model to separate the physical and biological drivers for the observed trends. Finally, we report on our progress in developing a gridded product from this database to be released to the community for additional analysis and model evaluation. Using these comparisons to determine how accurately the models are able to capture the observed variability and trends from 40 years of data will allow for improved confidence in ocean carbon cycle models and help to pinpoint areas where more data is needed.

The Simultaneous Determination of In-situ Vertical Transitions of Color, Redox Sensitive Dissolved Metals and Infaunal Activity in Marine Sediments Using G-SPI

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Currently unanswered questions in marine sediment biogeochemistry include the amount of remineralisation of carbon at the sediment water interface and the amount of carbon that is sequestered into sediments. After the biological pump has delivered organic matter to the sea bed, what effect does bioturbation have on the sequestration and recycling of carbon and macro- and micronutrients? These are key questions that need to be addressed as changes in the climate can have an effect on the changing supplies of macro- and micronutrients in the upper ocean which subsequently leads to changes in the transfer of matter across the ocean interfaces (sediment-water). Here we present the first data from a proof of concept study in the North Sea at two sites which showed fundamentally different biological communities. We have for the first time combined sediment profile imaging (SPI) together with diffusive gradient thin (DGT) gels (g-SPI) to obtain simultaneous in-situ measurements of sediment color profiles, dissolved Fe and Mn profiles and faunal activity (through time-lapse imaging) as a first step towards determining the relationship between sediment color, biogeochemical processes (dissolved metal profiles) and particle movement (faunal activity). This combined approach of SPI and DGT has the potential to be applied to deep sea environments receiving differing quantities and quality of organic material to elucidate organic carbon cycling at the sediment-water interface and allow the biogeochemical processes to be more accurately interpreted in light of the infaunal biological activity.

Spatio-Temporal Phasing Between Primary Production and Vertical Particle Export in the Fram Strait (Arctic Ocean)

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Long-term relationships between primary production (PP) and vertical export were widely studied in different oceanic regimes in the last decades. However, the lack of extended dataset in the Arctic Ocean has so far prevented an inclusive understanding of these relations. Moreover, in most studies, the particle fluxes have been collected with deep ocean sediment traps (>1000 m). While the upper twilight zone (<300 m), where the vertical flux attenuation is most prominent, remained poorly analyzed. In this study, we make use of modeled PP data (SinMod) that overlapped in time with the vertical flux time-series collected with a sediment trap deployed at ~300 m depth from 2000 to 2005 as part of the Hausgarten observatory in the eastern Fram Strait (isobath ~2500 m). Our central goal is to investigate the spatial (i.e. catchment area) and temporal (i.e. time-lag) linkages between PP and the biogenic flux components. Our initial analyses indicate that gross PP obtained for different circle areas centered on the mooring (5 to 100 km radius) explains at best ~35% of the biogenic matter flux when applying a time-lag of ~60 days between PP and export. Interestingly, we identified a cycle of in- and out-phasing when plotting the strength of the PP-export relationship (R2) against the time-lag applied between PP and export (0-120 days). Hence, our results suggest that primary-produced organic matter in the Fram Strait is not solidly coupled with export and appears to be already heavily processed by the pelagic food web of the upper water column when injected into the twilight zone.

The Ocean's Biological Pump in Times of Global Climate Change: Is There a Potential for Significant Feedbacks to Atmospheric CO2?

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Global marine primary production fixes an average of 52 GtC/y as particulate organic carbon. An estimated 11-22 GtC/y leave the euphotic ocean as export production. The net ocean sink of CO2 is evaluated to approx. 2 GtC/y. Quite frequently magnitudes of export production and ocean anthropogenic CO2 sink are quoted side by side thereby suggesting the potential for biological processes to be at the origin of significant feedbacks to atmospheric CO2. This is however misleading since primary production and remineralization - integrated over time and space - fix, respectively release C and nutrients with a similar stoichiometry. As a result, the biological soft-tissue pump operates with a close to zero net effect on air-sea exchange of CO2. In order to feedback to atmospheric CO2, its efficiency has to be changed either by modifying the magnitude of export production or the remineralization depth profile. The biological pump may be altered through the reorganization of ecosystems and biogeochemical changes in response to (1) changes in ocean physics: stratification and alteration of nutrient supply; (2) changes in external supply of nutrients; (3) changes in ocean chemistry: ocean acidification due to rising CO2. I will present a synthesis of available evidence for future changes of the biological pump in response to these drivers and, whenever possible, a quantification of associated feedbacks to atmospheric CO2. The re-assessment of the role of marine biota as feedback to the carbon cycle has social and economic implications, in view of emission targets for greenhouse gases and suggestions for geo-engineering involving marine biology.

Export flux of biogenic elements and their main sources (faecal pellets, plankton mineral skeletons) to the deep sea along the Humboldt Current System off Chile (21º-37ºS)

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Vertical fluxes of biogenic elements (carbon, carbonate) and their main sources (faecal material, phytoplankton, microzooplankton) were studied at three oceanic mooring stations along the Humboldt Current System off Chile at 1000 and/or 2300 m depth. The sites were, from north to south, off Iquique (21ºS; time-serie station 2005-2007), off Coquimbo (30ºS; time-serie station 1993-2004), and off Concepción (37ºS, time-serie station 2003-2006).

The average fluxes of particulate organic carbon (POC) at 2.300 m depth in Iquique, Coquimbo and Concepción were 2.8, 5.3 and 16.0 mg m^{-2} d^{-1}, respectively. Faecal material, mainly euphausiid faecal strings, made the main contribution to the total POC flux at all locations. The average fluxes of particulate inorganic carbon (PIC) at 2.300 m depth were significantly higher than those of POC only in some locations (i. e. Coquimbo). This suggests that the deep-water delivery of biogenic carbon is highly variable, fluctuating between regions where the main pathway removing carbon from the upper ocean is POC (i. e. Concepción) or PIC (i. e. Coquimbo). We discuss the relevance of the information on key species and/or functional groups of the plankton that mediate the biological carbon pump along the Humboldt Current System off Chile, through their excretion products (euphausiid faecal strings in Concepción) or their mineral skeletons (foraminifers in Coquimbo).

Sub-mesoscale Variability of Particle (>100 µm) Export Around Station ALOHA: The OPEREX Cruise

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The North Pacific Subtropical Gyre (NPSG) is characterized by low nutrient concentration and low biomass standing stocks. However, large cells and high surface phytoplankton concentration are usually associated with late summer chlorophyll blooms in the region. These blooms are characterized by a wide range of scales, from sub-mesoscale (~2 km) streaks to mesoscale (~100 km) patches, and their triggering mechanism is unknown. The OPEREX cruise was an observational survey designed to investigate the formation and evolution of these blooms and their impact on particle export. The study area was occupied by a mesoscale dipole, with a cyclonic eddy to the north and the anticyclone to the south. The high resolution (7-10 nautical miles) survey revealed patchiness at the sub-mesoscales (Data from the Underwater Video Profiler). Optical measurements and sediment trap data revealed that large particles converged to the region between the eddies and were exported down to 300 m. Identifying the biological and physical processes responsible for the particle distribution and export is crucial not only for regional but also basin scale estimates of carbon export and parameterization of global climate models.

Deep Ocean Export and Sinks for Dissolved Organic Carbon

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The ocean pool of dissolved organic matter contains 662 Pg C. Net DOC production occurs in the surface ocean, with eventual export to depth with overturning circulation at a rate of about 20 per cent of total export production. Until now, our knowledge of DOC biogeochemistry on the global scale had been limited to few high precision measurements scattered widely across ocean basins. Here we employ a new, vastly enlarged global ocean data set (about 20,000 measurements) to produce unprecedented resolution and insights on the distribution and dynamics of DOC in the deep ocean. Highly resolved DOC concentration gradients trace the flow of the thermohaline circulation, allowing characterization of the deep water masses by their DOC signatures. DOC removal rates at depth are very slow, as evidenced by removal in the North Atlantic at less than 1 umol/kg/yr and 2-3 orders of magnitude slower yet in the deep Pacific. Rates of removal are positively correlated both with ambient DOC concentrations and temperature, with the latter providing a climatic link to the deep DOC pool.

Estimating Losses to the Radiative Forcing Benefit From Nitros Oxide Production Under Increased Flux in the Biological Carbon Pump

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Adding nitrogen to the oligotrophic surface ocean has been proposed as a potential global warming mitigation strategy. Anthropogenic activities are already introducing around 54 Tg N /year to the open ocean surface layer, leading to an increase in productivity and increased carbon drawdown by the biological pump (Duce et al, 2008). When new reactive nitrogen enters the ocean nitrogen cycle, some of it is lost through the processes of nitrification and denitrification, this adds to the base load of nitrous oxide that escapes the sea surface each year. N2O is a powerful greenhouse gas, that when released to the atmosphere causes a reduction in efficiency of the radiative forcing benefit provided by increased carbon storage. Duce et al (2008) put this figure as high as 66% loss of radiative forcing benefit. The current flux of new nitrogen (fixation + atmospheric deposition) into the open ocean is approximately 170 Tg N /year (Gruber, 2004) with a residence time of 3300 years (Gruber, 2008) and the current flux of N2O to the atmosphere is around 5 Tg N year-1 (Duce et al. 2008) with an atmospheric lifetime of 114 years (IPCC, 2007).

An important question when extrapolating the flux of N2O is what scaling to apply when considering an increase in annual turnover of the biological carbon pump. This paper contrasts several different methods of estimating the change in annual N2O flux from the ocean to the atmosphere and hence estimating the loss in radiative forcing benefit from an increase to new primary production.

In the absence of any evidence that the capacity of the biological pump has been reached a linear relationship is often assumed. Using the figures above and assuming that extra reactive nitrogen in the biological pump ties up carbon in the Redfield ratio of 6.6 for C:N, we can calculate the new steady state radiative loss by assuming inputs equal losses in the open ocean. We find additional carbon stored away from the atmosphere to be 1.4*10^7 Tg of CO_2. N_2O added to the atmosphere is 896 Tg which multiplied by 296 (IPCC, 2007) converts to 2.65*10^5 Tg CO_2 equivalent. Or a 2% loss of radiative benefit due to the production of N_2O after approximately 3300 years from the start of a sustained additional flux of reactive nitrogen to the surface open ocean.

Of course refreshment times in the ocean are long and the open ocean will not reach a new equilibrium quickly. Additional new nitrogen stored in the ocean will be no more than the 54 Tg N /year ; this can be compared to the present value of around 600,000 Tg N. Therefore during the first few hundred to thousands of years the concentration of nitrogen in the deep ocean changes very little, and the increase to new primary production due to increased upwelling of N is considered negligible. Upwelled nitrogen is the dominant source of nitrogen (around 90%) to the photic zone, where it is assimilated as new primary production and thus drives export. Another method of calculation is based on the assumption that N_2O flux results mainly from the nitrification and denitrification of nitrogen flux through the aphotic zone, which on an annual basis can be considered equal in magnitude to global export production and thus is approximately equal to the new primary production (Yool et al, 2007).

The increase in export due to returned anthropogenic nitrogen (from below the thermocline) will be very small initially and increase asymptotically towards the steady state value over a time period that is set by the rate at which export nitrogen returns to the surface ocean. The Duce et al (2008) estimate assumes a rapid return time, of order decades to centuries based on the observation that most atmospheric deposition occurs over the tropics and sub tropics (Duce et al, personal correspondence, 2009). Orr and Aumont (1999) simulated direct injection of dissolved carbon dioxide at 7 sites around the word at 1500m depth using a global ocean circulation model. They found 80% efficiency in the reduction of atmospheric carbon after 200 years compared with the control, although with large variance between sites. This implies that on average 80% of carbon exported to 1500m would not have returned to the mixed layer after 200 years.

An estimate of the increase to the N_2O flux can be calculated by using the figure of 1900 Tg N /year for total present new production from Duce et al. (2008) Table 2. The AAN deposition (54 Tg N /year) results in the N_2O production of 54x(5/1900) = 0.14 Tg N_2O-N year-1 This estimate gives an initial 6% loss in radiative cooling efficiency without taking into account the respective residence times.

The two calculations presented give representative figures for the long and near term loss of radiative benefit that could be expected due to increased and sustained introduction of reactive nitrogen to the surface open ocean. The estimated losses of 2% and 6% respectively are based on linear scaling using whole ocean averages, and are an order of magnitude lower than the estimate published in Duce et al 2008. These estimates contain large uncertainties and constitute ballpark estimates, ultimately the level of nitrous oxide production is likely to depend heavily on the location of introduced nitrogen. The range of estimates and time dependence should be resolved further through modelling studies using coupled biogeochemical global ocean circulation models.

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Impact of the North Atlantic Oscillation on Export Flux at the Subpolar – Subtropical Gyre Boundary

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The phase of the North Atlantic Oscillation (NAO) is shown to have implications for decadal variability in the timing of primary production. A combined satellite data and modelling study demonstrates the expansion of the sub-tropical gyre in negative phases of the NAO. Results from the vicinity of the Porcupine Abyssal Plain site illustrate the interannual to decadal variability in productivity and timing of bloom events. The implications for variability in export flux and benthic food supply are discussed.

Modelling Phytoplankton Distributions in the Ocean: a Novel Multi-Species Approach

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Modelling phytoplankton communities in the oceans is critical for accurate prediction of carbon export and biogeochemical cycles. A novel modelling approach is presented in which tens to thousands of phytoplankton 'ecotypes' are initiated in a global ocean model (Follows et al. 2007, Science). 3-D global model outcomes are compared to phytoplankton distributions observed during Atlantic Meridional Transect (AMT) cruises. A 1-D application for the South Atlantic Gyre is then used to reveal the detailed competition between model ecotypes, and investigate the role of light, nutrients and temperature in forming the resulting community structures.

For the South Atlantic Gyre, the model successfully reproduced observed vertical gradients in phytoplankton community structure and highlighted the importance of spectral optics for phytoplankton species selection. Specifically, spectral light absorption restricted phycobillin-containing ecotypes to surface waters whilst carotenoid-containing ecotypes occurred deeper in the water column, in keeping with the distributions of Synechococcus and picoeukaryotes in the data. In contrast, photoinhibition was necessary to reproduce vertical gradients in high-light and low-light Prochlorococcus. These outcomes were consistent for the 3-D model run which also reproduced the distributions of large eukaryotes and silica-requiring ecotypes along the Atlantic Ocean transect.

This novel model approach provides a new ecosystem framework for future studies of carbon export. The model is currently being developed to incorporate a full radiative transfer component,

which will allow the light scattering properties of calcifiers to be resolved.

Phytoplankton Community Characterization Using Imaging Multivariate Optical Computing (IMOC) and Spectral Fluorescence Signatures

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Characterization of phytoplankton size and taxonomic composition is critical to understanding carbon export in marine ecosystems. As phytoplankton community structure can be highly variable in space and time, its characterization requires sensors that can monitor continuously, and be deployed at multiple fixed locations or used on tethered or autonomous underwater vehicles (AUVs). While most ocean sensing platforms are equipped with a fluorometric sensor for chl a, this information cannot be used to discriminate between different phytoplankton taxa or to discern cell size. As an alternative, we are developing a new instrument based on an approach called “imaging multivariate optical computing” (IMOC) that uses image and fluorescence excitation spectral information to "bar code" different phytoplankton taxa by optical discriminant analysis. The IMOC approach works by creating interference filters, one mimicking each linear discriminant function required for classification of different phytoplankton taxa. The filters encode the discriminant functions in their transmission spectra. To date, we have identified functions that discriminate between differently-pigmented phytoplankton groups, between similarly-pigmented groups and between N-replete and N-depleted cultures of the coccolithophore Emiliania huxleyi. With our partner company, Ometric Corporation, we have just produced our first set of filters which allows the discrimination of E. huxleyi, the diatom Thalassiosira pseudonana and the cyanobacterium Synechococcus. These filters are now being incorporated into a shipboard prototype for testing in the laboratory. Future research will produce an IMOC instrument for installation on gliders or AUVs that will be compact, inexpensive and require low power.

Chemical Mass Balance of the Surface Layer in the Southern Ocean for Obtaining Export Production

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In the polar oceans, the hydrographic conditions are particularly favorable for obtaining estimates of the export of organic material from the surface layer using the distributions of biologically-mediated properties, like nutrients, oxygen and Total CO2 concentrations. As a typical and pivotal Southern Ocean region, we focus on the Weddell Gyre in the Atlantic sector of the Southern Ocean. In the Weddell region deep and bottom water ventilation takes place, which can be a conduit for the sequestration of organic matter and remineralized nutrients and CO2. The

Weddell Gyre being a large elongated cyclone, upwelling of intermediate water occurs into the surface layer. Since the entire surface layer is essentially generated from this sub-surface water mass, the difference of the properties of both surface and subsurface waters may be used to gain insight into the implications of biological processes in the surface layer.

It should be realized that this method has at least two different applications in the Weddell Gyre. First, the surface layer concentrations of nutrients, oxygen and TCO2 are compared to the corresponding concentrations in the nutrients- and TCO2 maxima and the oxygen minimum below it. If active biological activity in the surface layer can be excluded, this method yields an estimate (upper bound) of the export production. The consequence of this condition is that the measurements must be performed in winter or early spring, which may be difficult to realize because of the adverse weather and ice conditions and consequently bad accessibility of the Southern Ocean. A second application uses the fact that during the spring and summer period, a seasonal pycnocline develops in the surface layer. Below this the properties show essentially end-of-winter values, while above it the properties have changed as a consequence of biological processes – but also due to other processes, which should thus be catered for. This application thus yields an estimation of the net community production until the moment of sampling. These measurements may thus well be carried out in the summer or autumn, seasons when the Southern Ocean is much better accessible.

We will show the potential of this method as exemplified for the Weddell region, but also for adjacent regions in the Southern Ocean. All such methods have in common that with a relatively small effort (as opposed to seasonal sampling, i.e. covering the vegetative season with measurements), larger-scale estimations of biological properties, such as export production can be obtained.

Twilight Zone Carbon Reineralization Efficiency in the Southern Ocean

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The biological pump efficiency is set by the different processes controlling formation and export of biogenic material from the surface layer and also the processes consuming organic C deeper in the mesopelagic. We applied different proxy-approaches to evaluate the potential for C export (new production), C export production from the surface (234Th deficit) and remineralization of organic C at greater, mesopelagic depths (BaSO4 accumulation, bacterial activity) for different functional entities of the Southern Ocean. These include SAZ and PFZ systems differing in planktonic composition and functioning, as well as shelf and margin systems naturally supplied with Fe, studied during S.O. expeditions including KEOPS/2005 and SAZ-SENSE/2007. Production, export and mesopelagic remineralization rates are compared between these different provinces to investigate spatial variability of C sequestration efficiency. Our findings about efficiency of C export and remineralization highlight the importance of: -type of phytoplankton dominance, with diatoms dominated systems leading to shallower remineralization; -phytoplankton biomass and grazing, with evidence for relatively less mesopelagic remineralization under conditions of high biomass and high grazing pressure; -the important control of prokaryotes on organic carbon remineralization length scales; - the possible impact of Fe availability.

The Importance of Large Cell Size Diatoms to Export Flux of POC and Potential Indicators of Nutrient Change Scenarios in Patagonian Fjords System

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It has been estimated that about half of the export flux of carbon to the deep ocean is synthesized by diatoms, thus it is important to consider the factors influencing the relative contribution of diatoms to total primary production and its response to climate change. Furthermore, carbon fixed in surface waters is recycled to the atmosphere, back into seawater, or buried in sediments. Since Patagonian fjords have been suggested as “CO_2 sink” areas during the productive season, it will be relevant to understand the processes/factors that modulate the efficiency of the biological pump in these systems. Here we present a comprehensive data in southern Patagonian fjords, which represent an area of relatively high primary productivity, high diatom abundance, and active accumulation of diatoms valves in sediments. It has been pointed out that the increase in nutrient loading in these systems (from natural or anthropogenic sources) is associated to changes in ambient nutrients (mainly inorganic nitrogen and phosphorus sources), which in turn have been used to explain shifts in phytoplankton assemblage composition, thus autotrophic biomass and primary productivity. Additionally, large scales phenomena (*i.e.* El Niño, Global Change) may decrease freshwater stream flow, with actual lower river discharges, as it is suggested for larger southern Patagonian rivers. In this scenario, we hypothesise that a decrease in freshwater input (then decrease in silicic acid input) and nutrient loading from anthropogenic activities (mainly nitrate and ammonia) may directly influence phytoplankton population and community properties, such as shift in species composition (from diatoms to flagellates), and decrease in autotrophic biomass and primary productivity of coastal waters of Patagonian fjords.

Primary productivity, composition of the dominant species and their relationships with environmental factors have been studied in the Patagonian fjords system between 2005 to 2009 period. The region is characterized by horizontal buoyancy input of freshwater from river run-off with important ecological-oceanographic implications. Primary productivity in fjord areas varies greatly in magnitude (100 and 5000 mg C m^{-2} d^{-1}). In general, the vertical flux of POC out of the photic zone (5 – 30%) is largely size-dependent and highly variable on seasonal scale. Micro-phytoplankton (>20 µm), mainly chain-forming (*Chaetoceros*, *Thalassiosira*) and large single-cell (*Rhizosolenia*) diatoms, contribute more (50 – 70%) to primary production and biomass in the fjords region during spring seasons. The high autotrophic biomass and primary productivity estimates at the studied fjords are associated to higher stability of the water column, being favourable to growth of cold waters phytoplankton. The results obtained in four Patagonian fjords during the last four years represents an unique opportunity to carried out next observational/experimental studies of future scenarios of low/high availability of nutrients for diatoms where the primary production and nutrients flux are important. Results may provide information on the response of marine phytoplankton to nutrients change. Such information will be critical to understand the past, and may be the future changes in the marine carbon cycle and changes induced by the input of nutrient compounds into the fjords from anthropogenic activities. Here we hypothesise the following possible scenarios: (1) A potential shift in dominance from diatoms to flagellates/bacteria (Si:N ratio departed of 1); (2) A potential decrease in average primary productivity (due to reduction in diatoms growth); (3) A potential reduction in the diatom flux through a diminished “biological pump” and a reduction in the fjord capacity to act as a “sink” for CO_2.

Marine Microbial Carbon Pump

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(On behalf of the SCOR WG 134)

A fraction of the labile DOC taken up by the microbes in seawater becomes metabolically converted to recalcitrant DOC (RDOC) as a substantial carbon pool. This process may be envisioned as “microbial carbon pump” that enhances the C:N and C:P ratios and prolonging the residence time of carbon in the ocean. Compared with inorganic carbon storage, RDOC is less sensitive to environmental changes and has no chemical equilibrium limitations. The microbial carbon pump is analogous to the better-known “biological pump” which is driven by photosynthetic fixation of CO2 and subsequent sinking of POC in the ocean. The microbial carbon pump however is based on RDOC generation rather than sinking process. RDOC generation involves multiple trophic and metabolic pathways including microbial exudation and cell lysis, POC degradation, and partial hydrolysis of complex polymers. The relative contributions of RDOC generation pathways, and the degree of recalcitrance of RDOC components vary in different biogeochemical scenarios. The relative importance of the RDOC based microbial carbon pump to the POC based biological pump is expected to vary along environmental gradients. Quantification and explicit integration of carbon flux via recalcitrant DOC due to microbial biosynthetic and degradative activities in the microbial carbon pump should contribute to a better understanding of the mechanisms of carbon cycling and carbon sequestration in the ocean.

The Scientific Committee for Oceanic Research (SCOR) has launched a new Working Group on microbial carbon pump in the ocean, which will last for four years starting from 2009.

Mechanistic Model of Sinking Biogenic Particles

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Rising atmospheric CO2 and acidification of oceans affect phytoplankton physiology. Production of CaCO3, which serves as ballast in sinking aggregates, is decreased. The production of transparent exopolymer particles (TEP) that are sticky and aid aggregation, is increased, resulting in larger and faster sinking aggregates. In an effort to understand the competing effects of increased aggregation and decreased ballasting on organic carbon transport in response to rising CO2 concentrations, we have developed a one dimensional Lagrangian model of sinking marine particles.

Our model tracks a statistical sample of the particles throughout the water column. Coagulation and disaggregation occur stochastically according to probabilities calculated theoretically. The geometry of marine aggregates exhibit fractal properties; we use data on their fractal dimension to calculate porosity and thus density and sinking velocity. The model accounts for respiration of organic carbon and TEP due to bacteria and zooplankton. Organic carbon fluxes in the water column seem to require a slowing degradation rate with depth, which motivated us to implement multiple age groups with slowing degradation rate constants, as also observed more broadly in organic geochemistry. Size spectrum data of suspended particles in the deep ocean suggest disaggregation is a major mechanism. We model disaggregation to be due to a combination of swimming zooplankton and the degradation of TEP.

To validate the model, fluxes are compared to sediment trap data in 3 regions: the calcitic North Atlantic Ocean, the HNLC Equatorial Pacific, and the silica dominated Southern Ocean, each driven by production data from the respective region. We examine the effect of changes in ocean chemistry and biology on the efficiency of the biological pump, i.e. on the fraction produced that reaches the deep sea. We also explore the response of the rain ratio at the sea floor to rising atmospheric CO_2 concentration.

Comparison of O2 Observations and Model Predictions in the Southern Ocean

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This project study NCP and GPP in the Southern Ocean by examining observed O_2 properties in the oceanic mixed layer, along with atmospheric O_2/N_2 variations, in the context of remotely sensed biological properties and simulations of 3-D ocean biogeochemistry models. Here we present some early results from testing two state-of-the-art ocean biogeochemistry GCM's against a large data set of O_2 measurements. Our final goal is an improved understanding of the controls on fertility in the Southern Ocean, and models that better simulate Southern Ocean This project study NCP and GPP in the Southern Ocean by examining observed O_2 properties in the oceanic mixed layer, along with atmospheric O_2/N_2 variations, in the context of remotely sensed biological properties and simulations of 3-D ocean biogeochemistry models. Here we present some early results from testing two state-of-the-art ocean biogeochemistry GCM's against a large data set of O_2 measurements. Our final goal is an improved understanding of the controls on fertility in the Southern Ocean, and models that better simulate Southern Ocean biological processes.

Rapid Oxygen Utilization in the Ocean Twilight Zone Assessed with the Cosmogenic Isotope ^7 Be

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The rate of oxygen utilization beneath the sunlit surface ocean provides a measure of the export rate of biologically produced carbon to the deep sea, and its variation with depth suggests where remineralization of that carbon occurs. The latter consideration is relevant to the efficiency of carbon sequestration in deep water. However, accurate characterization of this process, particularly within 200m of the euphotic zone where carbon utilization is most intense, has been difficult owing to limitations of techniques applied to these shallow depths. A novel approach utilizing the cosmogenic isotope ^7 Be indicates that at a site in the subtropical N. Atlantic, 65% of sinking carbon is remineralized within 200m of the ocean's surface and thus readily available for return to the atmosphere. The corresponding oxygen utilization rates are appreciably greater than would be suggested by the attenuation with depth of organic matter measured by shallow sediment traps.

Relation Between POC and Mineral Composition of Sinking Particles in the Water Column: Causes and Consequences

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The efficiency and time scales for oceanic CO2 sequestration through the marine biota (the biological carbon pump) depends critically on how much POC is exported and respired below the winter mixed layer. Recent studies, have shown that the flux of POC in the deep sea is strongly coupled to the fluxes of lithogenic material and biominerals (CaCO3 and opal) with roughly constant ratios between POC : mineral fluxes below 1000 m depth. Here we present results on an analysis of the relation between POC export and mineral composition of sinking particles in the upper 1000 m of the water column. Results are discussed in the light of surface biological and chemical characteristics in an attempt to unravel mechanisms determining the variability in export ratios of POC and biominerals at depth.

Parameterisation of Export, Sinking and Remineralisation and its Effect on Simulated Tracers in Large-scale Models of Marine Biogeochemistry

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Sinking and remineralisation of particulate organic matter (POM) in large-scale models of marine biogeochemistry is typically parameterized using prescribed functions of an idealised particle's settling velocity and decay rate. Here, we investigate the impact of different representations of sinking (remineralisation) on sedimentation profiles, in an idealised water column model. We additionally investigate the effect of a spectral surface particle size spectrum on deep sedimentation, and, conversely, the potential effect of sinking on deep particle size spectra. According to our analysis, spatio-temporal variations in the surface size-distribution of POM may explain regional variations in remineralisation length scales. While simulated sedimentation fluxes are difficult to constrain directly, on long time scales the parameterisation of sedimentation, in conjunction with transport by ocean circulation, will impact the simulated nutrient and oxygen fields. We examine the effect of various export and sedimentation parameterisations on long-term global nutrient and oxygen fields by comparing observed tracer distributions to output from different biogeochemical models coupled to a global offline tracer-transport model.

The Impact of Remineralization Depth on the Air-Sea Carbon Balance

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A big challenge in the ocean biogeochemistry modeling community is the high cost associated with spinning up 3D global models to equilibrium. This challenge is especially pronounced when water column remineralization processes are changed because deep waters take thousands of years to come to equilibrium. Thus systematic sensitivity analyses of 3D models to remineralization parameterizations have been limited in scope and depth, and the impact of remineralization depth on nutrients and carbon distributions is poorly known. We use a time-efficient 3D global ocean biogeochemistry model to carry out a sensitivity analysis of air-sea carbon exchange to remineralization depth. We show that remineralization depth plays an important role in air-sea carbon exchange. For example a small increase in the e-folding depth (the depth by which 63% of organic matter exported from the surface has become remineralized) from 204 m to 228 m results in decreasing atmospheric pCO2 by 10-27 ppm. The carbon uptake is due to a transport of respired carbon from relatively well-ventilated waters to poorly ventilated waters. Associated alkalinity change also contributes significantly to the carbon uptake. Our study suggests that the effects of climate change on remineralization depth may have significant feedbacks on the rising pCO2 in the atmosphere.

A Brief Review of Recent Advances in Twilight Zone Sinking Particle Collection

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The development of several instruments designed to more reliably collect sinking particles and describe their size distributions/sinking velocities has offered a chance to test our understanding of the oceanic biological pump with new tools. In a number of recent field programs, these devices have been deployed in several contrasting ocean regimes with a special focus on the Twilight Zone, that part of the water column where the majority of particle flux attenuation occurs. In this presentation, we will review some of these recent advances, drawing heavily on the results from the VERTIGO, MEDFLUX, PELAGRA and TZEX studies, and contrast them with established and on-going programs that use/d drifting sediment traps as the primary collection system (e.g., JGOFS, HOT, BATS). We will place special emphasis on the examination of: neutrally buoyant sediment traps and the issue of trap under-/over-collection; inherent scales of flux variability in space and time; blank correction and the preservation of trap material; in-situ measurement of sinking velocity and respiration; accurate determination of trace element fluxes on short timescales; and dispatches from the front lines of the war on “swimmers.”

Spectral Fluorescence Approaches to Characterizing Phytoplankton Community Composition: Towards Continuous In Situ Observations of “Sinkers and Floaters”

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The size and taxonomic composition of marine phytoplankton communities determine rates of recycling and export of phytoplankton-derived carbon from the surface ocean. Size and functional group-based models of carbon export require information on phytoplankton community composition, but direct measurements require oceanographic cruises and provide only sporadic coverage. Ocean observing systems often characterize temporal variability in phytoplankton biomass with a chl a fluorometer, but provide no information on taxonomic composition. Spectral fluorometers, however, which use multiple excitation wavelengths targeted at specific photosynthetic pigments, provide information on both taxonomic composition and phytoplankton biomass and can be used for continuous monitoring. We investigated the predictive capabilities of one commercially-available spectral fluorometer, the Algae Online Analyzer (AOA; bbe Moldaenke, Germany) in both discrete sampling mode with natural phytoplankton communities and in continuous monitoring mode by installing it on a ferry that traverses an estuary several times daily. The AOA did a relatively good job of predicting phytoplankton community composition, but estimates of total phytoplankton biomass were ~ 1.2-3.4x higher than direct determinations of chl a by HPLC. The extent of the over-estimate varied but the sign of the inaccuracy was consistent between samplings and was related to diel variations in the ratio of fluorescence to chl a, used as a conversion factor.

The Role of Calcite in Enhancing the Flux of Particulate Organic Carbon Into the Deep Ocean. CalMarO project RT12

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The incorporation of biominerals such as calcite into carbon aggregates, might play a key role in carbon export by ballasting particulate organic carbon (POC) to ocean interior. A paucity of data from the upper ocean means that the mechanisms leading to export are poorly understood. This supposed "ballast effect" might be impacted by ocean acidification and thereby has feedbacks on the biological carbon pump efficiency. This issue will be addressed by a combination of fieldwork using radionuclides (234Th and 210Pb) to estimate POC and biominerals export. Experimental work using roller tank incubations, and modelling techniques using the Ocean Global Circulation Model coupled with biogeochemical parameters (HAMOCC) to simulate carbon export in future high CO2 world following IPCC scenario. This project is in the framework of the Marie Curie fellowship CalMarO (2009-2012). Preliminary results of 234Th/238U disequilibria during the D341 cruise (July-August 09) on board the RRS Discovery at the Porcupine Abyssal Plain (45ºW; 16.5ºE) will be presented.

A Multi-year Increase in Shallow POC Export is Countered by Enhanced Mesopelagic POC Attenuation in the Sargasso Sea

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Regional variability in the attenuation of particulate organic carbon (POC) flux with depth and the mechanisms controlling POC transfer efficiency have received renewed attention. We present data from the Bermuda Atlantic Time-series Study indicating a coordinated increase in the magnitude of the biological carbon pump during the winter/spring period. Integrated epipelagic chlorophyll a (Chl a), primary production, suspended POC, and 150m POC flux all increased by 30-86% from 1997 to 2007. These changes in the shallow biological carbon pump are associated with significant decreases in relative abundance of diatoms and haptophytes and increases in Synechococcus. Over the same period, remineralization of POC flux between 150-300 m doubled such that the increase in the shallow biological pump did not increase the carbon flux to the mesopelagic. The increase in remineralization may be related to changes in the importance of zooplankton carbon demand. These findings document a disconnect between the shallow biological carbon pump and mesopelagic carbon sequestration in the oligotrophic oceans mediated by changes in plankton community structure.

Seasonality of Bloom Formation in the Permanently Stratified North Pacific Subtropical Gyre

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Oligotrophic subtropical gyres are permanently stratified, low nutrient regions that are dominated by small (less than one micron) picoplankton cells. To understand how export of particulate carbon is sustained in these regions, we must consider the processes that shift the community structure from suspended, small cells to large, sinking cells. Mesoscale physical processes, such as eddies and Rossby waves are thought to be partially responsible for promoting dense blooms through fine-scale upwelling of nutrient-rich deep water. However, observing the biogeochemical response of autotrophic communities to these physical features is difficult as they are stochastic in space and time. A series of 11 experiments were performed in the North Pacific subtropical gyre over a two-year period to study the physiological and community response of autotrophs to the addition of deep nutrient-rich seawater. There were two distinct responses; a slow-low response during autumn/winter experiments and a rapid-high response during spring/summer experiments. Complete nutrient drawdown, dramatic increases in biomass and primary production, and a shift in community structure to large diatoms were only observed during spring/summer cruises. Such a seasonal response was surprising given that these regions are permanently nutrient impoverished and the initial autotrophic biomass, rates of primary production and community structure was statistically similar. These findings imply that there are other processes, such as light and mixed layer depth, causing growth or suppression of blooms of large celled autotrophs in these regions. Indeed, the seasonal response of autotrophs to nutrient addition has implications regarding the importance of mesoscale physical features in driving export production in these vast permanently stratified regions.

Thorium-234 Excess and Particle Remineralisation Below the Euphotic Zone

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Thorium-234 deficits with respect to Uranium-234 are commonly used to study biogenic particle export from the surface ocean. Thorium-234 excesses with respect to Uranium-238 are also sometimes observed and explained as a result of particle remineralisation. Extensive Thorium-234 datasets were recently collected during the EDDIES (Sargasso Sea), VERTIGO (NW Pacific Ocean) and EFLUX (Hawaii) research programs, spanning a range in primary production and hydrography. High resolution vertical profiles from these programs show narrow layers (20–30 m) of excess Thorium-234 below the deep chlorophyll maximum at each of these sites, which would have been missed with standard sampling for Thorium-234 and/or with sediment traps. These excess Thorium-234 layers, presumably associated with particle remineralization, result in decreases in net flux with depth and are observed at depths of 100-200 m (also ~300m) for EDDIES, 80-100 m at K2 during VERTIGO and 100-130 m for EFLUX. At this depth below the euphotic zone, particle production has stopped, yet these excess Thorium-234 layers indicate that particle remineralization has occurred and particle fluxes with depth have decreased, likely due to consumption of labile sinking material by bacteria and/or zooplankton. Here, we reexamine these Thorium-234 excess remineralisation peaks in light of other available data, including physical surroundings (e.g. temperature), phytoplankton and bacterial community structure, zooplankton grazing, and particle composition (e.g. ballast hypothesis, dust input), in order to understand the processes that might control the ultimate fate of organic carbon exported below the euphotic zone.

The Morphometrics of Pennate Diatom Frustules in the Sediments are Potential Indicators of Iron-limited Growth in Past Oceans

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Diatoms are a major group of phytoplankton that account for approximately 40% of the ocean carbon fixation and the vast majority of biogenic silica production through the construction of their cell walls (termed frustules). These frustules accumulate and are partially preserved in the ocean sediments. Diatom growth and nutrient utilization in large regions of the world's oceans are regulated by iron availability. Under iron limitation, both centric and pennate forms of diatoms decrease in size. The associated increase in surface area-to-volume (SA:V) ratio may improve nutrient uptake kinetics. In parallel, cellular Si concentrations are elevated in iron-limited diatoms relative to N and C. Variations in nutritional requirements of diatoms acclimated to low-iron conditions have been hypothesized to account for higher cellular Si or lower cellular N and C. Changes in the Si-containing valve surface area relative to volume in some diatoms may also account for variations in the cellular Si:N and Si:C ratios. In particular, iron-limited pennate diatoms of the genus Pseudo-nitzschia have reduced widths relative to their lengths (i.e. lower length normalized widths, LNW) compared to iron-replete cells. In the pennate diatom Fragilariopsis kerguelensis, the mean LNWs of valves preserved in sediments throughout the Southern Ocean (a well-characterized iron-limited region) is positively correlated to satellite-derived, climatological net primary productivity in the overlying waters. Because of the specific morphological changes in pennate diatom frustules in response to iron availability, we propose that the physical properties (e.g. LNWs) of frustules preserved in the sediments can be a valuable paleoceanographic proxy for Fe-limited diatom growth.

Sensitivity of Atmospheric pCO2 to Changes in the Biological Pump: Does Anthropogenic CO2 Matter?

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The objective of my work is to develop a mathematical theory that explains how the ocean carbon pumps control atmospheric pCO2. I have recently (Marinov et al, 2008a and 2008b) developed a mathematical theory for the soft tissue pump, showing that under conditions of perfect equilibrium between the atmosphere and ocean, atmospheric pCO2 can be written as a sum of exponential functions of the total preformed nutrient in the ocean.

Here I will examine in detail the sensitivity of atmospheric pCO2 to changes in the soft tissue pump, using theory and simulations in the GFDL ocean general circulation model. I will show that my theory predicts well the sensitivity of atmospheric pCO2 to changes in the soft-tissue pump (following large-scale nutrient depletion or imposed changes in mixing or winds) observed in the general circulation models. I will also examine through theory and models how the addition of anthropogenic carbon due to fossil-fuel emissions changes the sensitivity of atmospheric pCO2 to the biological pump.

Tracing the Biological Carbon Pump Through the Full Water Column: Insights From the Porcupine Abyssal Plain Site

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The Porcupine Abyssal Plain site (49N 16.5W) in the North Atlantic is one of few places where the flux of organic material from the surface to the sea floor has been intensively studied across the full water column. A synthesis is presented comprising time-series and process studies, moorings and meso-scale survey, spanning 17 years (1989-2006). A complex picture is revealed. Seasonal cycles and stirring of different water masses drive strong variability in surface production and community composition, both strong drivers of export flux. Deep sediment traps also display considerable seasonal and inter-annual variability. However, no simple relation is found between the surface and abyssal fluxes. Nevertheless, a demonstrated dependence of abyssal fauna on specific surface plankton pigments gives hope that a mechanistic connection between surface and deep fluxes – the ‘input’ and ‘output’ of the biological carbon pump - may yet be established.

Export Pulses During Sedimentation of the North Atlantic Spring Bloom

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High latitude diatom blooms contribute significantly to sequestration of particulate organic matter (POM) below the winter mixed layer. Studying the sedimentation process of blooms therefore contributes to understanding controls on an important component of the biological carbon pump. We present measurements of POM flux taken in the mesopelagic with neutrally-buoyant sediment traps (PELAGRA) during the North Atlantic spring bloom. Fluxes rose from initially 10-30 mg POC m-2 d-1 to 150 mg m-2 d-1 as predominantly Chaetoceros sp. resting spores were caught. Flux thereafter diminished to 100 mg POC m-2 d-1. The change in flux over time, and the elemental composition of fluxes, imply that distinct pulses of material were caught during each trap deployment. 234Th disequilibria suggest that shallow export flux during the cruise totalled 2.4±1.4 g C m-2, or ~10% of likely annual export, implying significant export after our study. The timing of the trap catches and of the 234Th depletion implies that the main pulse of diatom detritus sank at a rate of ~100 m d-1. We conclude that spring bloom sedimentation proceeds as distinct pulses of material, which differ in their chemical composition and pass relatively rapidly through the mesopelagic.

Developing PELAGRA: Advances in the Use of A Neutrally-Buoyant Sediment Trap

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Neutrally-buoyant sediment traps (NBST) are a recent and significant technological advance for studying the mesopelagic, but only two different models exist. One of these is PELAGRA (Particle Export measurement using a LAGRAngian trap), an NBST developed in Southampton. We present the PELAGRA design, the scientific insights we have learned from PELAGRA deployments so far and how these have shaped deployment strategy. PELAGRA has been improved over time: all traps are now isopycnal and equipped with an opening/closing mechanism for the collection cups. Recent deployment successes show that we can ballast PELAGRA accurately to target density surfaces without over- or under-ballasting. PELAGRA has shown that selective export of only particular phytoplankton species may occur, that particle flux during post-bloom conditions in the Northeast Atlantic may be very rapidly attenuated with depth, and that particle export out of a diatom bloom may proceed as a series of distinct pulses. The latter observation motivated the largely successful attempt to continuously collect particle flux out of the Lohafex iron fertilised patch over five weeks by deploying traps in a staggered sequence for up to six days per trap. Thus significant advances have been made in NBST technology and deployment strategy.

Relating Stocks and Sinking Fluxes of Particles in the Mesopelagic Zone: Case Studies from the Subtropical North Atlantic and the West Antarctic Peninsula

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We utilize a new combination of sampling techniques and analysis to study the flux of carbon through the mesopelagic zone at two very different ocean biogeochemical locations: the Bermuda Atlantic Time-series Site (BATS) in the subtropical North Atlantic Ocean, as well as the West Antarctic Peninsula (WAP) region of the Southern Ocean. These techniques include in situ imaging of particles with the Video Plankton Recorder (VPR) and the collection of sinking particulate matter in viscous polyacrylamide gels and cylindrical sediment traps. Images from the VPR were analyzed to determine the particle size distribution of suspended and sinking particles throughout the water column. Additionally, the size distributions of sinking particle fluxes were determined through photography and image analysis of particles collected in the polyacrylamide gels. These particle size spectra are then compared to each other in order to calculate the average size-specific sinking velocities of particles at different depths in the water column. We find that flux at the BATS site decreases with depth and that the sinking material intercepted in the traps consists of a wide variety of small particles and aggregates. By contrast, sediment trap measurements along the WAP indicate that there is very little attenuation of flux with respect to depth through the mesopelagic zone, and that the high fluxes in this region are primarily a result of large quantities of quickly-sinking krill fecal pellets and diatom aggregates. Our results elucidate key differences between the nature and dynamics of sinking carbon fluxes through the mesopelagic zone at these globally relevant sites.

Quantifying Past Aarbon Export and Burial in the Southern Ocean

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Biogenic barite (Ba-xs) accumulation in oxic sediments has become a widely used proxy for the strength of the past biological carbon pump (BCP). The fidelity of this proxy is assessed in a region of natural iron fertilization within the Southern Ocean and compared with the behaviour of this proxy in an adjacent high-nutrient, low-chlorophyll (HNLC) region. Upper water column particles are compared with satellite derived chlorphyll timeseries, deep sediment trap deployments and core top sediment accumulation. Carbon and biogenic barite are decoupled in the sinking particles (>53 micron) and Th-234 derived fluxes demonstrate that Ba-xs export is offset from primary production and major carbon export events. The annual variability in carbon and Ba-xs export is evaluated in deep traps to further constrain the timing of Ba-xs sinking relative to the major components of the BCP. Th-230 normalised Ba-xs preserved vertical fluxes are higher in sediments from the site of natural iron fertilisation compared with the HNLC site. The impact of iron

fertilisation on the strength of the BCP implied by the Ba-xs proxy is compared with multiproxy (organic carbon, compound specific carbon isotope, biomarker, 231Pa/230Th, opal and carbon fluxes inferred from microelectrode oxygen profiles of intact sediment cores) evidence from the sediment in this region. Ba-xs fluxes provide a qualitative record of past carbon export in the Southern Ocean but quantitative reconstructions require a detailed understanding of the complex and interlinked controls on proxy records that are only now emerging from integrated process studies of the BCP.

Biologically Mediated Carbon Export in Different Trophic Environments in the South-East Pacific

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The vast South-East Pacific ocean includes contrasting physical and trophic environments. These range from the hyperoligotrophic waters of the central gyre, the bluest waters of the world ocean, with a euphotic zone 160 m deep and an integrated primary production of ~170 mg C m-2 d-1, to the mesotrophic waters near the Marquesas Archipelago and the eutrophic waters off the South-American coast. In the latter two, the euphotic zone is approximately 70 and 35 meters deep, respectively, and the primary production ranges from 0.7 to >4 g C m-2 d-1. The composition of the phytoplankton community at these various sites is also very different. Particulate organic carbon produced by the biological community and exported as sinking material ranges from 1 mg POC m-2 d-1 in the central gyre to 17 mg POC m-2 d-1 in the Marquesas and 62 mg POC m-2 d-1 in the upwelling area off Chile. The e-ratios, the fraction of carbon produced in the upper waters that is sinking below the euphotic layer, ranges from <0.01 to 0.05. This relatively large range in ratios highlights the large difference in carbon production and export regimes in this part of the ocean. The data reported was obtained in the period October-December as part of the BIOSOPE program.

Molecular Time Series of Phytoplankton Export From the Upper Water Column at the Bermuda Atlantic Time-Series Station (BATS)

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The biological carbon pump in subtropical gyre regions plays an important role in the global carbon cycle, but little is known about the contribution of specific taxa to the downward flux. Recently, small pico- and nanoplankton have been identified as important players in export flux, but this is difficult to test experimentally. We are now able to use molecular techniques to identify specific taxonomic groups not only from the water column, but also from DNA isolated from trap material. Here we present first results from an ongoing study investigating the phytoplankton community in the upper water column and from corresponding 150 m particle traps at the Bermuda Atlantic Time-Series Station (BATS). Small subunit ribosomal DNA sequences were amplified from each sample using either universal eukaryotic (18S rDNA) or cyanobacterial (16S rDNA) primers.

Denaturing gradient gel electrophoresis (DGGE) was then used as a tool to assess the contributions of different taxonomic groups to particle flux and to monitor changes in these patterns over time.

Interactions Between Large Scale Circulation and Iron Supply to the Atlantic Ocean: Implications for Nitrogen Fixation and the Biological Carbon Pump

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The balance between nitrogen loses due to denitrfication and nitrogen inputs, principally resulting from biological N_2 fixation, is crucial for the long term maintenance of oceanic production and the biological carbon pump. However uncertainties remain concerning the spatial and hence temporal scales over which these two biologically mediated processes are coupled in the modern ocean. Upper water column data from cruises in the Atlantic Ocean are presented which strongly suggest proximal control of diazotrophy by iron rather than excess phosphorous availability. Moreover, subsequent analysis of large scale nutrient transports reveals an important role for interactions between the large scale overturning circulation and the spatial distribution of aeolian iron input as a control on nitrogen and phosphorous coupling. Specifically, northward transport of the thermocline and intermediate waters forming the upper limb of the Atlantic Meridional Overturning Circulation (AMOC) appears to supply the excess phosphorus required to support observed high rates of nitrogen fixation in the (sub-)tropical North Atlantic. In addition, the majority of the resulting fixed N input appears to enter the deep oceanic circulation within North Atlantic Deep Water. Consequently the global deep ocean nitrogen inventory and hence a proportion of the biological component of air-sea CO_2 partitioning, appears to be sensitive to interactions between large scale circulation and dust deposition patterns in the Atlantic.

Marine Food Chain Possibly Attributed to Petroleum Deposits

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Petroleum production out of offshore petroleum deposits is often coincided with abundant fisheries in the world. The coincidence is tried to be proved by superposition of marine microorganism concentration distribution and offshore petroleum field distribution from published various data. Tokyo Bay, Sakhalin Island coastal regions, North Sea, Gulf of Mexico, etc. are chosen for the superposition. Significant conformity is observed between the plankton concentration distribution and the offshore petroleum deposit distribution in all those regions. Also, most of studies reported on the consequence of oil spills to marine echo-system are mostly focused on hazardous marine pollution caused by high concentration of spilled petroleum into marine environment. However, some of those data clearly indicates stimulation of plankton population at properly low concentration level of dissolved hydrocarbons and dissolved petroleum compositions. Further, increase of hydrocarbon concentration leads to its inhibition from its stimulation conditions across over a critical concentration level; a plankton-stimulation/inhibition threshold concentration (SITC) of hydrocarbons. The SITC is varied depending on hydrocarbon compounds, petroleum compositions, and microorganisms such as planktons. Further, petroleum composition diffusing through subterranean layers from petroleum deposits reacts with dissolved oxygen at ocean floor to precipitate the hydrocarbons to give agglomerate suspension, leaving the sea water in oxygen depletion on the ocean floor. Such incidents are also briefly discussed.

Si-OC Interactions in Diatoms and Their Impact on Diatom Degradation

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In situ observations have shown relationships between ballasts and carbon sedimentation fluxes. Regarding the importance of diatoms in many sites of the Global Ocean, the relationship between bSiO2 and carbon could be due to the fact that diatom frustule protects associated organic matter from degradation (Hedges et al., 2001). We tested this hypothesis using a laboratory experiment on the diatom Skeletonema marinoi by following the degradation of different pool of carbon relative to the dissolution of the frustule. Using a set of models we started to elucidate mechanisms driving bSiO2 dissolution and organic carbon degradation. Results suggest that the diatom frustule which is made up of two bSiO2 phases partially protected the carbon from degradation. The more reactive phase is mainly associated with membrane lipids and the amino acids glutamic acid, tyrosine, and leucine. A second phase was more refractory and contained more neutral lipid alcohols and glycine. Enclosed between these phases, a pool of amino acids probably originating from the silicification processes was trapped. The first bSiO2 phase protected the second bSiO2 phase and much of the organic matter from degradation: POC, PON and the total pool of amino acids. In contrast, most lipids were associated to, rather than protected by, silica. Interestingly FTIR (Fourier Transformed. InfraRed spectroscopy) of S. marinoi confirms the close relationship between amino acids and bSiO2. Moreover these new results showed that the structure of the refractory bSiO2 phase mainly associated to secondary amides is more stable under variable growing conditions than the more reactive phase.

Assessing the Influence of Biominerals, Calcite and Opal, on the Euphotic Zone Export of Particulate Organic Carbon

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The downward flux of particulate matter from the euphotic zone to the oceans interior is an important component of the global carbon cycle. In the deep ocean, statistically significant correlations exist between the downward fluxes of particulate organic carbon

(POC) and the biominerals calcite and opal. Therefore, the transfer efficiency, which is defined as the ratio between export at a given depth and export production out of the euphotic zone, is said to be higher for POC that is export in association with calcite and opal, with calcite predominating over opal. This suggests that the export of POC is potentially coupled to the export of biominerals and is known as the ballast hypothesis. In the upper ocean, a paucity of data prevents us from determining the potential role of biominerals in an analogous manner. Using 234Th deficits we measured the export of POC, calcite and opal at two depths and at ten stations in the Iceland Basin during summer 2007, as part of the D321 cruise on RSS Discovery. These data will be used to assess the impact of ballasting minerals on the downward transfer efficiency of POC.

Satellite Retrieval of Phytoplankton Community Size Structure in the Global Ocean

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Phytoplankton cell size is important to biogeochemical and food web processes and can be optically differentiated. The feasibility of retrieving phytoplankton community structure was investigated by isolating the effect phytoplankton cell size had on varying spectral remote sensing reflectance in the presence of other optically active constituents. This was achieved through the use of optical and radiative transfer models that were linked in an off-line diagnostic calculation to monthly output of a global biogeochemical/ecosystem/circulation model. This revealed important implications on when and where the satellite standard algorithms will overestimate/underestimate chlorophyll concentration due to remote sensing reflectance being significantly affected by phytoplankton size. Global monthly maps of phytoplankton size structure for the first ten years of the SeaWiFS mission (September 1997 - August 2007) were retrieved from satellite imagery of remote sensing reflectance. The spatial and temporal patterns of phytoplankton size structure that emerged agreed well with in situ observations. Spatial and temporal patterns of phytoplankton size structure in relation to chlorophyll concentration were investigated and revealed there were scales at which these parameters were not directly linked. These results point to the importance of considering phytoplankton cell size in investigations of primary production, biogeochemistry, carbon flux and cycling.

Biological Carbon Pump Comparisons Across a Subtropical Gyre: What Have We Learned?

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The western and eastern Atlantic subtropical gyres have similar rates of primary production, but earlier work has shown that the biological carbon pump differs between the two provinces. Export production at Bermuda is consistently higher compared to the eastern subtropical time series station ESTOC, derived both from moored and drifting trap data. Higher new nutrient input observed at Bermuda compared to the eastern subtropical gyre might explain part of the difference in export production but alone is insufficient. Here we show that significant differences in rain ratios indicate differences in the plankton community sinking into the traps in winter, and we hypothesize that non-calcifying plankton contribute more dominantly to export production at Bermuda compared to ESTOC during that season. Pulsed production events resulting in labile organic matter sinking out of the euphotic zone might explain both the higher export production as well as flux attenuation found at Bermuda.

The Impact of Natural Fe Fertilisation to the Scotia Sea

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Despite the general high-nutrient low-chlorophyll status of the Southern Ocean several regions are characterised by large seasonal phytoplankton blooms. Most notably these productivity features occur in proximity to island systems due to an enhanced supply of dissolved iron; e.g. northwest of South Georgia, north of Crozet Islands and over the Kerguelen plateau. Understanding the biogeochemical controls on the development and duration of these blooms represents an important constraint on the potential strength and efficiency of the biological carbon pump in the Southern Ocean. The South Georgia bloom is the largest and longest lived phytoplankton bloom in the Southern Ocean with surface chlorophyll concentrations that can reach up to 7 mg m-3. During this study we attempted to elucidate the seasonal dynamics of dissolved iron supply to the South Georgia bloom area. Dissolved iron concentrations were similar during spring and summer conditions despite evidence of considerable production and macronutrient utilisation. As such our results indicate that continual horizontal transfer of iron from the island system can explain the longevity and areal extent of the South Georgia bloom. In addition iron/light bioassay experiments were carried out close to the South Georgia and South Orkney Island systems to assess the response of phytoplankton communities. The phytoplankton response north of South Georgia was dominated by large diatoms compared to cryptophytes north of South Orkney. Overall our results highlight that the biogeochemical dynamics of Southern Ocean island systems can vary greatly with important implications for the biological carbon pump.

A New Record of Particle Flux at the Bermuda Atlantic Time-Series Site From Neutrally Buoyant Sediment Traps

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Beginning in June 2007, monthly time-series measurements of particle flux at the Bermuda Atlantic Time-series (BATS) Site were made using a pair of neutrally buoyant sediment traps (NBSTs). These traps were deployed at 150 m, concurrent with particle interceptor traps (PITS) used in the monthly BATS sampling regime. The aim of this work was to achieve a baseline measurement of particle flux at this site, representing the first long-term sampling program using these non-traditional sediment traps, and to establish meaningful links between biological community structure and export flux at BATS. The results revealed a pattern of particle export consistent with the seasonal plankton community succession. High flux followed spring and fall blooms while low flux was measured during the winter months. The long-term nature of this study allowed for examination and comparison of collection, processing, and analytical methods for particle flux sampling. Early measurements in the summer of 2007 revealed lower collection of material by the NBSTs relative to the PITS; a detailed inter-comparison study of flux collectors and analyses was carried out in the summer of 2008 in an attempt to account for these discrepancies. The results of this work have implications for design of future sediment trap programs and contribute to our understanding of biogeochemical cycling at BATS.

Up or Down: The Biological Pump and Global Change

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Scientists are asked to assess consequences of global change to the biological carbon pump of the ocean, although they are currently unable to even predict if the biological pump of the future will be strengthened or weakened. Increased temperature appears to increase the ratio of ecosystem respiration to autotrophic production, suggesting a weakening. A weakening of the pump has also been predicted from the expected reduction in the production of calcium carbonate due to increased CO2 and the resulting scarcity of calcium carbonate deemed necessary for rapid sedimentation. However, observations of increased production of transparent exopolymer particles (TEP) and increased loss of organic carbon from the surface layer at elevated atmospheric CO2 led to the hypothesis that the biological pump will be strengthened. Results of a set of experiments investigating the effect of ocean acidification on aggregation and sinking suggested a different explanation, postulating a decrease in downward flux due to an accumulation of the additional TEP at the sea surface micro layer. Decreased polarity of organic matter impacted TEP formation and aggregation, with severe consequences for sedimentation, implying a weakening of the pump.

A Global Determination of Marine Stoichiometric Remineralization Ratios

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We investigate the spatial variability of macronutrient remineralization ratios in the ocean by using the tool of water mass analysis together with a global non-linear optimization algorithm. We invert a mixing model with a simulated annealing scheme applied to the GLODAP data set to solve for the remineralization stoichiometry after correcting the dissolved inorganic carbon concentrations for anthropogenic contamination. The magnitudes of our stoichiometric ratios are consistent overall with previously reported values but the uncertainty around each determination is large. Much of this uncertainty is driven by the uncertainty in the definition of the preformed quantities. Preformed values remain poorly defined as water mass formation regions are not well known and these formations locations are in data poor regions. Our results are internally more consistent in the Pacific and Indian than in the Atlantic. This is reflective of the hydrographic complexity of these basins. In shallower layers, the uncertainty envelope also incorporates true variability but the exact fractionation between preformed uncertainty and true variability has not yet been assessed. While we observe positive deviation from the Redfield values in the Mode and Intermediate waters and spatial variability of the remineralization ratios exist between hydrographic basins, the uncertainty envelope does not allow us to unequivocally interpret these features as true signals. Anomalies tend to be associated with known hydrographic features, suggesting that they more likely arise from errors in our determination of the preformed component and should in general not be interpreted as true manifestations of variability in the remineralization process. Oxygen minimum zones also show deviations from Redfield. This is expected since only oxygen minimum zones are capable of altering respiration metabolic pathways and so have a large-scale impact on the dissolved nutrients. Unfortunately, at this point our results are still too noisy to establish spatial variability and so assess the role of food source composition on the remineralization signal.

234Th, POC and PON Fluxes Along a Transect From Cape Basin to the Northern Weddell Gyre (BONUS-GOODHOPE)

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Understanding the fate of biogenic material from surface layer to mesopelagic zone is necessary to better estimate the efficiency of the biological carbon pump and the oceanic CO2 sequestration capacity. Using the short-lived radiogenic nuclide 234Th, POC and PON export fluxes were assessed along the BONUS-GOODHOPE transect (Feb-March 2008, R/V Marion Dufresne) from the South-Atlantic subtropical domain (40°S) till the eastern extension of the Weddell Gyre (58°S) crossing the Subtropical Front, the Subantarctic Front, the Polar Front, the Southern ACC Front and the Southern ACC Boundary. Total 234Th activity was determined by beta-counting on board (RISO beta counters) from 4L 230Th-spiked seawater, sampled at 11 stations from the surface to 1000 m deep. Size-fractionated particulate 234Th was obtained using large volume in-situ pumps deployed at 5 stations along the whole water column. For the two size classes (1< <51µm; >51 µm) of particulate matter, beta-activity were determined on board. POC, PON concentrations and isotopic compositions were determined by EA-IRMS. Strongest 234Th-deficits occur in Cape Basin subsurface waters (80 to 100m) north of the Subtropical Front. Between the SAF and the Southern Boundary also significant 234Th-depletions appear,

confined to the upper mixed layer. The density gradient marking the bottom of the mixed layer marks the transition to 234Th-enriched waters (150-600m depth) suggesting mesopelagic remineralisation of sinking particles. Estimates of 234Th fluxes performed using a steady state one box model were converted into POC and PON fluxes using 234Th/POC and 234Th/PON ratios of sinking particles. Zonal and depth variability of POC and PON fluxes from the Cape Basin to the northern Weddell Gyre will be discussed.

Trace Metal Distributions and Effects in one of the Most Productive Antarctic Polynyas: the Amundsen Sea

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The Amundsen Sea, West Antarctica, includes one of the most productive polynyas of the Southern Ocean, where summer primary production can reach up to 3 g C m-2 d-1 . Despite the unusually high productivity of this region, its remoteness has meant that no systematic study of the biogeochemistry has yet been conducted. This is of particular interest now as the polynya is bordered by glaciers that are accelerating faster than any in Antarctica as a presumed result of recent climate change. This presentation will discuss findings from the US-Swedish Oden 2007 cruise during which 23 stations were sampled in open water and ice covered regions of the Amundsen Sea, both on and off the shelf. Stations were also occupied in the Ross Sea, and the resulting data are also presented as a way of comparison. Size fractionated particles (0.45-5.0µm and >5.0µm) and filtered seawater were collected for trace element analysis. While analyses were carried out for a broad suite of elements, the distribution of Fe in its various potentially bioavailable forms was an important target. Particulate Fe concentrations in the euphotic zone ranged from 10-20 pM in open ACC waters off the shelf to about 20,000 pM near the Getz ice shelf, suggesting an important continental and/or ice shelf Fe source. Here the various sources of Fe and its bioavailable forms that can fuel the very high productivity seen in the polynya are investigated by looking at inter-element relationships and dissolved Mn data. Finally, the recycling of particulate trace metals and their effect on the C removal from the euphotic zone is assessed using trace metals to C ratios in different productivity areas.

The Possible Contribution of Higher Trophic Levels to the Biological Pump

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In a recent study (Ragueneau et al., 2009, see companion abstract), we have re-assessed the global export of POC which is suggested to be lower (2-3 Gt C y-1) than amounts required by ocean general circulation models (about 10 Gt C y-1). Reconciling these estimates implies that more carbon must be transported to the deep in a form that is not POC, or not POC caught by sediment traps or accounted in in classical models. Here, we use a simple box model of the ocean (based on Tyrrell, Nature, 1999) in which a simple parameterisation of higher trophic levels is included to provide first estimates of the possible contribution of higher trophic levels to the biological pump. The mass balance of each trophic level is governed by four main processes, i.e. ingestion, feces production, excretion and natural mortality. Model parameters are constrained using standard allometric relationships. This model is subsequently used to estimate the possible contribution of higher trophic levels to the export of organic matter towards the deep ocean. A sensitivity analysis is also performed to estimate the robustness of model outputs. Preliminary results suggest that higher trophic levels, i.e. organisms larger than mesozooplankton, may contribute to 10-40% of the export of nitrogen and phosphorus below 200 m. These preliminary models outputs are discussed and criticised with regards to current estimates of the contribution of higher trophic levels to export.

Coccolithophores and the Efficiency of the Biological Carbon Pump

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Coccolithophores, one of the major calcite (Cinorg) producers in the modern ocean, have dual roles in the Biological Carbon Pump (BCP): as calcifiers they remove alkalinity causing CO2 outgassing which decreases BCP efficiency; while their organic carbon production (pCorg) and calcite-ballasting of organic carbon export increase BCP efficiency by promoting CO2 ingassing. Clearly, the balance of Cinorg:Corg production and calcite ballasting ('rain ratio') control the overall impact that coccolithophores have on the BCP. In this talk we will examine the ratio of Cinorg:Corg from the individual cell to the community and sinking particle, the possible factors controlling these ratios and highlight future work to clarify the role of coccolithophores in BCP efficiency.

A Low Global POC Export Controlled by Seasonality

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The most recent estimates of the carbon flux to the deep ocean are in the range of ~7-15 Gt C yr-1. There is no consensus on the mechanisms controlling the efficiency of the oceanic biological pump. Here, we combine a meta-analysis of regional budgets of carbon and silica fluxes(Ragueneau et al., 2002) along with in vitro diatom-silica dissolution experiments (Moriceau et al., 2007a) and mechanistic modelling of bSiO2 downward fluxes(Moriceau et al., 2007b), to (1) better understand the mechanisms controlling the spatial and temporal variations of the biological pump and (2) reassess at global scale, the magnitude of the biological pump in the form of POC in today's ocean.

On an annual basis, the efficiency of the biological pump, measured by the export ratio, is shown to be much lower (range 0.01 – 0.10) than estimated from models or other algorithms. A highly significant correlation is found between the export ratio and a combination of the seasonality index (Berger and Wefer, 1990), primary production and the depth of the winter mixed layer. This relationship demonstrates that the efficiency increases with increasing seasonality but decreases with increasing primary production and depth of the winter wind mixed layer (WML).

This relationship is used to reconstruct the POC downward flux at the base of the WML in the 50 biogeochemical provinces defined by Longhurst et al. (1995), for which data on seasonality, mixed layer and primary production can be compiled. Results of this meta-analysis yield a global export of 2.3 Gt C yr-1, i.e. much lower than the range cited above. At global scale, the e-ratio is close to 5%.

Although these results may appear counterintuitive or even contradictory with other approaches, especially from global models, I will show that they are rather complementary and open new perspectives for further research. That the efficiency depends strongly upon seasonality implies that we understand better the mechanisms leading to bloom termination and the formation of large, rapidly sinking particles. The fate of these large particles within the mesopelagic needs to be explored as well (see abstract by Moriceau et al.) if we are to understand the mechanisms leading to carbon sequestration below the WML. Finally, a low global export near 2-3 Gt POC y-1 when global models need about 10 Gt C y-1, implies that carbon is being transferred to the deep by other means than only POC particles that can be caught in sediment traps. Other contributions through DOM, zooplankton excretion and vertical migration, the auxiliary biological pump from continental margins, or the contribution of the larger trophic levels, are poorly quantified; they need to be assessed (see abstract by Pondaven et al. for first estimates of higher trophic levels) as they may hold some key answer concerning the discrepancy between carbon flux and bacterial demand in the deep.

Food Web Dynamics and Carbon Fluxes from the Surface Ocean: Primary Producers and Their Protozoan Predators

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My talk will focus on the role of primary producers in food webs and how the size and taxonomic structure of phytoplankton communities influence trophic interactions and carbon export from the surface ocean. I will highlight current challenges in estimating phytoplankton size- and group-specific primary production and its consumption by microzooplankton grazers. I will also address how assumptions about food web model structure affect our predictions of contributors to export fluxes.

Vertical and Horizontal Carbon Transport through the Ontogenetic Vertical Migration of Copepods

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The ontogenetic vertical migration (OVM) of copepods is an effective carbon transport mechanism to the ocean twilight zone. The copepods accumulated carbon in the epipelagic zone and actively transport to mesopelagic inhabiting depth without the “vertical attenuation” observed in sinking particle flux. The inhabiting depth in the mesopelagic zone is different even between sibling species in same genera as well as the timing of down-migration and mesopelagic inhabiting duration. Such species specific OVM characteristics determine the efficiency of the biological pump. In the subarctic North Pacific, 4 ontogenetic vertical migrating copepods (3 species of Neocalanus and Eucalanus bungii) are dominant in zooplankton assemblage, and the carbon transport to

1000 m by OVM is estimated to be 0.1 GtC y-1. It is estimated that the biomass of these copepods in each ocean domain induce the regional difference in the strength of active biological pump. The IBM model of Neocalanus copepods coupled with GCM revealed the migration depth influence not only the efficiency of biological pump but also the horizontal carbon transport. The transport paths per generation are long along the western boundary currents, and the longest path was observed for the shallowest migrator N. flemingeri reaching 5000 km. On the other hand, the transport distance was short for the deepest migrator N. cristatus. The timing of vertical migration, migration depth and life cycle of each ontogenetic migrator are not persistent. These OVM characteristics vary with physical and biological environment of the ocean domain, e.g., sea ice coverage. These results indicate that 1) the biogeography of the key species for biogeochemical cycling is essential for understanding the strength and efficiency of the biological pump, 2) the influence of regional environmental change can reach to all over the North Pacific and adjacent waters through OVM copepods, 3) natural and/or anthropogenic environmental change influences the active biological pump through impacting the OVM and life cycle of copepods.

Diagnosing Phytoplankton Uptake of Dissolved Inorganic Carbon (DIC) From Space

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The goal of this project is a global estimation of the degree to which biological processes perturb surface DIC, and affect the atmospheric sequestration of CO2. First we derive a biological dissolved inorganic carbon anomaly from data contained within the global in-water carbon dioxide database from the Oak Ridge Carbon Dioxide Information Analysis Center. From these data we select seven multi-annual time series that are contained within unique “Longhurst” Provinces for further analyses. Next we develop satellite-derived indices of phytoplankton-particulate organic carbon (POC) concentration, based on statistical distributions of chlorophyll versus POC. Within the provinces we find very good agreement between the net uptake of DIC and the net production of satellite-derived phytoplankton POC. Efforts are now underway to correct satellite-derived DIC uptake estimates for the effects of mixing, particle sinking, air-sea DIC exchange and net calcification, using satellite data and physical circulation models. Progress on these efforts will also be reported.

The Impact of Diatom Community Structure on the Biological Carbon Pump: Results From a Naturally Iron-fertilised Region of the Southern Ocean

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Phytoplankton productivity in the high-nutrient low-chlorophyll (HNLC) Southern Ocean is limited by the availability of iron. As such, changes in the supply of iron are thought to critically influence the export of organic carbon from the upper ocean and hence concentrations of atmospheric carbon dioxide. Artificial iron addition experiments have unequivocally demonstrated increased phytoplankton productivity in response to iron whilst naturally-fertilised systems indicate a concomitant increase in carbon flux. However, controls on the biological carbon pump of these systems, particularly with respect to phytoplankton ecological structure, remain poorly characterised. Our results demonstrate that the ecological structure of phytoplankton communities significantly modifies the functioning and elemental stoichiometry of the biological pump. Specifically, large diatom-species characterised by high cellular Si:C/N ratios dominated deep-ocean flux in the iron-deplete HNLC environment. In addition, microscopy and biochemical characterisation of sinking particles from iron-fertilised waters demonstrated that the enhanced carbon flux is dominated by the resting stage ecology of a single diatom species, Eucampia Antarctica. Our results suggest that the enhanced carbon flux observed in naturally fertilised systems is not entirely attributable to iron relief of open ocean diatoms. Instead we indicate that the advection of neritic diatom assemblages from island systems can significantly contribute to carbon sequestration in the deep ocean. Our findings may help to explain the large differences in C:Fe ratios deduced from natural and artificial experiments. In combination with observations of enhanced nitrate utilisation and dominance of E. antarctica in glacial sediments our results suggest a potential role for Eucampia resting stage ecology in glacial-interglacial carbon dioxide transitions. More generally our data outline the importance for future modelling and paleoceanographic studies to address the ecological adaptations of diatom communities and the potential impact this can exert on the biological carbon pump.

A New Estimate of Sinking Carbon Export From the Photic Zone

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The biological carbon pump (BCP) is a significant component of the global carbon cycle whose strength is commonly estimated locally using 15N ¬ f-ratio based estimates of new production (NP). A strong relationship exists between f-ratio and seasurface temperature (SST), this has been combined with satellite derived SST and productivity maps to estimate the global strength of the BCP. Recent results suggest that nitrification and the subduction and respiration of dissolved organic carbon (DOC) may cause particulate export estimated from f-ratios to be too high. An alternative method of estimating the local strength of the BCP is the 234Th technique which estimates the sinking of organic matter and which can be combined with productivity to estimate the efficiency of export (ThE). We have estimated ThE at the sites used in the construction of the f - ratio - SST regression discussed earlier and applied the resultant regression to a productivity map. We estimate the globally integrated sinking export of organic carbon to be about 40% lower than estimates of NP from the f-ratio ¬ SST relationship. This difference is consistent with estimates of the fraction of oxygen utilisation driven by the respiration of subducted DOC and therefore suggests that the role of nitrification in biasing estimates of new production made using the 15N technique is minor.

The Status of Modeling Water Column Remineralization

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Despite many decades of observational and modeling research, we continue to struggle with how to model water column remineralization and to be surprised by some of the results that come out of our model simulations. In this overview presentation, we summarize recent results from modeling research and observational analysis at Princeton and Kiel Universities, including new findings on the sensitivity of the atmosphere-ocean CO_2 balance to the depth of remineralization, and on the difficulty of models in properly simulating the geographic extent of suboxia. We conclude with a discussion of the possible implications of these findings for our understanding of water column remineralization processes.

Quantification of Downward Carbon Fluxes and Remineralization Rates by Assimilation of Water Column Data

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Biological production of particulate material near the ocean surface and the subsequent remineralization during sinking and after deposition on the seafloor strongly affect the distributions of oxygen, dissolved nutrients and carbon in the ocean. Dissolved carbon and nutrient distributions therefore reveal the underlying biogeochemical processes, and these data can be used to quantify the downward fluxes as well as remineralization rates using data assimilation techniques. Use of a wide variety of reactive and conservative tracers is essential to allow separation of biogeochemical processes from physics. This talk summarizes results from a large number of model runs, some of which using ocean circulation fields calibrated with global ocean radiocarbon and CFC data. Emphasis will be on integrated carbon fluxes as function of depth and remineralization rates throughout the water column.

Plankton Evolution and the Biological Carbon Pump: Moving From How Much, to Why

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The elemental composition and magnitude of the vertical flux of particles in the ocean are determined by the properties of the organisms evolving in them by natural selection. The structure and functioning of these organisms are no doubt constrained by physical factors of the environment and the chemistry of biogenic elements, i.e. physico-chemical laws, but within these bounds there is enormous scope for variation, sufficient to have fundamentally changed the physics and chemistry of the planet's surface over its evolutionary history. So to further our understanding of the

workings of the current biological pump in order to predict its future trends we need to take Dobzhansky's exhortation to heart that: "Nothing makes sense in biology except in the light of evolution." However, because of the meagre fossil record, our knowledge of evolutionary trends in the pelagial is limited compared to what is known from the land. Nevertheless an evolutionary approach, no matter how tentative, will provide the framework for formulating relevant hypotheses of how pelagic ecosystems function to produce the structures and fluxes we observe in the current ocean. Such a scheme must assemble, in a coherent framework, the life-history strategies of the dominant organisms, their interactions amongst each other and the resultant impact on the vertical flux of elements. In my talk, I provide some directions for development of this scheme.

Abyssal Ecosystems and the Biological Carbon Pump: Food Limitation, Climate Warming and Iron Fertilization

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The abyss covers 54% of the Earth's surface and may be a major locus of biodiversity and ecosystem services. Many aspects of abyssal ecosystem structure and function are likely to be strongly modulated by the quantity and quality of particulate organic carbon (POC) sinking to the seafloor, i.e., by the functioning of the "biological carbon pump." We synthesize recent studies on the biological carbon pump, abyssal biodiversity and ecosystem function. Over regional scales, abyssal biodiversity has been postulated to be driven by "slope-abyss source-sink" processes, i.e., by distance from the continental margin; in contrast, we provide data suggesting that abyssal diversity in the largest ocean basin (the Pacific) is likely to by driven by the overlying biological carbon pump. Because deep POC flux is controlled by upper-ocean biogeochemistry, climatic and anthropogenic alterations of ocean biogeochemistry will propagate rapidly to abyssal habitats. Using data from synchronous studies of POC flux and ecosystem properties, we make quantitative predictions of changes in abyssal ecosystem structure and function expected from climate change and iron fertilization. These changes are profound and must be considered in assessments of environmental impacts of global warming and iron fertilization of the oceans. Because abyssal ecosystems integrate changes in the nature of the biological carbon pump over broad space and time scales, monitoring abyssal ecosystems can provide important insights into regional alterations to the overlying carbon pump and pelagic ecosystem function.

Formation of SI-OC Interactions During Diatom Growth, Under Variable Limitations

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Interactions between carbon and silica in the diatom frustule play an important role in the degradation of the diatom carbon (Moriceau et al., 2008). In order to understand better this process and to develop a mechanistic model describing the relative fate of Si and organic matter during degradation, we first have to understand the origin of these interactions and better characterize them. We undertook laboratory experiments with an ubiquitous diatom,Skeletonema marinoi, grown under nutrient limitations that alter the relative composition of the different carbon pools as well as the composition of the frustule itself. By coupling biochemical and structural analyses, we investigated the Si-OC interactions in diatom frustules to understand how both components interact reciprocally on diatom degradation. A protocol using Fourier Transformed InfraRed (FTIR) spectroscopy was developed to qualify the Si-OC interactions and the changes in macromolecular composition in diatom cell and particularly in the frustule. To quantify these interactions, carbon and nitrogen fluxes were followed by using isotopic tracers for different fractions (lipids, proteins, and carbohydrates) obtained from the protoplast and from the frustule, following sequential biochemical extractions. First results will be presented during the conference, emphasizing the importance of phosphorus limitation.

Modeling Nitrogen Isotopes in a Global Marine Ecosystem Model: Constraints on the Coupling Between Denitrification and Nitrogen Fixation

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A new model of nitrogen isotopes incorporated into the three-dimensional ocean component of a global Earth System Climate Model suitable for multi-millennial timescale simulations is presented. The model includes prognostic tracers for the stable nitrogen isotopes, 14N and 15N, in the nitrate, phytoplankton, diazotroph, zooplankton, and detritus variables of the marine ecosystem model. Fractionation during the assimilation of nitrate into phytoplankton, denitrification and excretion are considered as well as the input of atmospheric nitrogen via nitrogen fixation. A global database of d15NO3 measurements is constructed and compared to the model results on a regional basis where sufficient observations exist. It is shown that a model version that includes simple formulations of sedimentary denitrification and iron limitation on the growth rate of diazotrophs shows a much better agreement with N* and d15NO3 observations than model versions that neglect one or both of those processes. Sedimentary denitrification in the Atlantic Ocean is found to be the primary mechanism which creates an ecological niche for enough nitrogen fixation to occur in the North Atlantic to match d15NO3 observations. Iron limitation shifts the main location of nitrogen fixation from the Eastern Tropical South Pacific to the Western North Pacific and prevents a tight coupling between denitrification and nitrogen fixation in the Eastern Pacific which occurs if iron limitation is neglected. We speculate that a multi-centennial to millennial timescale can exist before nitrogen fixation can completely balance changes in denitrification because low N* water in denitrification zones may circulate for a long time and cross different ocean basins before conditions exist to stimulate nitrogen fixation.

Fe Recycling Relative to C From Particles Leaving the Upper Ocean in the Southern Ocean

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The Fe to C ratio is a critical parameter for particles leaving the upper ocean and descending to the deeper ocean in high nutrient low chlorophyll (HNLC) zones of the ocean, as it indicates the efficiency of removal of C from the mixed layer per unit Fe present; i.e. the Fe based carbon export efficiency. More intense recycling of particulate Fe to dissolved forms in the mixed layer relative to POC would increase the efficiency of C removal to deeper waters. Here we present Fe and C flux data from the base of the mixed layer in a naturally Fe fertilized area to the North of the Crozet Islands and at adjacent true HNLC areas, that infer such preferential recycling occurs. These observations differ to those from a trap flux study in the Pacific sector of the Southern Ocean away from island systems (FeCycle). Understanding relative fluxes and recycling of Fe and C through the upper ocean is essential for the efficiency and implications of any proposed geo-engineering of carbon dioxide removal from the atmosphere via Fe fertilization to be assessed.

Biological Controls on Flux Through the Twilight Zone: What do we Know, and What do we Need to do Next?

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The mesopelagic or 'twilight' zone (base of the euphotic zone to ~ 1000 m) is a zone of significant decomposition, recycling, and repackaging of particulate and dissolved organic matter. The interplay between biological and geochemical processes in this zone has significant effects on the magnitude of the biological pump, which regulates in part atmospheric CO2 and hence can impact climate. This introductory presentation will address recent progress in our understanding of how biology affects C flux from field studies of the twilight zone, and what are some of the important gaps in our knowledge that still remain. The community structure of mesopelagic microbes is closely tied to organic matter composition, and metazoans directly affect organic matter cycling in the mesopelagic through their grazing and metabolism. There also exists a tight coupling between epipelagic and mesopelagic ecosystems via vertical migration behavior of zooplankton, nekton, and top predators. Yet much remains to be learned about linking microbial and metazoan diversity with ecosystem function and elemental cycling in this zone. Carbon inputs and respiration in the mesopelagic zone do not balance, suggesting either an overestimation of both geochemical and ecological estimates of respiration, or underestimation of POC export. While C transport by metazoan vertical migration, lateral advection of suspended POC, chemosynthesis, or comparisons on different time scales, may contribute to in part to the discrepancy, we need to improve the database of "reliable" measurements in the mesopelagic (e.g., increased sensitivity of respiration measurements). The location of future field studies may include time-series sites, places of contrast or with strong gradients, and where effects of global change are large. Spatial and temporal variability must also be considered.

Diatoms and New Production: From the Tropics to Sub-polar Waters

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Diatoms are considered to be the major planktonic driver of oceanic production, new production and export, with estimates indicating that they are responsible for around 50% of global primary production. We examine this paradigm by examining measurements of opal production (dissolved silica uptake) and the f-ratio (nitrate uptake/nitrogen uptake) in three contrasting oceanographic settings: the low-latitude subtropics, the high latitude spring bloom, and late summer in sub-polar waters. We incorporate this data with an algorithm by Henson et al (2006) which uses chlorophyll concentration data acquired by SeaWiFS and sea surface temperature data from the AMSR-E to show silicate uptake on a basin scale. Combined with Si:C uptake ratios we can predict carbon uptake and hence evaluate the role of diatoms in primary production.

Distribution of Dissolved Organic Nutrients and Their Effect on Export Production Over the North Atlantic Ocean

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Large-scale distributions of dissolved organic nitrogen (DON) and phosphorus (DOP) are mapped over the Atlantic Ocean using data from 4 meridional cruises and 2 North Atlantic zonal cruises. Dissolved organic nutrients dominate the upper 100 m of the surface ocean, contributing more than 70% of the total dissolved nutrient pools. Highest concentrations of DON and DOP in surface waters are found over the eastern side of the northern subtropical gyre and over the central part of the southern subtropical gyre . In contrast, there are lower concentrations of DON and DOP over most of the gyre interior. The effect of DON and DOP transport and cycling on export production is examined using a coupled physical and nutrient model. In the model, organic nutrients are produced in the upwelling zones along the eastern boundary and are then transported laterally into the gyre interior. The model suggests that inputs of semi-labile DON and DOP play an important role in sustaining export production, supporting up to 50% and 70% of the modelled N and P export.

Phase Lags, Sinking Rates and the Transport of Organic Carbon to the Ocean Interior

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The transport of organic carbon to the ocean interior is a race against time, with the time it takes to decay back to CO2 driven by community respiration. Fast sinking particles penetrate further into the ocean, and thus sinking rate is a key variable in the efficiency of transport. But sinking rates are poorly known, especially in the ocean interior, as are their relationships to particle forms and organic carbon contents. This talk will briefly review relationships between food-web structures and export processes, and then present 3 short studies of: i) sinking rates determined in-situ at ~300m depth, ii) sinking particle forms determined using polyacrylamide gel sediment traps, and iii) the application of stable isotopes to the characterization of food-web controls on the selective export of organic matter.

Sources and Sinks of Chlorophyll and Phytoplankton Carbon

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Satellite observed chlorophyll (chl) concentrations are analyzed in conjunction with surface velocity fields from a model to diagnose sources and sinks of chl and carbon on time scales of weeks to months. In addition to the temporal change in chl concentration, we estimate the transport of chl by surface currents so as to infer the rates of chl production/disappearance within various subregions of the Atlantic Ocean. Our results are interpreted in terms of phytoplankton carbon. We apply this analysis to the SeaWiFS and MODIS data sets to determine regional patterns and trends in phytoplankton carbon production/consumption.

Assessing Rates of Bacterial Carbon Demand in the Twilight Zone: Results From VERTIGO and Future Approaches.

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Heterotrophic bacteria play an important role in attenuating the flux of particulate organic carbon (POC) flux through the twilight zone; along with zooplankton, heterotrophic bacteria contribute to both particle disaggregation and attendant organic carbon respiration. The rates of heterotrophic bacterial processes in the twilight zone are substantially slower than in the euphotic zone, and accurately measuring these rates in the twilight zone presents numerous technical challenges. A widely-applied tactic is to bring twilight zone water samples to the surface and apply scaled-up versions of incubation-based methods originally designed for use in the euphotic zone; these methods are applied at atmospheric pressure and the effects of depressurization are assumed to be negligible. This was exactly what we did during the VERTIGO project where we measured rates of tritiated thymidine incorporation by heterotrophic bacteria. We converted these thymidine incorporation rates to rates of bacterial

carbon demand (BCD), and although this rate conversion imparts large uncertainties, we were nevertheless able to make important comparisons between BCD, zooplankton carbon demand, and the loss of sinking POC flux. We found, both in North Pacific subtropical gyre and the subarctic North Pacific, that twilight zone BCD greatly exceeded the loss of POC, suggesting either: 1) that BCD was overestimated, 2) that POC flux attenuation was underestimated, or, 3) that there were additional, large sources of organic carbon to the twilight zone. Presently, our efforts are focused on better constraining the rates of BCD. For example, enzymatic POC hydrolysis rates determined during VERTIGO are adding much needed additional bounds to the BCD dataset. We are also developing new incubation-based and in situ approaches for measuring BCD, which are showing promise for eventual application in the twilight zone.

Interannual to Decadal Variations of Export Production in the Equatorial Pacific: A Basin-Scale Modeling Study of Climate Impacts

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The equatorial Pacific plays a large role in the global carbon cycle because of its significant sea-to-air fluxes of carbon dioxide (CO2), and direct linkage to climate variability of the El Nino/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). There has been evidence of climate impacts on the equatorial Pacific physics and biogeochemistry, including ocean circulation (McPhaden and Zhang, 2002), ecosystem dynamics (Wang et al., 2005), and the carbon cycle (Feely et al., 2006; Wang et al., 2006). This modeling study presents the spatial and temporal variations of export production over the past 50 years, and demonstrates significant climate impacts on the biological carbon pump in the equatorial Pacific Ocean. Carbon export from the upper ocean is significantly stronger during the cold phase of ENSO or PDO than during the warm phase, reflecting enhanced biological activity in association with intensified upwelling under the stronger trade winds. While the ocean physics drives the basin-scale spatiotemporal variability of the carbon cycle, biological carbon export determines the strength of the equatorial Pacific CO2 source.

Principle Aspects of the Particulate Carbon Flux Through and From the Upper Layers

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Examples of vertical C export through and from the upper layers of the twilight zone are presented, mainly from sub-boreal to high arctic regions of the North Atlantic and euphotic zones ranging from 10 to about 30 m depth. Vertical flux profiles of drifting, short-term deployed and 234Th-calibarated traps are presented. Factors that regulate vertical flux export in this depth interval will be discussed, among those stratification/vertical mixing, the composition of vertical export and in particular the role of mesozooplankton. It is concluded that the strength of stratification and the dynamics of vertical mixing are essential for vertical C flux regulation. Further, only during major blooms does vertically exported phytoplankton cell C consist of large cells such as diatoms; small to very small cells dominate. In scenarios where mesozooplankton is essential, grazing can reduce vertical export to a large extent, but only a small fraction of their rapidly sinking faecal pellets contribute to vertical export from the upper layers. The retention of vertically exported C is most intense in the upper 50 m below the euphotic zone or upper mixed layers. During bloom conditions > 50 % of the export production is retained over a 30 – 50 m depth interval. The upper layers, in particular the first 50 m of the aphotic zone are of upmost significance for the biological C pump where frequently 70 % of the export production is retained by the pelagic. The regulation of vertical C export through and from the upper layers of the twilight zone appears to be a step child of biogeochemical cycle research in the ocean, but is never-the-less indispensible for understanding the C pump. The "missing link" between C fixation/production and the injection of C into the deeper layers or sediments deserves attention, i.e. combined, balanced approaches between surface ocean physical oceanographers, planktologists, vertical export specialist and C flux modelers are needed.

Topography causes wide variations in the properties of alpine snow within small areas, and a knowledge of the spatial variation of many properties is essential for the application of distributed hydrologic models and for establishing the surface boundary condition for regional climate models. However, the topography affects the electromagnetic remote sensing signal by shadowing some terrain and by modifying the angles of incidence, emission, and reflection of the signal, and our knowledge of the elevation model is usually not precise enough to allow a priori calculation of the geometric relationships between the surface, sensor, and the Sun. Hence remote sensing algorithms must be robust to such uncertainties, except in areas where topographic knowledge is especially good. The most elementary snow property is the presence or absence of a snow cover, and snow mapping -- discrimination of snow from other types of surfaces and from clouds -- is best accomplished with a combination of visible and near-infrared wavelengths.

Benthic Carbon Mineralization: Importance for the Regional and Global Carbon Budget

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Most organic carbon is recycled in the pelagic, but a significant fraction of the organic material ultimately reaches the seafloor, where it is either re-mineralized or retained in the sediment record. On short time scales the benthic degradation of sedimentary organic matter regenerates inorganic carbon and nutrients for a continued water column production. On long time scales, however, sediments act as an important sink in the regional and global nutrient and carbon cycles.

Typically, the settling organic matter is oxidized trough a vertical redox cascade (O2-NO3-Fe-Mn-SO4) in surface sediments, hosting metazoans and high densities of microbes that mediate a 100-1000 times higher volume-specific degradation of organic material than the water column. The reduced products from anaerobic degradation are, to a large extent, ultimately re-oxidized by an equivalent amount of O2, and consequently, the benthic O2 uptake is a commonly used measure for the total benthic mineralization rate. Benthic O2 consumption is thus used (1) for aerobic heterotrophic activity of fauna and bacteria, and (2) for the re-oxidation of reduced inorganic products released during the anaerobic heterotrophic degradation.

Biogeochemical processes in marine sediments consequently play a key role in understanding the budget of the marine and global carbon cycle. To evaluate the efficiency of the biological pump this presentation relates the existing global data base on in situ benthic O2 uptake rates to surface water primary production, export production and water depth. The data set consists of benthic O2 uptake rates quantified from sediment incubations and O2 concentration profiles obtained in situ from a wide range of settings covering the oligotrophic central oceanic gyres as well as the high productive upwelling regions. Empirical relations between benthic mineralization, surface water primary production and water depth are established to identify provinces with high and low efficiency of “the biological pump”. The extrapolated maps for benthic mineralization are also used to establish regional, ocean-basin as well as global budgets for benthic carbon mineralization.

Contribution of Zooplankton Fecal Pellets to Carbon Flux in the Deep Ocean at Station M, an Abyssal Time-series Site in the California Current Region of the Eastern North Pacific Ocean

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Zooplankton are integral to the efficiency of the biological pump as they consume particulate organic carbon (POC) in the surface waters and then export it to the deep ocean via the sinking of fecal pellets or active transport by vertical migration, whereby carbon ingested in surface waters is metabolized at depth. Climate variation has been shown to affect the deep-sea pelagic and benthic environment and carbon flux, however there are few studies of the temporal role that deep-sea zooplankton play in affecting the efficiency of carbon transport from the upper ocean to the deep-sea. In this study, sedimenting material obtained regularly between 1991 and 2006 at the abyssal time-series Station M using a particle intercepting trap moored at 3500 m (600 m above the bottom), was analyzed via dissecting microscope and digital camera. Intact zooplankton fecal pellets were quantified from these samples and we measured size, shape, color, and estimated carbon flux. The results showed that median fecal pellet size and estimated carbon flux varied annually and seasonally, with lower POC flux samples having a higher percentage of pellet flux. The most common identifiable pellets in the traps were from larvaceans (ellipsoid) which are known to feed on small particulate organic matter. Other abundant pellets were likely produced by large copepods and euphausiids (cylindrical). Red pellets of various shapes, produced by carnivores such as chaetognaths, were also present but rare in the trap samples. Historical data showed that salp pellets had been present in some samples, however they were not observed in this study, possibly due to the sample freezing process and the overall fragility of salp pellets. Although the proportion of intact pellets to total POC flux varied and was generally low, we observed a high abundance of fecal “fluff” and partially degraded particles of likely fecal origin. The data generated from this study provide an important contribution to biogeochemical models that predict global carbon sequestration in the deep-sea.

Organic Matter Fluxes and the Response of the Deep-sea Benthos. Clues From the Southern Indian Ocean

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The supply of food to the ocean floor and benthic community responses to variations in the downward flux of organic matter (OM) over space and time are fundamental issues of biological oceanography. However, the relationship is not simple; for instance, dramatic changes in species dominance in the abyssal North Atlantic do not appear to be related to changes in total export flux, but instead to changes in the "quality" or composition of the OM arriving at the seafloor. Understanding patterns of biodiversity in the deep sea and their link to surface water productivity remains a major challenge. How does the connection work and how does it manifest itself?

In order to address this question, we studied a region of natural iron (Fe) fertilisation, the Crozet Plateau in the Southern Indian Ocean, where there is a contrast in the export flux between Fe enriched (+Fe) and non-enriched (-Fe) surface waters. We compared two abyssal locations (4200 m) to the East (+Fe) and South (–Fe) of the Crozet Islands, with carbon fluxes at the two sites of 25-34 vs. 7-17 mmol C m-2y-1, respectively. We show that the contrast in flux is mirrored by the biomass of the benthic megabenthos at +Fe and -Fe. Furthermore, we observe significant differences in the taxa at the two sites, which we attribute to differences in the nutritional quality of OM arriving at the sea floor at +Fe and -Fe. These observations lead us to conclude that the fluxes and quality of OM significantly impact the ecology of the deep sea.

Controls on the Remineralization Profiles of Sinking Organic Matter

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As organic matter sinks through the water column, it remineralizes to inorganic carbon and nutrients. The depth of remineralization controls the carbon sequestration efficiency of the biological carbon pump and may be influenced by a number of factors including the pelagic zooplankton and bacterial communities, temperature, oxygen concentrations, aggregation and disaggregation processes, and mineral ballast fluxes. In this study we use a global database of particulate organic carbon fluxes measured from sediment traps together with export fluxes and primary productivity estimates from the Biogeochemical Elemental Cycling (BEC) ocean model to identify which combination of factors appear most significant in controlling the attenuation of the POC flux with depth. The factors we consider in our statistical model are (1) primary production, (2) water column temperature, (3) water column oxygen concentration, (3) the export flux of biogenic silica, (4) the export flux of calcium carbonate, and (5) the flux of dust. The statistical analysis is based on a Bayesian model comparison approach with a two level model designed to separate variations in the POC fluxes that can be attributed to systematic variations in the remineralization depth from the noise in the sediment trap dataset.