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Donner, B. and G. Wefer

BIOGEOCHEMICAL CYCLES: GERMAN CONTRIBUTIONS TO THE INTERNATIONAL JOINT GLOBAL OCEAN FLUX STUDY

Symposium in Bremen:
Universum Science Center and Geosciences Department, Bremen University

September, 18 - 21, 2000

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Biogeochemical Cycles:

German Contributions to the International Joint Global Ocean Flux Study

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September 18 – 21, 2000

Veranstalter

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Biogeochemical Cycles:
German contributions to the International Joint Global Ocean Flux Study
September 18 - 21, 2000, Bremen

Program

Monday, September 18, 2000, Universum Science & Conference Center

10:00	Eröffnung	Herr Prof. Gerold Wefer (Universität Bremen)
	Grußworte	Herr Willi Lemke (Senator für Bildung und Wissenschaft im Land Bremen)
		Herr Prof. Jürgen Timm (Rektor der Universität Bremen)
		Herr Prof. Eckart Ehlers (Vorsitzender des Nationalen Komitees für Global Change Forschung)
		Herr Hansvolker Ziegler (Ministerialdirigent, BMBF)
10:40 – 11:00	Karin Lochte	The Joint Global Ocean Flux Study: Overview
11:00 – 11:20	Gerold Wefer	Carbon cycle in the North Atlantic
11:20 – 11:40	Ulrich Bathmann	Effect of iron on plankton blooms and the CO_2 sink in the Southern Ocean
11:40 – 12:00	Venu Ittekkot	Monsoon-driven fluxes in the Indian Ocean
12:00 – 13:30	Lunch	

Subject: Boundary exchanges and effects

13:30 – 14:00	Hein de Baar	The role of iron in plankton ecology and carbon dioxide transfer of the oceans
14:00 – 14:30	Hermann Bange	Non-CO_2 trace gas measurements during JGOFS
14:30 – 15:00	Roger Francois	Geochemical proxies for paleoproductivity: Status and prospect
15:00 – 15:30	Richard Jahnke	The global flux of particulate organic matter to the deep sea estimated from sea floor studies: Regional variations in transfer efficiency
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16:00 – 17:00	Douglas Wallace	Anthropogenic CO_2 uptake by the ocean: Reconciling observations and models
17:00	Visit of Universum Science Center, Bremen	
19:00	Reception at Universum Science Center	

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09:30 – 10:00	Toshiro Saino	Year to year variability of new production in the northern North Pacific estimated from remotely sensed sea surface temperature and chlorophyll a
10:00 – 10:30	Ulrich Bathmann	The role of ecosystem structure in regulating export flux from the upper ocean
10:30 – 11:00	Coffee	
11:00 – 11:30	Wolfgang Koeve	Stoichiometry of the biological pump - evidence for systematic variations of the C:N ratio in the oceans
11:30 – 12:00	Iris Kriest	Modelling biogeochemical processes in the Arabian Sea
12:00 – 12:30	Christian Schäfer-Neth	Modelling dust phytoplankton aggregate formation and micronutrient cycling
12:30 – 13:00	Wolfgang Barkmann	Observation and modelling of isotopic compositions of organic and inorganic nitrogen
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09:30 – 10:00	Avan Antia	Variability in the characteristics of particle flux in the Atlantic Ocean and the implications for estimation of regional and basin-wide export
10:00 – 10:30	Tim Rixen	The monsoon driven organic carbon pump
10:30 – 11:00	Coffee	
11:00 – 11:30	Gerhard Fischer	Opal fluxes to the deep ocean: global distribution and long-term changes
11:30 – 12:00	Ralf Schiebel	Pelagic calcareous particle flux
12:00 – 12:30	Han Lindeboom	The role of the coastal zone and the continental margins in the transfer of materials including C, N, and P
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14:00 – 17:00	Poster session	
17:00 – 18:00	Wolfgang Berger	The Walvis Paradox - An unsolved problem in paleoproductivity
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10:00 – 10:30	Ulf Riebesell	Responses of the marine biosphere to global change
10:30 – 11:00	Coffee	
11:00 – 11:30	Andreas Oschlies	Climate sensitivity of biological production in a model of the North Atlantic
11:30 – 12:00	Mark Abbott	Ocean biogeochemistry using satellite observations – Challenges and opportunities
12:00 – 12:30	André Paul	Physical forcing of phytoplankton growth
12:30 – 13:00	Ralf Schneider	The sedimentary signal of past productivity
13:00	Gerold Wefer	Closure

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ABSTRACTS OF OVERVIEW TALKS
ABSTRACTS OF POSTERS WITHOUT ASSIGNEMENT TO A SECTION

Overview talk

EFFECT OF IRON ON PLANKTON BLOOMS AND THE CO_2 SINK IN THE SOUTHERN OCEAN

Bathmann[1], Ulrich, Victor Smetacek[1], Inga Hense[1], Hein deBaar[2], Michael Rutgers an der Loeff[1] & Volker Strass[1]

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[2]Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg /Texel, The Netherlands

Phytoplankton productivity is stimulated in the Southern Ocean in the presence of biogenic available iron. We support this theory with data from field studies and laboratory experiments obtained from Pacific and Atlantic sectors of the Southern Ocean as obtained during various POLARSTERN expeditions (ANT X/6, ANT XII/4, ANT XIII/2, and ANT XVI/3). With ocean water masses which carried reletively high amount of iron, phytoplankton developed blooms compared to the surrounding "iron-free" water masses. Consequently, high plankton productivity resulted in high under-saturation of CO_2 in surface waters of up to 50 µatm, with the net result of CO_2 uptake by the ocean. Sources of naturally occuring iron enrichment and the impact of iron addition on phyto- and zooplankton community structure and functioning will be investigated in future field studies and in a 3D physical-biological couppled mathematical model.

Poster

GERMAN JGOFS DATA MANAGEMENT

Herrmann, Joachim

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Data of German JGOFS expeditions are centrally collected, organized and re-distributed to scientists by the German JGOFS data manager located at the Institute of Marine Research in Kiel. Since the beginning of this year the position is newly filled.

A stock taking of the submitted data revealed that 700 MB of raw data stored in 4500 files are available at Kiel. About 90% of the data volume consists of times series and physical profile data. The files' content is classified by cruise leg, measured parameter, sampling gear and PI. The files are directly accessible through a database. The result of this inventory led to a newly developed website - www.ifm.uni-kiel.de/jgofs/dm/.

Passing several quality control procedures, consistency tests and plausibility checks the data and their metadata become transferred into a relational database management system (MS-ACCESS). Data values are linked with respective sampling and measuring methods as well as data handling information. The database model is presented. This database is the backbone for the local database management, for the compilation of datasets requested by scientists, the web presentation and the data exchange with other software packages.

Previously, data access for scientists was only possible via the data manager. The new website offers now downloads for physical data and metadata of some cruises. Gradually, this service will become extended. For the future it is intended to connect a database system directly to the internet so that interested users can search and retrieve data by themselves. But also in the future, the personal stewardship of a client's data request shall ensure optimum service and results for scientists.

During an international meeting of JGOFS data managers from seven countries which was held in Kiel this year is was agreed to produce an International Data Collection CD-ROM Set in an uniform data format and with an user-friendly interface. The project is coordinated by the U.S. National Oceanographic Data Center and the U.S. JGOFS Data Management Office at Woods Hole. Year of publication will be 2002.

Overview talk

MONSOON-DRIVEN FLUXES IN THE INDIAN OCEAN

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The oceans will respond to global environmental changes in ways that will affect many of their regulatory and socio-economic functions. Expected are, among others, a weakening of the global thermohaline circulation and changes in the strengths of coastal and open ocean upwelling systems. These changes will affect the nutrient distribution and availability in the oceans with consequences for marine biological production. The oceans' capacity to biologically sequester atmospheric CO_2 and their ability to sustain economically important fisheries will be seriously impaired.

Our current knowledge on the ocean's response, for example, to climate change comes from model predictions and from records preserved in ice-cores, corals and sediments. Although it is widely accepted that climate change will have an impact on oceans' chemistry and biology, information on the exact nature and magnitude of the potential impacts and their effect on the regulatory functions of the oceans is still lacking.

The JGOFS-Process Study in the Indian Ocean investigates the modulating effect of the monsoons on the chemistry and biology of the ocean and its impact on the biological uptake of carbon dioxide by the ocean. The monsoons induce changes in the distribution and availability of

nutrients in the upper ocean which determine the plankton community structure. This in turn, will influence the fluxes out of the surface layers and hence, the time scales at which biologically fixed carbon dioxide will be stored in the deep sea.

The ongoing work has helped to characterise the workings of the biological carbon pump under the influence of the monsoons and is currently providing information that will help to quantify the changes in the efficiency of the biological carbon pump in response to changes in monsoon strength. The data sets coming from the process study are also beginning to indicate possible links between the monsoons and El Niño events and the planned work is expected to provide further information on global teleconnections: the link between monsoons, El Niño events and the processes that operate in the North Atlantic.

Overview talk

THE JOINT GLOBAL OCEAN FLUX STUDY: OVERVIEW

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In the last decade the JGOFS programme has contributed substantially to the understanding of biogeochemical cycles in the ocean. Major achievements have been the quantification of primary production and the elucidation of factors controlling it in different ocean biogeochemical provinces. The effect of seasonal development of plankton on CO_2 exchange with the atmosphere and the export of particulate material from the upper ocean to the deep sea is now fairly well understood. The role of dissolved organic matter (DOC, DON, DOP) has been appreciated, although open questions still remain. These different aspects of the JGOFS programme are the pieces of the puzzle which we now have to put together to a comprehensive picture of the fluxes in the ocean. This is where the JGOFS programme stands at the moment.

The main goal for the last years of the JGOFS programme is to develop an integrated, quantitative view of the biogeochemical cycle of carbon in the ocean, indicating the role of biota, physical transport, air-sea exchange, particle settling and remineralisation. To this end the following steps have to be taken:

- ensure that all JGOFS data are secured for long term stewardship and are accessible for the scientific community
- create an advanced synthesis of ocean biogeochemical regimes from the major JGOFS regional process studies, time series and global survey studies
- develop a hierarchy of coupled biogeochemical models of varying ecosystem complexity and use them to enhance the understanding of natural variability and anthropogenic changes
- assess the capability of 3-dimensional ocean carbon cycle models with biogeochemistry to simulate observed global inventories
- assess the contribution of continental margins and seas to the CO_2 sequestration and the horizontal flux of carbon across the ocean-continental margin boundary

- make recommendations for future global ocean observations systems and present the JGOFS results in an easily understandable way to the general public

International JGOFS pursues these tasks by a data management task team, by synthesis groups dedicated to specific topics and by publishing synthesis articles and books. Several planned meetings will enhance the exchange of information and promote synthesis efforts.

An outlook to the future: A major task will be within IGBP to bring together the different core projects to a global synthesis. In particular the boundaries between the subsystems of the earth need to be considered: land-ocean, ocean-atmosphere, land-atmosphere. Three specific topics will be in the centre of attention "carbon", "water", "food and fibre". The results from JGOFS will be an important part in this global synthesis. While JGOFS has been very successful in analysing biogeochemical fluxes in the ocean, it has not been able to elucidate how different species alter these fluxes. If we want to understand changes in the past and in the future this will be an important question to solve in the future.

Poster

JGOFS MODELLING AT MPI METEOROLOGIE IN HAMBURG

Maier-Reimer, E. & C. Textor

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We document our current activities on modeling fluxes of carbon and related elements resulting from marine production. Basic variables are DIC, alkalinity, phosphorus, oxygen, phytoplankton, zooplankton, silica, DOC, POC. These tracers are embedded in the three-dimensional circulation of the C-HOPE Model. Surface pCO_2 and saturation level with respect to $CaCO_3$ are diagnosed from standard chemistry. At the seafloor the model is closed by a 12 layer sediment model. The modeling efforts focuse on the Arabian Sea. We run the model in a coarse resolution version (one deg) and a high resolution version (down to 15 km). The advantage of the coarse resolution model is that it allows for many experiments and it is easily transportable.

The code of the coupled model was applied also to an Atlantic topography (30S - 70 N) with one deg resolution and a global domain with a T42 resolution. Preliminary results from these runs are shown.

Poster

PRELIMINARY RESULTS FROM SIMULTANEOUS OPTIMIZATIONS OF A MARINE ECOSYSTEM MODEL IN THE NORTH ATLANTIC

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A nitrogen-based ecosystem model (with dissolved nitrogen N, phytoplankton P, zooplankton Z and detritus D) is optimized at three different locations in the North Atlantic simultaneously. Such data-assimilative investigations can provide reasonable estimates of the model's parameters which can be adopted for large scale predictions of coupled three-dimensional models (3D-model).

The combined data set includes observations from the time-series station near Bermuda at 31N 64W (BATS, collected by US-JGOFS groups, 1989-1993), a data collection from the Ocean Weather Ship India at 59N 20W (BODC-Prime data set, 1971-1975+1996), as well as measurements at 47N 20W (NABE-BODC/Lowry,-SOC/Fasham and German JGOFS IfM-Kiel/Koeve/Waniek, 1989-1996).

Monthly averages of nitrate+nitrite, chlorophyll a, ^{14}C-primary production, particulate organic nitrogen and micro-zooplankton biomass were determined from the collected data sets. These monthly averages are assumed to be the best representatives of any particular month at the corresponding location. The monthly model counterparts to the observations are calculated from a five years period of integration (1989-1993), including interannual variability. Temperature, eddy diffusivities and surface radiation at the respective locations were derived from three different realizations of the 3D-model with ECMWF reanalysis forcing (IfM-Kiel/Oschlies).

A micro-genetic algorithm (Univ. of Illinois/Carroll, http://www.staff.uiuc.edu/~carroll/ga.html) is applied to seek for the minimum of a cost function which is the overall least square misfit between model results and observations at all three locations.

The first optimization produced a preliminary solution of which the biological variables become extinct at the mesotrophic BATS site while at 47N 20W and 59N 20W the misfits between model results and observations are greatly reduced. This first result reveals that the currently applied weighting in the cost function, namely the misfit contribution from every station, is not appropriate. A simple idea of a modified scaling is proposed which helps to improve the algorithm's capability to simultaneously optimize the model results at the three locations.

Overview talk

CARBON CYCLE IN THE NORTH ATLANTIC

Wefer, Gerold

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German participation in the international JGOFS Project began with the tenth cruise of FS (RV) Meteor that departed from the harbor of Santa Cruz, Tenerife, on March 19, 1989. For this cruise, the Victor Hensen Commemorative expedition, the primary interest was the spring plankton bloom. Since then, many expeditions have been carried out, devoted not only to biological productivity but to a variety of biological, chemical, and paleoceanographic investigations, as well as to climatological questions. A few examples of the results of these investigations are given.

There is a better understanding of the role of the biological pump as a factor in the removal of carbon dioxide from the atmosphere. Although the Alps account for only about one five-hundredth of the world's total biomass, they are involved in ¾ of the uptake of total CO_2 assimilated by the ocean. Significant spatial differences in the biological pump and large variations in its efficiency have been determined. The paths of particles in the water column as they sink to the sea floor have been tracked. Export flux at the 1,000 meter isobath (f-ratio) has been determined for various production systems.

Based on analysis of material from almost 200 sediment stations, the importance of the sea floor in the return of nutrients to the water column has been illustrated. The path of anthropogenic CO_2 has also been traced from its incorporation at the sea surface into the deep sea. In the western North Atlantic water with anthropogenic CO_2 has already reached the sea floor, while in the east Atlantic it has only been confirmed to a depth of about 3,000 meters. These results illustrate that a basic understanding of the various systems can only be obtained through long-term investigations, requiring new technology, and with careful consideration of seasonal and interannual variability.

SESSION: BOUNDARY EXCHANGES AND EFFECTS

Talk

THE ROLE OF IRON IN PLANKTON ECOLOGY AND CARBON DIOXIDE TRANSFER OF THE OCEANS

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The Iron Age. In recent years it has been discovered that iron (Fe) limits biological productivity in 40% of the oceans. Moreover it appears a co-limitation in vast regions of the remaining 60% of surface waters. Meanwhile the paradigm of a single limiting factor for some or all marine ecosystems has given way to the awareness of co-limitation by several nutrients simultaneously, where light deficiency as well as grazing losses furthermore play an important role. So fundamental is Fe in regulating photosynthetic efficiency and electron transport, fixation of carbon dioxide (CO_2) and overall plant growth, that it is now thought to be intimately linked to atmospheric carbon dioxide and thus, global transitions in climate from glacial to interglacial times. The supply of Fe to the surface waters, either from below (reducing sediments) or above (dust) likely is changing over decadal to Milankovitch time scales.

Both in natural conditions, in shipboard incubations, as well as during intentional *in situ* Fe enrichments (1995, IRONEX II; 1999, SOIREE) an enrichment with Fe was found to stimulate plankton blooms, notably large diatoms thus also affecting the silicon (Si) cycle of the oceans. Apparently the relief of Fe limitation leads to a shift up from the recycling small foodweb to the large bloom-forming phytoplankton, notably big diatoms. Moreover concomitant drawdown of CO_2 from the atmosphere has been reported.

In addition to limitation by inadequate Fe supply, light is very important, most notably in the Southern Ocean. At high wind velocities in the Antarctic Ocean, blooms cannot exist, even when Fe supply is adequate. The European project CARUSO (Carbondioxide Uptake Southern Ocean) investigates the synergistics of light and iron in regulating diatom blooms and CO_2 drawdown. Simulation modeling of the plankton ecosystem and CO_2 budget has been validated versus the 1992 spring bloom evolution at the Polar Front. Next the model has been applied to assess various scenario's of increased Fe supply and shifting wind fields during the Last Glacial Maximum. During the upcoming CARUSO *in situ* Fe enrichment experiment (November 2000) we intend to obtain another time series of bloom evolution suitable for simulation modeling.

Recently another European project IRON-AGES was started placing Fe limitation in a global perspective. Iron Resources and Oceanic Nutrients - Advancement of Global Environment Simulations (IRON-AGES) aims at improving Ocean Biogeochemical Climate Models (OBCM's). The current class of OBCM's for simulating past, present and future re-distributions of CO_2 between ocean and atmosphere is restricted by a simplistic plankton module of one archetypical phytoplankter and usually just one limiting nutrient phosphate. IRON-AGES aims at

co-limitation by 4 nutrients (Fe, N, P, Si) of 5 major taxonomic plankton groups towards more reliable predictions of CO_2 exchanges between ocean and atmosphere.

Talk

NON-CO_2 TRACE GAS MEASUREMENTS DURING JGOFS

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A variety of atmospheric trace gases such as ammonia (NH_3), methyl amines (MA), nitrous oxide (N_2O) methane (CH_4), non-methane hydrocarbons (NMHC), dimethyl sulphide (DMS), and carbonyl sulphide (COS) were measured as part of the Joint Global Ocean Flux Study (JGOFS). The gases listed play important roles both in the atmospheric chemistry and in the radiation budget of the Earth. They are involved in many photochemical and biological transformation processes of the oceanic cycles of nitrogen, carbon and sulphur. For some gases such as N_2O, COS, and DMS the release across the ocean-atmosphere interface represents a major contribution to their global atmospheric budgets.

"What has been learned from measurements of non-CO_2 trace gases during JGOFS?":
To illustrate the progress resulting from the various activities of JGOFS, highlights of COS, CH_4, NH_3, and N_2O measurements during various JGOFS campaigns in the North Atlantic Ocean and the Arabian Sea will be presented. I will point to the role of non-CO_2 trace gases in mediating feedback mechanisms of the ocean-atmosphere system.

Poster

THE POSSIBLE EFFECT OF DEEP UPWELLING ON PARTICLE PRESERVATION - UPWELLING VELOCITIES FOR THE WEDDELL GYRE DERIVED FROM ^{227}AC DISTRIBUTION

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^{227}Ac (half-life 21.8 years) is a natural radioactive tracer which was previously used by Nozaki (1984) to determine diapycnal mixing coefficients. We show that ^{227}Ac is almost exclusively supplied by deep-sea sediments and therefore specific for waters having had contact with the deep-sea floor. We find a pronounced ^{227}Ac signal in the Weddell Gyre up to the sea surface which must be attributed to deep upwelling. Using the time information of this tracer we derive upwelling velocities for the Weddell Sea and discuss the possible effect of upwelling on particle

preservation. As upwelling enhances the residence time especially of smaller perticles in the water column, this may play a role in the poor particle preservation in this region.

Furthermore, we present a transect of ^{227}Ac together with nutrient data across the Antarctic Circumpolar Current (ACC). ^{227}Ac concentrations are there also closely related to upwelling and the isotope may therefore be a promising tracer for estimating the contribution of micronutrients (e.g. Fe) of deep waters to the ACC.

Further improvement of measurement techniques by α-scintillation according to Moore and Arnold (1996) will make ^{227}Ac a tracer with a wide range of possible applications in questions of transport and mixing of deep waters.

Poster

RA-228: A NATURAL TRACER FOR SHELFWATER INPUT AS A POSSIBLE TRANSPORT PATH OF IRON INTO THE SOUTHERN OCEAN

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Recent studies suggest that iron is a growth-limiting factor for primary productivity in the productive regions of the Southern Ocean. Yet it is not completely understood by what pathways the iron reaches the open ocean. Possible iron sources are: upwelling of deep waters, aeolian input of continental dust from South America and the Antarctic Peninsula and advective inputs from their respective continental shelves.

We use Ra-228 (half-life 5.75 years) as a natural tracer for shelfwater. To depict possible signals, we have taken surface water samples for dissolved Ra-228 from possible source regions as well as on several N-S-sections across the ACC taken during cruises with RV POLARSTERN (ANT XV/3 and ANT XVI/3) in 1998 and 1999. Increased Ra-228 activities have been measured on the shelf areas of the eastern Weddell Sea, along the Antarctic Peninsula and on the Argentinian Shelf. High activities have also been found in the Agulhas Current south of Africa.

Due to very low activities, analysis of Ra-228 on the N-S-transects is done by the so-called Th-228 ingrowth method, but measurements of the distribution of its daughter product Th-228 (half-life 1.92 years) itself can give approximate values of the final Ra-228 concentrations. We will present results of absolute Ra-228 activities in the ingrown samples as well as Th-228 activities from the 1999 cruise. The latter indicate higher Ra-228 concentrations in surface waters close to Africa and in the Antarctic coastal current (south of 69°S). In the ACC at 20°E, peaks of enhanced Th-228 occur at 46°, 49° and 53° S. The peaks at 46° and 49° coincide with the approximate location of the Subantarctic and Polar Front. In the Weddell Gyre, between 53°S and the coastal current, activities of Th-228 were uniformly low. The data show that shelf signals may indeed be distinguished in the frontal jets at 20°E.

Talk

THE GLOBAL FLUX OF PARTICULATE ORGANIC MATTER TO THE DEEP SEA ESTIMATED FROM SEA FLOOR STUDIES: REGIONAL VARIATIONS IN TRANSFER EFFICIENCY

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The deep sea floor is the ultimate sediment trap, serving as the location for remineralization, dissolution or permanent burial of the biogenic components settling from above. Quantitative understanding of the rates of remineralization, dissolution and burial provides a direct measure of the particle flux to the sea floor. Utilizing sea floor studies to estimate the deep water particle fluxes has several advantages. First, these processes are either destructive or, in the case of burial, a permanent removal process. Thus, unlike sediment traps deployed near the sea floor or topographic features that may collect resuspended materials, there is little potential for over estimating the flux from sea floor studies. Second, although different components may dissolve or be remineralized at different rates, many of the components of most interest, such as organic carbon and nutrients, have reaction half-lives of several months to a few decades. These life-times are long enough to dampen much of the short term variability in the vertical flux facilitating the estimate of mean fluxes and are short enough to minimize major lateral exchange which would de-couple vertical flux patterns from sea floor characteristics. Additionally, these reaction time scales are of the same order as the duration of the JGOFS program facilitating comparisons.

Since the majority of the organic matter that reaches the deep sea floor is remineralized, accurate estimates of deep particulate organic carbon fluxes from sea floor studies require high quality benthic flux estimates. In general, the most accurate methods for estimating benthic fluxes are in situ flux chamber incubations or diffusive flux calculations based on fine-scale near-surface gradients such as those obtained by in situ microelectrode profilers. While numerous research groups have developed these technologies, acquisition of data is slow. Chamber incubations in the deep sea often require days to more than a week of incubation time to provide accurate flux estimates. Pore water gradient measurements can generally not be made at more than one site per day. Thus, while the technology is available to obtain the required measurements, global distributions will require objective methodologies to extrapolate the benthic flux estimates from a relatively small number of locations throughout the ocean basins.

As an initial attempt to develop a global flux description, benthic oxygen flux results were correlated to the calcium carbonate-free organic carbon burial rate. The latter can be estimated at thousands of sea floor locations because of the abundance of sedimentary organic carbon, calcium carbonate and accumulation rate measurements. Using the distribution of this parameter and the measured benthic oxygen fluxes, the magnitude and distribution of the particulate organic carbon (POC) rain rate to the oceanic sea floor between 61°N and 61°S has been estimated. These results suggest that the sea floor is a major location for organic matter remineralization in the deep sea, accounting for approximately 45% of the total oxygen demand below the main thermocline. Distribution patterns in general follow that of surface water primary production with elevated fluxes observed along continental margins, especially adjacent to wind-driven upwelling systems, and along the equator. Absent are high fluxes in the northern North Atlantic.

While the value at individual, specific locations may change in the future as more data are gathered, the overall pattern and integrated total flux appear to be very reasonable.

We have compared the sea floor flux distribution to published primary production maps to examine regional variations in the transfer of particulate organic carbon from the photic zone to the deep sea. Significant variations are observed at different latitudes and near continental margins. These results suggest that the processes that control vertical transport may vary with location, perhaps in response to ecosystem type, and that a single transfer function may not adequately describe the relationship between particle flux and water depth at the global scale. Processes that may account for the differences observed include: down-slope lateral transport within the nepheloid layer adjacent to the sea floor; resuspension due to increased mixing in the bottom boundary layer coupled with horizontal transport and particle sinking; and increased particle settling due to the species composition of the plankton community or mineral content.

Poster

DISTRIBUTION OF NUTRIENTS, C_T AND OXYGEN DURING WINTER IN THE ATLANTIC OCEAN

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JGOFS, the Joint Global Ocean Flux Study, is concerned with carbon fluxes within the ocean and at ist boundaries. Many of the modells developed in support of this program, however, use nitrogen (or phosphorus) as the prime currency. The conversion to carbon, f.e. when comparing model simulations with observations, is typically done using fixed C:N or C:P ratios, often applying the well known standard Redfield ratios of 6.7 and 106 for C:N and C:P, repectively. Recently, serveral studies have indicated that the ratio of carbon to nitrogen uptake (i.e. the ratio of the rate of change of dissolved organic carbon and nitrate over time, $\Delta DIC : \Delta NO_3$, may show systematic variations depending on the trophic status of the ecosystem. A basin scale test of this hypothesis although obvious has been hampered by the lack of data (DIC, NO3 and PO_4) from prior to the vegetation period of plankton. Direct observations from winter time are, for obvious reasons, very scarce. Building on earlier attempts from our group to provide local or regional estimates of winter time nutrient concentrations, methods were developed to reach at basin scale estimates of winter nitrate, alkalinity, oxygen and DIC for the Atlantic ocean between 65°S and 65°N. Alternative approaches are presented and results are compared with the few observations and other estimates of winter properties which are available. Based on this comparison, the most reasonable approaches are selected. Currently, work is under progress to combine these winter time data fields with data from hydrographical WOCE sections carried out during summer time in the North and South Atlantic and to estimate $\Delta DIC : \Delta NO_3$ uptake ratios thereafter.

Talk

ANTHROPOGENIC CO_2 UPTAKE BY THE OCEAN: RECONCILING OBSERVATIONS AND MODELS

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The JGOFS/WOCE Global CO_2 Survey has resulted in the amount of available data concerning oceanic CO_2 distributions increasing by approximately an order of magnitude compared to all prior data holdings. The quality of the data has also increased by approximately an order of magnitude. The consequence is that we are now, for the first time, able to evaluate the role of the global ocean in the uptake of anthropogenic CO_2 from *in-situ* data as well as from models. These data, in addition to allowing better defininition of the current behaviour of the global carbon cycle, are necessary to guide future development and refinement of the carbon cycle models required to predict future carbon cycle behaviour and sinks of anthropogenic carbon under a potentially altered climate.

Whereas the present-day global net oceanic sink for anthropogenic carbon can now also be resolved quite well from the measurement of time-series of O_2/N_2 in the atmosphere, such atmospheric time-series measurements integrate over very wide geographical scales and provide little information on the specific oceanic regions and processes that are responsible for such uptake. The latter information is critical for modelling (prediction) of future oceanic uptake under an altered climate. In this presentation I will review the potential for Global CO_2 Survey data to act as a test and reference point for ocean models with respect to:

- the regional distribution of the inventory of anthropogenic CO_2
- the regional distribution of anthropogenic CO_2 uptake across the air-sea interface

Preliminary comparisons reveal some important discrepancies between observation-based and model-based distributions. Resolution of such differences will be critical for confidence-building with respect to model depiction of future anthropogenic CO_2 uptake, as well as for guiding the design of future observational programs.

SESSION: UPPER WATER COLUMN PROCESSES

Talk

OBSERVATIONS AND MODELLING OF THE ISOTOPIC COMPOSITIONS OF ORGANIC AND INORGANIC NITROGEN

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Variations in the natural abundance of the stable nitrogen isotopes have a variety of applications, including the determination of the trophic structure of marine plankton communities, nitrate utilization, and the implications of nitrogen isotope fractionation for the sedimentary record. The distribution of stable isotopes in aquatic systems has been related to specific processes of elemental cycling or to the sources of carbon and nitrogen that are utilized by the organisms. Such studies have shown that nitrogen isotopic compositions of algae in natural systems are affected by three factors: the isotopic composition of nutrients consumed, isotopic fractionation during the uptake of those nutrients, and by fractionation during catabolic processes. While carbon isotope ratios reflect the source of material and the productivity important to the ecosystem energy flow, nitrogen isotope ratios reflect the trophic status in most ecosystem food webs. Observations of $\delta^{15}N$ in sedimenting particles in the northern North Atlantic show a clear seasonal signal of nitrate utilization, with values ranging between 3 and 8 $^{0}/_{00}$ at 500m depth. Measurements of $\delta^{15}N$ in suspended particulate organic matter in the Arabian Sea revealed typical values between 8 and 12 $^{0}/_{00}$. Here, and in the eastern tropical North Pacific, denitrification processes and the associated fractionation play an important role in the determination of the $\delta^{15}N$ signal observed in suspended and sinking particles in the water column. In these regions, the most important source of nitrogen to the euphotic zone can be found in the form of upwelled nitrate. Nitrate with high $\delta^{15}N$ results from denitrification, a process with a large fractionation factor. In the eastern tropical North Pacific, this factor was estimated from $\delta^{15}N$-NO3 data to vary between 22 and 35 $^{0}/_{00}$. Subsequent vertical transport will introduce this enriched nitrate into the water column where it can be taken up by phytoplankton and in turn provide higher $\delta^{15}N$ values for marine organisms.

Since stable isotope ratios offer an effective natural tracer to follow energy and nutrients flow in ecosystems, idealized mathematical isotopic mass-balance models of the nitrogen cycle have been developed to study the fluxes of nitrogen and its isotopic composition in the upper ocean. Applied to the denitrification layers of the oxygen minimum zone and to the euphotic zone, these models are capable of simulating the observed patterns of $\delta^{15}N$-PON and $\delta^{15}N$-NO3 successfully. The potential of this type of model for investigating the $\delta^{15}N$ pathways in the ecosystem becomes much clearer, if coupled to a physical mixed layer model capable of simulating diurnal and seasonal cycles in the upper ocean boundary layer, and to a model of plankton dynamics incorporating several trophic levels. The results of a fully coupled model resolving the fractionation processes in both the euphotic and in the denitrification zone of the Arabian Sea show highly variable distributions of $\delta^{15}N$ in particulate and dissolved nitrogen. Phytoplankton and zooplankton contribute with similar magnitude but opposite sign to the isotopic composition of the sinking detritus. The $\delta^{15}N$-PON profile changes its value according

to the fractionation factors applied to different processes, but δ^{15}N-PON below the seasonal boundary layer is to a first order approximation determined by the isotopic composition of the nitrate that enters the euphotic zone. Ecosystem models, particularly when coupled to physical models, are not only useful tools for the diagnosis of biogeochemical processes, but they can also serve to define the boundary conditions for proxy formation and thus help to understand historical changes in system functioning.

Poster

A MODEL OF NITROGEN CYCLING IN THE CENTRAL ARABIAN SEA: SIMULATING THE ISOTOPIC COMPOSITIONS OF ORGANIC AND INORGANIC NITROGEN

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The cycling of nitrogen compounds associated with nitrification, denitrification and nitrogen uptake by phytoplankton is in general accompanied by isotopic fractionation, resulting in a shift in the isotopic composition of nitrogen. Denitrification in the region of the oxygen minimum zone results in an increase of ^{15}N in the remaining nitrogen, which in turn may affect the isotopic composition of organic and inorganic nitrogen in the surface layers. Consequently, the biomass of sinking particles formed through biological activity can retain an isotopic signature, which is related to the source of the nitrate that enters the photic zone, and to the biological processes controlling the recycling of the sinking organic matter.

A one-dimensional model of plankton- and mixed layer dynamics was coupled to a reaction-diffusion model of nitrogen cycling in the oxygen minimum zone, in order to study the pathways of the isotopic signature throughout the upper ocean biogeochemical system. The coupled model comprises seven compartments (NO_3, NH_4, NO_2, N_2, P, Z, D), to each of them is a δ^{15}N-value assigned. Changes of isotopic composition in each individual compartment are related to the cycling of nitrogen, and to isotopic fractionation during nitrogen assimilation of phytoplankton and bacteria.

Preliminary model results show well-developed annual cycles of biomass and isotopic compositions in the seasonal boundary layer, but little annual variability in the deeper ocean. The predicted isotopic signatures of particulate organic matter depend on the fractionation factors applied, as well as on the percentage of nitrogen fixation, which is incorporated into the model in form of a mass balance closure hypothesis. Further investigations of the δ^{15}N cycles may contribute to a better understanding of the factors controlling the climate-related variations of the δ^{15}N-PON values recorded in the sediments.

Talk

THE ROLE OF ECOSYSTEM STRUCTURE IN REGULATING EXPORT FLUX FROM THE UPPER OCEAN

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The export of new production from the oceans' surface waters is constrained in principle by the rate of delivery of limiting nutrients and the ultimate need for balanced inputs and outputs. Within these general constraints, however, carbon export can be substantially influenced by the composition and size structure of the plankton community, through their effects on the timing of export relative to nutrient inputs, the depth of flux penetration into the inner ocean, and the carbon:nutrient ratios of particulate and dissolved material that exit the euphotic zone.

This presentation will briefly review the evolution and progress of community structure-flux paradigms during the SO-JGOFS era, focusing on the magnitude of variability that we can attribute to biological processes and examples of regulating responses and relationships that remain unpredictable.

Poster

THE SIGNIFICANCE OF BIOOPTICAL CHARACTERISTICS FROM DIFFERENT BIOGEOCHEMICAL PROVINCES OF THE SOUTHERN OCEAN FOR ESTIMATING PIGMENT CONCENTRATIONS

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Various biooptical measurements, including the spectral composition of the underwater light field, phytoplankton absorption characteristics were performed in the Atlantic sector of the Southern Ocean in order to provide basic data which can be used for developing algorithms for deriving pigment concentrations from satellite data. The composition of the phytoplankton

communities was derived from HPLC data on pigment composition and from the distribution of the various size fractions on total chl *a*.

Phytoplankton composition in the study showed a regional distribution which was reflected in different biogeochemical provinces of the Southern Ocean: the Antarctic Polar Front (APF) with a diatom, the interfrontal area between the APF and the marginal ice zone (MIZ) of the Antarctic Circumpolar Current (ACC) with scarce phytoplankton biomass and the MIZ with a *Phaeocystis* bloom of large colonies. The observed phytoplankton blooms occured at sites of shallow upper mixed layers (UML; at least <50 m) and stratified water columns creating a light climate giving enough potential to result in high production and growth rates.

Differences in biooptical characteristics in the study coincided with the different biogeochemical provinces of the Southern Ocean, where the study was performed: compared to other oceanic regions, attenuation of light by non-algal material was low since in the Southern Ocean riverine input of terrestrially derived humic and dissolved material is very low. At a large scale the diffuse attenuation coefficient of underwater light, $k_d[\lambda]$, was correlated with changes of chl *a*. However, measurements of the spectral absorption by phytoplankton showed more subtle variations in the optical properties that are related to the phytoplankton population structure, which were missing in the bulk analyses to which the diffuse attenuation coefficient is subjected. Absorption by phytoplankton normalised to chl *a*, $a_\phi^*[\lambda]$, within the blooms was far lower than outside of the blooms, and decreased significantly below the upper mixed layer. The regional differences in absorption characteristics are due to differences in pigment composition and the package effect, which depends on phytoplankton cell size and photoacclimation in accordance to the UML.

The comparison of *in situ* chl *a* to reflectance data of our survey, obtained from upwelling data measured *in situ*, showed that due to the low concentration of non algal material the chlorophyll algorithm developed by Reilly et al. (1998) fails for deriving chl *a* from remote sensing reflectance data in the Southern Ocean because of the observed regional differences in $a_\phi^*[\lambda]$ result in different relationships between chl *a* and reflectance. Using different algorithms for the different provinces improved estimates by 50%. In future, algorithms for deriving pigment concentrations from remote sensing reflectance data, should be even specific for the various biogeochemical provinces.

Literature

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Poster

SILICATE LIMITATION IN A FILAMENT: A TYPICAL TEMPORAL FEATURE WITHIN COASTAL UPWELLING SYSTEMS?

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We observed variations in primary nutrients and phytoplankton biomass in an upwelling event off Oman during the strong SW-monsoon 1997. A so called filament, originating in the coastal upwelling, was tracked, marked with a drifter and followed for 19 days while intensive water sampling took place. The first stations in this upwelling event showed a severe silicate limitation. With the silicate limitation a diverse diatom community vanished. Although after a couple of days new silicate became available, another phytoplankton community of smaller organisms (< 20 µm) with nearly no diatoms bloomed. These results raise fundamental questions about the interactions between silicate limitation and the control of carbon export in the worlds most productive areas. It is discussed, whether these limitation events might be typical short term features of coastal upwelling ecosystems, not described as yet.

Talk

THE MAGNITUDE OF BACTERIAL PRODUCTION IN THE OCEANS: A NEW ASSESSMENT AND BIOGEOCHEMICAL PROVINCE APPROACH

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Bacterioplankton are widely recognized as a quantitatively significant component of ocean ecosystems, and they are pivotal in the cycling of dissolved organic matter in marine systems. Until the past decade there were few extended studies of their stocks and dynamics in the open sea. Following completion of the field phase of JGOFS and several other studies, we can begin to assess variations in euphotic zone stocks and production, and compare these quantities to other plankton groups (e.g., phytoplankton). Comparison of various ocean provinces reveals a wide range in stocks of DOC, yet surprisingly little variability in bacterial biomass (< 2-fold). The most striking feature of oceanic bacterial biomass is the relative uniformity of the stock from one province to the next. This is caused by an inverse relationship between euphotic zone depth and bacterial abundance, such that the most oligotrophic regions have bacterial stocks equal to, or somewhat larger than eutrophic systems. However as a consequence of greater variation in phytoplankton stocks, ratios of bacteria to phytoplankton biomass vary from 0.2 - 3.6 across provinces. Bacterial production (BP), in contrast, is less variable, ranging from about 2 - 15% of primary production (PP) in most oceanic provinces. This ratio (BP:PP) was once thought to be closer to 20-30% but synthesis of more recent, larger data sets, and reassessment of conversion

factors has resulted in lower estimates of BP:PP. The highest apparent specific growth rates (P/B ratios) are in the subarctic and polar provinces (0.3 d-1), and there is little dependence, if any, of growth rate on temperature. We will review these new data, on a province-by-province basis, in this presentation.

There is a need to uncover the causes and mechanisms of such variability in the microbial loop if we are to better understand its importance in marine biogeochemical cycles. Topics which require study include the origin of DOM and efficiency with which it is utilised by bacteria, and the question of whether bacteria are regulated top-down (by predators) or bottom-up (by resources). The results of steady-state flow analyses to address these issues, and applied to contrasting ocean provinces, will be presented. Bacterial and phytoplankton properties will be reviewed for the following ocean provinces (sensu Longhurst, 1998): North Atlantic Drift Region, N. Atlantic Subtropical Gyre, Pacific Subarctic Gyre, N. Pacific Tropical Gyre, Pacific Equatorial Divergence, Antarctic, Austral Polar, Subantarctic Water Ring, NW Arabian Upwelling, Indian Monsoon Gyre. The analyses will be used to study the efficiency of utilisation of DOC by bacteria from observed primary production to bacterial production ratios.

Poster

CONTRIBUTIONS OF TRANSPARENT EXOPOLYMER PARTICLES (TEP) TO THE MARINE CARBON CYCLE.

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Seven years after Transparent Exopolymer Particles (TEP) have first been described, several studies have shown that this special class of particles is ubiquitous and abundant in the Ocean. Based on results of several laboratory and field studies we can now envision the impact of TEP on the marine carbon cycle:
TEP are gel particles that form abiotically from dissolved polymeric carbohydrates exuded by phytoplankton. Their production continues even when nutrient shortage limits biomass production and is stimulated by the availability of CO_2. The elemental composition of TEP differs from the expected "Redfield Ratio" as TEP are enriched in carbon, with a mean molar C:N ratio of 26. In surface waters of coastal areas the carbon concentration of TEP can be as much as the concentration of particulate organic carbon (POC) and equal to 25% of the POC concentration at the JGOFS North-East Atlantic site. Because TEP are an essential component of fast sinking marine snow appreciable amounts of TEP sediment to great depths. The elevated carbon content of sinking TEP-rich aggregates can explain observed variations in C:N:P ratios of sedimenting material.

These results have several implications for the marine carbon cycle: Our data indicates that an important fraction of the DOC generated during primary production will abiotically form particles which sink rapidly and reach the Deep Ocean. Because these particles appear to be generated even when growth is limited and because they are enriched in carbon over nitrogen,

their formation and sedimentation may provide a pathway for the sequestration of "excess - carbon" to the deeper water column.

Poster

SPACIAL AND TEMPORAL PATTERNS OF DISSOLVED ORGANIC MATTER DYNAMICS IN THE SEA: INVERSE NO_3^- - DOC RELATIONSHIP

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Dissolved organic carbon and nitrate concentrations are inversely related on a variety of temporal and spacial scales in the surface ocean. Extremes are represented by the tropical Arabian Sea on the one hand, where there is permanent oligotrophy associated with permanently high concentrations of DOC, and the Southern Ocean with high nutrient concentrations and low DOC levels. In the temperate North Atlantic, the system oscillates between two comparable states between summer and winter. Nutrient depletion enhances the production and supresses the utilization of DOC. Experimental nutrient addition to samples from nutrient depleted, high-DOC water enhances the utilization of DOC by channelling it into growth of bacteria rather than respiration.

Poster

MARINE DISSOLVED ORGANIC MATTER: CAN ITS C:N RATIO EXPLAIN CARBON OVERCONSUMPTION?

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Carbon overconsumption, i.e the consumption of inorganic carbon relative to nitrate in excess of the Redfield ratio at the sea surface, which was described by Sambrotto et al. 1993 (Nature 363, pp. 248-250) for spring situations, is examined in its relation to the dynamics of dissolved organic carbon and nitrogen (DOC and DON) in the North-East Atlantic. We observed the buildup of N-poor dissolved organic matter in surface water during summer requiring the consumption of inorganic carbon and nitrogen in a ratio exceeding the Redfield ratio. The C:N ratio of bulk dissolved organic matter is not only different from the Redfield ratio but also variable, i.e. no fixed conversion factor of C and N exists where DOM is important in C and N transformations. The buildup of N-poor DOM is recognised as a feature typical of oligotrophic systems. At the same time, the C:N ratios of particles conform to Redfield stoichiometry as does deep-ocean

chemistry. The implications of this finding are discussed, the conclusion being that, while DOM buildup contributes to CO_2 drawdown seasonally, its impact on the long-term carbon and nitrogen balance of the ocean is small.

Poster

AN ECOSYSTEM MODEL FOR THE ARABIAN SEA EMBEDDED IN A PRIMITIVE-EQUATION CIRCULATION MODEL WITH AN EDDY-PERMITTING RESOLUTION

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A nitrogen based, pelagic ecosystem model has been coupled with an eddy-permitting ocean general circulation model forced with monthly mean climatology. Distinct seasonal variation can be found in the model: during the southwest monsoon season, phytoplankton increases in the western Arabian Sea due to Ekman upwelling and the effect of the Great Whirl (Figure 1); during the northeast monsoon season, phytoplankton abundance is large in the northern Arabian Sea because of the enhanced nitrate entrained by relatively deep vertical mixing. These features are basically consistent with the ones observed.

Two major differences are, however, found in the basin-wide comparison between the model results and the observations: too low primary productivity in oligotrophic regimes and an unrealistic nitrate maximum in the subsurface layer of the northern Arabian Sea. Possible causes for the former include fast nutrient recycling, carbon fixation decoupled with nitrogen uptake and nitrogen fixation. The latter may be attributed to the lack of denitrification and of Persian Gulf Water (PGW) production in the model.

The model has been run also with daily mean wind stress because high frequency variation of wind stress may enhance the vertical mixing and thus increase upward transport of nitrate, thereby solving the problem of too low primary production. The result shows, however, that the vertical mixing is not significantly changed and that the primary production remains almost the same. The remedy for this problem must be sought elsewhere; it is planed to incorporate a fast nitrate recycling loop in the biological as proposed by Oschlies (2000).

To assess the influence of PGW concerning the latter problem of nitrate maximum, we performed a sensitivity experiment where nitrate concentration is restored toward annual mean climatology in the Persian Gulf. The reduction of nitrate concentration in the maximum is not significant, indicating that the main cause for the formation of the unrealistic maximum is not the lack of PGW in the model but may be that of denitrification. Further, an experiment with a set of artificial tracers has been carried out. The tracers adopted here have a unique feature that they can track the fate of nitrate, which is transported through the combination of biological and physical processes. This experiment shows that the upwelling along the coast of Oman is feeding nitrate to the maximum zone.

The artificial tracers described above also show that eddies formed during southwestern monsoon season around the Great Whirl (GW), which contains a lot of nitrate through upwelling along the coast of Somalia, are important for ``withdrawing'' nitrate from GW and carrying it to the northeast.

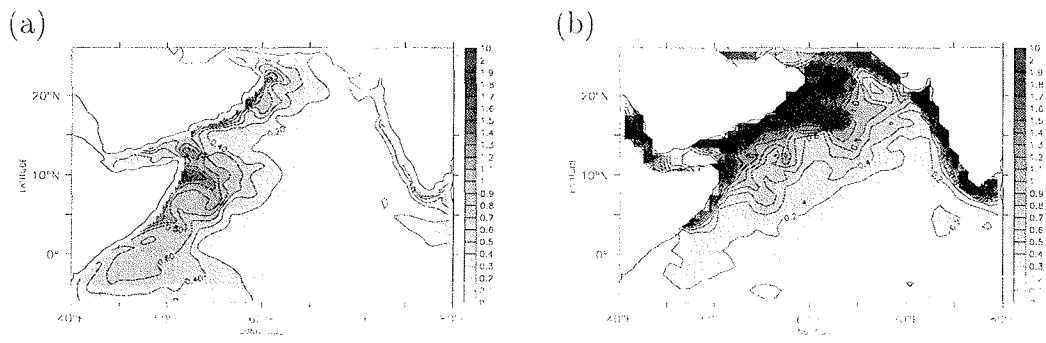

Figure 1:
Chlorophyll distribution (a) obtained by the model and (b) measured by CZCS averaged over the period Jul. - Sep. For the model result, averaging has been also applied over the upper 20m. Contour intervals are 0.2 μg/l for contour lines and 0.1 ug/l for shades. Care must be taken when one compares these figures because CZCS data are not very credible during this season near the coast of Oman due to constant cloud cover and possible atmospheric dust loads due to the strong wind.

Poster

C:N RATIOS IN THE MIXED LAYER DURING THE PRODUCTIVE SEASON IN THE NORTHEAST ATLANTIC OCEAN

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Redfield stoichiometry has proved a robust paradigm for the understanding of biological production and export in the ocean on a long-term and a large-scale basis. However, deviations of carbon and nitrogen uptake ratios from the Redfield ratio have been reported. A comprehensive data set including all carbon and nitrogen pools relevant to biological production in the surface ocean (DIC, DIN, DOC, DON, POC, PON) was used to calculate seasonal new production based on carbon and nitrogen uptake in summer along 20°W in the northeast Atlantic Ocean. The 20°W transect between 30 and 60°N covers different trophic states and seasonal stages of the

productive surface layer, including early bloom, bloom, post-bloom and non-bloom situations. The spatial pattern has elements of a seasonal progression. We also calculated exported production, i.e., that part of seasonal new production not accumulated in particulate and dissolved pools, again separately for carbon and nitrogen. The pairs of estimates of 'seasonal new production' and 'exported production' allowed us to calculate the C:N ratios of these quantities. While suspended particulate matter in the mixed layer largely conforms to Redfield stoichiometry, marked deviations were observed in carbon and nitrogen uptake and export with progressing season or nutrient depletion. The spring system was characterized by nitrogen overconsumption and the oligotrophic summer system by a marked carbon overconsumption. The C:N ratios of seasonal new as well as exported production increase from early bloom values of 5–6 to values of 10–18 in the post-bloom/oligotrophic system. The summertime accumulation of nitrogen-poor dissolved organic matter can explain only part of this shift.

Talk

STOICHIOMETRY OF THE BIOLOGICAL PUMP - EVIDENCE FOR SYSTEMATIC VARIATIONS OF THE C:N RATIO IN THE OCEANS

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Redfield stoichiometry has proved a robust paradigm for the understanding of biological production and export in the ocean on a long-term and a large-scale basis. However, deviations of carbon and nitrogen uptake ratios, i.e. $\Delta DIC:\Delta NO_3$ ration in the surface ocean or, in short, the (C:N)uptake ratio, from the Redfield ratio have been reported from a variety of ecosystems. Recent studies from the northeast Atlantic (see also Körtzinger, Koeve, Kähler and Mintrop, poster, this meeting) showed that (C:N)uptake ratios were similar to the classical Redfield value of 6.7 under conditions of replete nitrate concentrations but did increase after the phytoplankton spring bloom had used up all nutrients. During summer, under nitrate depleted conditions, (C:N)uptake ratios increased continuously, with highest uptake ratios of about 18 south of 40°N. C:N ratios of the seasonally exported matter showed similar seasonal and regional patterns while particle C:N ratios hardly differed from ‚Redfield'. The trend of increasing (C:N)uptake ratios with progressing season is also evident from surface ocean composite data sets of DIC and nitrate compiled from studies near the Biotrans quasi time series site (47°N, 20°W; Koeve, Kähler and Mintrop, poster, this meeting) and from intensive observations at the Bermuda Time Series Station (BATS). There, detailed studies proved that excess DIC uptake (excess over Redfield equivalents of nitrate uptake) is due to biogenic processes and not an artefact of data analysis. In the Sargasso Sea unexpectedly high N_2-fixation has been suggested as a possible nitrogen source of such carbon uptake. Several other studies conducted during the decade of JGOFS and WOCE likewise enable estimates of (C:N)uptake ratios. Building on these observations an overview of our current understanding of (C:N)uptake ratios, the fate of excess DIC uptake and our ability to provide large scale estimates of (C:N)uptake ratios is presented.

Talk

MODELLING BIOGEOCHEMICAL PROCESSES IN THE ARABIAN SEA

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The JGOFS Arabian Sea Process Study focuses upon the quantification of primary production, transformation and fate of phytogenic carbon, and upon the role the oxygen minimum plays in biogeochemical cycling. The western Arabian Sea exhibits a strong seasonality in primary production and sedimentation in response to the oscillating physical forcing. The seasonal signal is less pronounced, and the rates are lower in the central Arabian Sea. The observations collected during the study are necessarily scattered in time and space. Numerical models of the biogeochemical processes are based on our a priori knowledge about how the oceanic biota functions, and are a tool to interpolate these rules over space and/or time. In addition to quantification of flows, a mismatch between model predictions and observations may point towards deficiencies in the model, and consequently to deficiencies in our understanding of how the biogeochemical components interact.

A vertically resolved NPZD model was fitted to observations made at two sites in the western and central Arabian Sea. The model has been extended to include the aggregation of marine snow, and simulates the size structure and sinking speed of marine snow as dependent variables. Compared to observations made during the 1995 process study in the Arabian Sea, the temporal development of standing stock is reproduced relatively well by the model, but there is a mismatch between observed and simulated primary production in oligotrophic regimes. The mismatch may be explained by too low recycling of nutrients in the models, but also by a transient decoupling of carbon and nitrogen uptake by phytoplankton. Modelling aggregation, and the production of large, fast settling aggregates is sufficient to simulate the observed pattern of particle flux at the western site.

A three-dimensional model of ocean circulation coupled to an NPZD model shows the same mismatch between modelled and observed primary production under oligotrophic conditions. Tracer experiments carried out with this model stress the importance of transport of nitrate upwelled along the Arabian Peninsula for the northern region of the Arabian Sea, where oxygen is depleted and denitrification is enhanced. Further results presented in this paper address the representation of denitrification in a one-dimensional model, and the scavenging of dust particles by marine snow aggregates.

Poster

INTERANNUAL VARIABILITY OF CARBON FLUXES AT THE NORTH ATLANTIC STATION ESTOC

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The impact of physical processes on primary production, export production and CO_2 exchange with the atmosphere at the ESTOC station (29°N, 15.5°W) north of the Canary Islands is the focus of our investigations.

A one-dimensional carbon and nitrogen cycling model is applied for the years 1987 – 1996 continuously. The simulation results are compared with observations for the years 1994 – 1996.

The simulated annual primary production varies between 30 and 97 g C m^{-2} a^{-1}; 2.5 – 2.75 % of the primarily produced material is exported out of the water column 0 – 1000 m. The CO_2 air-to-sea flux varies between –0.5 and 7.6 g C m^{-2} a^{-1}.

The simulated large interannual variability of carbon fluxes is seemingly in contrast to the low interannual variability of the meteorological forcing typical for this subtropical regime. The key for this phenomenon lies in the sensitivity of this ecosystem on nutrient supply: depending on the meteorological situation, in different years the mixed-layer depth can or cannot reach the nitracline.

The results compare well with observations but 3-D effects like advection or eddies which are identified in the observations were not part of the simulations. Therefore we have implemented our model into a 3-D transport model using the hydrodynamical results of the North Atlantic CME model. First results show that the general circulation of the subtropical gyre determines the horizontal transport of a passive tracer at ESTOC: the simulated Canary Current obviously influences local processes.

Our next aim is to estimate the regional and basin-wide carbon fluxes of the North Atlantic for one annual cycle. The contribution of the shelf seas to open ocean carbon budgets will be one of the following steps of our investigations.

Talk

YEAR TO YEAR VARIABILITY OF NEW PRODUCTION IN THE NORTHERN NORTH PACIFIC ESTIMATED FROM REMOTELY SENSED SEA SURFACE TEMPERATURE AND CHLOROPHYLL *A*

Saino, Toshiro & Joaquim I. Goes*

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Introduction

The uptake of carbon dioxide by phytoplankton and its export out of the euphotic zone via the ocean's "Biological Pump", is an important avenue by which carbon dioxide is sequestered into the oceans. Understanding what regulates the efficiency of this "Biological Pump" and factors control the export of carbon into the ocean's interior, represents one of the major goals of the JGOFS.

Our present knowledge is that the magnitude of carbon transported into the ocean is balanced by "new production", or phytoplankton photosynthesis associated with allochthonous nitrogen, primarily nitrate, imported into the euphotic zone. Hence, measuring nitrate based new production is important as an alternate measure of the ocean's capacity to mitigate the build up of the atmospheric CO_2. Despite its importance, acquiring nitrate data by conventional shipboard means, at basin- annual to inter-annual scales required to fulfill the need for global synthesis and modeling of the oceans carbon cycle are grossly inadequate. Satellites have been suggested as an alternative, but the greatest impediment has been that nitrate lacks a remotely measurable signal. There have been some concerted attempts to meet such a requirement of large scale estimates of nitrate via remotely measurable proxies (Traganza *et al.*, 1983; Dugdale *et al.*, 1989; Sathyendranath *et al.*, 1991). Until now, one of the best known proxies for remote sensing of nitrate has been sea surface temperature (Traganza *et al.*, 1983; Sathyendranath *et al.*, 1991), because of its close negative relationship with nitrate (Kamykowski and Zentara, 1986; Chavez and Service, 1996). However, since temperature-nitrate algorithms are highly variable over space and time, the use of sea surface temperature to estimate nitrate from space has been limited. In our early study (Goes *et al.*, 1999), we have shown that this limitation in nitrate estimates from space could be overcome if biologically mediated changes in temperature-nitrate relationships are taken into account. We also demonstrated how estimates of new production, or more specifically that fraction of new production that could result from nitrate present in the euphotic zone at the start of the growth season, could be attained using satellite measurements of nitrate in conjunction with summer nitracline depths also obtained from remotely sensed data. Here we have used these findings to compare new production in the North Pacific for the years 1997, 1998 and 1999 and to show how the differences between these years could have been influenced by the El- Niño event of 1997/1998 winter.

Estimation of new production

A complete account of the method for estimation of new production has been presented in Goes *et al.*, 2000). In brief, the method utilizes satellite derived chlorophyll *a* and sea surface temperature to obtain estimates of sea surface nitrate. Monthly averaged estimates of nitrate are

then utilized to estimate the magnitude of nitrate uptake between winter and late summer. Using a molar carbon:nitrogen of 106:16 and a satellite based estimate of the depth of the water column above which nitrate is consumed, new production is calculated.

A comparison of the annual rates of new production for the years 1997 through 1999 using satellite data with those based on sediment trap flux measurements have been presented in Table 1. The highest values of new production for the years 1997 to 1999 were estimated in the western North Pacific, in the vicinity of the Kuril Island chains, where values ranging from about 31 to 38 g C m^{-2} y^{-1} were observed, probably as a result of intense vertical mixing and nutrient injection known to occur here. Sediment trap export flux values in excess of 50 g C m^{-2} y^{-1} have been measured. In the central Pacific (48N, 175E), annual carbon flux referenced to 100m approximated 37.4 g C m^{-2} y^{-1}, which is higher than our value of 17 g C m^{-2} y^{-1} for 1997 but, almost similar to our estimate for 1998. Towards the south, new production values decreased to attain values of *ca.* 2 to 20 g C m^{-2} y^{-1} around 30-35N consistent with sediment trap export flux values of *ca.* 7 to 13 g C m^{-2} y^{-1} (referenced to 150 m at these latitudes) for this region.

Although, a comparison between sediment trap and satellite estimates is not straightforward, the spatial trends observed in the estimates of new production are remarkably coherent with sediment trap estimates. These findings suggest that satellites could be utilized effectively to monitor basin scale- annual to inter-annual variations in new production, presently not possible by conventional means.

Location	Year	Meas.	Satellite			Reference
			1997	1998	1999	
50.0N, 145.0W (PAPA)	1982-1983	18.1[a]	17	19	14	Honjo (1997)
48.0N, 175.0E (NOPACCS)	1993-1994	37.4[a]	17	36	24	Harada (unpubl)
41.5N, 146.5E (W-PAC)	1983	54.1[c]	31	38	ND	Noriki & Tsunogai (1986)
34.0N, 142.0E (J-TRENCH)	1989-1990	12.6[a]	20	6	7	Handa *et al.* (1997)
33.0N, 139.0W (VERTEX)	1981-1984	13.0[b]	2	6	8	Martin & Knauer (1987)
30.0N, 175.0E (NOPACCS)	1993-1994	6.5[b]	3	10	7	Harada (unpubl)

a Converted to 100m b Converted to 150m a,b differs in euphotic depth
c Result from August to mid September

Table 1: Comparison of new production estimate from satellite data with POC flux ($gC/m^2/y$) measured by sediment traps

Year to year variability

A large year to year variation of the estimated new production is observed in the northwestern North Pacific. Examination of the monthly nitrate fields shows that this variation can be ascribed to the variability in the surface nitrate concentration which is maximal in March. In relation to the ENSO event which reached peak intensity in 1997/1998 winter, it can be clearly seen that the surface nitrate in March 1998 was higher than 1997 and 1999 in the western subarctic North Pacific, but lower in the eastern North Pacific along the coast of North America. These changes could result from the global scale change in the atmospheric circulation pattern associated the ENSO event. It is known that the Aleutian Low Pressure System intensifies and shifts westward in the El Niño years. This causes stronger winds, deeper mixing, and higher nitrate concentration than during normal winters in the western subarctic Pacific. In the eastern subarctic Pacific close to the west coast of North America, the reduction in new production can be related to the warming of surface waters by the northward propagating Kelvin waves carrying equatorial waters

along the coast. The reduction in biological production can be related to the shoaling of the mixed layer, dampening of coastal upwelling and a reduction in nutrient exchange that occurs during this time.

Talk and poster

MODELLING DUST-PHYTOPLANKTON AGGREGATE FORMATION AND MICRO-NUTRIENT CYCLING

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Correlations of organic and mineral particle fluxes are often observed in the water column. Both particle types originate from fundamentally different sources and the seasonality of their inputs into the ocean is different, too. Thus, there must be an efficient interaction between them in the upper ocean and during sedimentation, governed by processes like aggregation, adsorption, scavenging, and transfers associated with biological activities.

Mineral particles - dust grains - are the primary marine source of micro-nutrients like Fe, Mn, Ni, or Co that can be limiting factors of primary production and oceanic carbon fluxes. Furthermore, marine dust concentration can serve as an independent and conservative tracer in process studies and is useful for model verification and adjustment of model parameterizations.

To study the relative importance of these different processes which link organic and mineral particles, that is, to better understand the factors important for the provision of micro-nutrients, a new one-dimensional model was developed: "adam" (= algae, dust, animals, and trace metals). Adam combines two conceptual parts: (i) a nitrogen-based model of nitrate, ammonia, phyto-, zooplankton, and detritus with prognostic computation of phytoplankton aggregation, and (ii) additional aggregation of dust grains with phytoplankton and the transfers of dust between the different biological compartments. The model is driven by daily and annual cycles of insolation, mixed layer depth, and up- and downwelling. Due to a modular code structure, adam can be easily extended to include additional variables and/or embedded into other (e.g. 3-D) models.

Adam succeeds well to reproduce observed profiles of mineral particle concentrations (in the form of Al or particulate Fe): Free dust particles are efficiently removed from the mixed layer by aggregation with phytoplankton and sinking of the aggregates. After leaving the mixed layer, the aggregates partly decay because of remineralisation and phytoplankton mortality, and the dust grains are released to the water column.

Absolute dust concentrations as well as vertical gradients depend critically on the sinking speeds of aggregates, detritus and free dust particles, the rates of remineralisation and mortality, and the dust-phytoplankton stickiness. As one of the most important factors, higher remineralisation rates will increase the dust concentration below the mixed layer. More rapid sinking of free dust or detritus can reduce it because of faster transport to deeper layers, or increase it due to faster refill

from above. Model parameters of these processes are difficult to constrain, but with a reasonable choice, modelled and observed profiles are in good agreement.

Poster

SW-MONSOON IN THE WESTERN ARABIAN SEE: PHYTOPLANKTON DYNAMICS

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Monsoons are a determining feature of the Western Arabian Sea, reversing the general current directions twice a year. During the SW-monsoon (June to September) a region of intense upwelling occurs along the coast of Oman, from which long filaments of relatively cold and nutrient rich water develop and finally do stretch for several hundred kilometers into the open ocean.

Naturally, with changing monsoons, conditions for phytoplankton communities are changing too. Thereby three major regions within the Western Arabian Sea could be distinguished physicochemically for the SW-monsoon period: (1) the 'Central Arabian Sea' with stable oligotrophic conditions: SST above 28°C, a deep thermocline (about 80 – 100 m), nutrient concentrations below detection limit down to about 90 m associated with a deep chlorophyll maximum (DCM); (2) the 'Coastal Upwelling Region' with typical upwelling features of low SST (about 20°C) combined with relatively high nutrients in surface water (NO_3 and $Si(OH)_4$ concentrations from 5 to 18 µmol l^{-1} and from 7 to 10 µmol l^{-1} respectively) and (3) the highly variable 'Findlater Jet Region' with conditions ranging from oligotrophic to eutrophic from the outside to the inside of filaments: SST between 24°C and 27°C, a thermocline between 35 m and 102 m and NO_3 and $Si(OH)_4$ concentrations in surface water ranging from 0 to 10 µmol l^{-1} and from 0 to 5 µmol l^{-1} respectively.

Concerning phytoplankton dynamics these regions can easily be described and characterized with general parameters like surface chlorophyll a (chl a) and particulate organic carbon (POC) concentrations as well as primary production: 'Central Arabian Sea': 0.4 mg chl *a* m^{-3}, 85 mg POC m^{-3} and 10 – 14 mg C m^{-3} d^{-1}; 'Coastal Upwelling Region': 0.9 mg chl *a* m^{-3}, 150 mg POC m^{-3} and about 40 – 190 mg C m^{-3} d^{-1} and 'Findlater Jet Region': between 0.4 and 0.5 mg chl *a* m^{-3}, 120 mg POC m^{-3} and 80 mg C m^{-3} d^{-1}.

Analysis revealed a huge variety of different phytoplankton communities within the Findlater Jet region as well as the coastal upwelling.

Conceptional models of the different regions are presented which demonstrate the necessity of intense measurements for the understanding of a pelagic system.

SESSION: EXPORT AND DEEP OCEAN FLUXES

Talk

VARIABILITY IN THE CHARACTERISTICS OF PARTICLE FLUX IN THE ATLANTIC OCEAN AND THE IMPLICATIONS FOR ESTIMATION OF REGIONAL AND BASIN-WIDE EXPORT

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The oceans' biological pump is responsible for the formation of biomass from inorganic nutrients and carbon and, through the sinking of biogenic particles, for export to the oceans' interior (the tissue pump). The resulting drop in pCO_2 causes a drawdown from the atmosphere that is countered by a) biogenic carbonate production (the alkalinity pump) and b) the ventilation of deeper water with higher DIC values; both of which increase oceanic pCO_2 and are thus antagonistic in direction to photosynthesis as regards ocean – atmosphere gradients in pCO_2. Any net effect over climatically relevant time scales must thus not only take these effects into account but also consider them at the boundary across which the ocean reacts with the atmosphere in the exchange of soluble gasses i.e. at the depth of maximum surface mixing.

As part of the JGOFS Synthesis we have undertaken a compilation of a large number of sediment trap data from the Atlantic Ocean (81 years from 25 stations) with the following objectives:

- to determine regional characteristics of particle export within and between biogeochemical entities and to relate these to the mode of export and quality of sinking particles
- to formulate and differentiate regional algorithms relating export to new and total production and estimate the consequences thereof to particulate carbon export on the basin scale
- to estimate the relative contribution of the tissue pump and the alkalinity pump to carbon fluxes across the winter mixed layer depth and their net effect on potential ΔpCO_2 at the surface ocean / atmosphere boundary and determine its regional variability
- to thus attempt a quantitative, basin-wide estimate of the „net" carbon export for the Atlantic Ocean excluding the continental margins.

Site-specific variability in export is significant and yields a consistent pattern in grouping of and delineation between based on a large number of characteristics (export ratio, depth degradation rates, stability values, contributions of POC, PON, inorganic carbon and opal flux to mass flux). Contrary to expectation these did not correspond to the biogeochemical provinces as defined by Longhurst, but showed meridional and zonal differences more related to water masses and hydrography. Using the empirically determined flux patterns to estimate new production and f-ratio yields results closely correlated to those from model estimates (r^2=0.84). Pulsed export systems generally have higher export ratios (POC Flux / Primary production) and greater degradation with depth, that results in low variability of flux below 2500 m water depth but high site-specific variability at the winter mixed layer depth. Local algorithms thus derived differ

markedly from the global mean with implications for the response of the biological pump to changes in physical forcing.

Talk

THE WALVIS PARADOX - AN UNSOLVED PROBLEM IN PALEOPRODUCTIVITY.

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In most areas of the world where upwelling occurs, the intensity of upwelling seems to have been greater during glacial than during interglacial periods. This also seems to be true for the Benguela upwelling system, based on work on DSDP sites, ODP sites, and gravity and piston cores. However, as pointed out by Diester-Haass (1985) who studied sediments from Walvis Ridge, opal deposition suggests lowered productivity of silica-precipitating organisms during glacial periods. This poses a paradox: Increased upwelling seems to result in fewer diatoms deposited.

Recent work based on the sediments recovered during ODP Leg 175 (Wefer et al., 1998) has shed new light on this paradox, and has shown that it extends in scale at least to the last 3 million years, and involves a number of major astronomical cycles, between 400,000 years (eccentricity) to 41,000 years (obliquity). Opal deposition seems to be more or less in phase with astronomical forcing (or with d18O) in the same sense as found on Walvis Ridge, within the entire Benguela system. There is some indication that maximum opal deposition tends to center on times of cooling, slightly after the maximum warm time (or maximum seasonal contrast in insolation). The "Matuyama Diatom Maximum" (MDM), which is centered between the Gauss epoch and the Olduvai chron, may be another manifestation of this effect in phasing, since it is centered on a time period of major cooling of the planet. Coastal upwelling increases after the MDM but opal deposition decreases, on the whole.

A number of possibilities must be considered when attempting to explain the Walvis Paradox and the Matuyama Diatom Maximum. All of these have to do with the supply of silicate to the centers of coastal upwelling, and to the Benguela Current in general. During glacial times, apparently, the silicate supply was diminished. This could come from a decrease in the poleward transport of silicate in the deep undercurrent (which at present crosses the shelf, and during glacials would be confined to the upper slope), from a decrease in silicate (relative to phosphate) in thermocline waters (from moving subantarctic convergence areas into lower latitudes with more sunlight), or to an increased fractionation of phosphate from silicate in the water column, during glacial time - or a combination of these. Sporadic excursions of surface water of subantarctic origin have to be considered as a possibility for MDM time, because of the presence of high latitude species.

There are other regions where similarly paradox situations have been observed, notably in the North Pacific. Solving the Walvis Paradox should also help in explaining the counterpoint fluctuations of opal in the North Pacific and in the western equatorial Pacific.

Poster

HIGH VARIABILITY NEAR-BOTTOM SEDIMENT TRAP FLUXES ON THE EASTERN SLOPE OF THE FAEROE-SHETLAND CHANNEL

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An array of 4 moorings combining 2 sediment traps, equipped with optical backscatter sensors (OBS), and 2 current meters each was deployed in April/May 1999 along a cross slope transect in the stratified water of the Faeroe-Shetland Channel. In order to study the influence of internal waves on the generation of nepheloid layers on the slope, the sediment traps were situated at 2 meters and 30 meters above the bottom, at water depth of 550, 700, 800 and 1000 m on the southeastern side of the channel. They were each containing 12 cups programmed to collect for a 24 hours period and running synchronously for the 4 moorings. The results show very high variability of the total mass fluxes in time and depth. Fluxes correlated well with the particulate matter concentration data given by the OBS. The highest fluxes, up to 350 $g^{-1}m^{-2}day^{-1}$in the 800-m water depth trap, mainly consisting of silty material clearly suggested resuspension from the seabed. For the mid-slope traps (700 and 800 m water depth), the maximum fluxes were ~ 30 times higher than the background value (~ 1-5 $g^{-1}m^{-2}day^{-1}$) and occurred during the same period. For the 1000-m mooring the pattern differed, displaying a minimum and a sudden increase when the traps situated upslope recorded a maximum and a decrease respectively. Of all trap fluxes, those at 700 m increased the most abruptly with values going from 1.17 $g^{-1}m^{-2}day^{-1}$ to 97.4 $g^{-1}m^{-2}day^{-1}$ within a single day. This increase corresponded to rapid changes in hydrodynamics, resulting in shallowing of the pycnocline and enhanced turbulence of the near-bottom water column. The OBS data, providing a high time resolution, revealed that resuspension events were due to very short-term and abrupt processes taking place within a few hours, only.

Poster

DIFFERENT FEEDING STRATEGIES IN THE DEEP SEA: INSIGHTS FROM LIPID ANALYSIS

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We used lipid analysis to investigate the different feeding strategies in the deep sea of the Porcupine Abyssal Plain (PAP, 48°50' N, 016°30'W) in the Northeast-Atlantic. Some species of the benthopelagic calanoid copepods and benthic holothurians were studied.

The two groups showed differences in their fatty acid composition, which could be explained with different feeding strategies. The most common fatty acid in the copepods was the 18:1(n-9),

which is described as a constituent of carnivorous copepods (Albers et al., 1996). Other important fatty acids were 16:1(n-9) and the polyunsaturated 20:5(n-3), which, in combination, are biomarkers for diatoms (Dunstan et al. 1994). They are often incorporated largely unchanged into the storage lipids of copepods (Lee et al. 1971). The most abundant polyunsaturated fatty acid in the studied copepods was 22:6(n-3), which is described as typical for dinoflagellates (Sargent et al.1985) and haptophytes (Pond & Harris, 1996). The (n-3) polyunsaturated fatty acids are essential dietary components of marine animals and the production has conventionally considered to be supported by phytoplankton only. High amounts of these fatty acids may be an indicator of relatively fresh phytodetritus as one of their major food sources. Another possibility is, that these polyunsaturated fatty acids derive from deep-sea bacteria (Fang et al. 2000). By gut content analysis, Gowing & Wishner (1992) found bacteria-like bodies to be an important food source for deep-sea copepods.

The polyunsaturated fatty acids made up to 52 % of all fatty acids in the investigated holothurians (*Oneirophanta mutabilis* and *Psychropotes longicauda*). The 20:5(n-3) and 22:6(n-3) fatty acids were found in high amounts, however the 20:4(n-6) was most common. This is an astonishing fact since this fatty acid is described as a biomarker for litoral algae, especially for Rhodophyceae (Sargent & Whittle, 1981). However, benthic algae are commonly teared off and drifted into the open ocean (Hoek, 1987) and, in fact, Koppelmann (1994) found Rhodophyceae in flocculant material at the nearby BIOTRANS site.

Both, copepods and holothurians, use phytodetritus as one of their major food sources. But the fatty acid composition of the copepods reflect a carnivorous feeding behaviour, too. The holothurians in contrast fully exploit the phytodetritus.

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Poster

PRIMARY PRODUCTIVITY IN THE NORTHERN CANARY ISLANDS REGION AS INFERRED FROM SEAWIFS IMAGERY

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A 19 month record from September 1997 to March 1999 is presented of the productivity gradient along a 29°N transect through the Canary Islands region using SeaWiFS (Sea-viewing Wide Field-of view Sensor) chlorophyll data and the primary production method of Antoine and Morel (1996). Productivity estimates were made at points corresponding to three fixed sediments traps positioned during the same period east of the island of Fuereventura (EBC) and north of the islands of Gran Canaria (ESTOC) and La Palma (LP). The mean annual productivity during the 19 month period was observed to decrease westwards along the 29°N transect from 237 g C m^{-2} yr^{-1} at EBC to 164 and 145 g C m^{-2} yr^{-1} at ESTOC and LP, respectively. The high productivity at EBC indicates that this station is strongly influenced by the seasonal coastal upwelling off the adjacent Moroccan coast which is confirmed by SeaWiFS chlorophyll images showing incursions of the Cape Yubi filament over the EBC station. The ESTOC and LP stations are more characteristic of oligotrophic ocean with minimal if any influence of coastal upwelling in near surface waters. Comparison of model and *in situ* ^{14}C bicarbonate uptake productivity estimates suggest that the productivity difference between EBC and ESTOC/LP may be even larger than the model results indicate. This investigation suggests that the application of remote sensing to estimate primary productivity gradients in upwelling regions when combined with suitable ground truth data is a potentially very useful method.

Talk

OPAL FLUXES TO THE DEEP OCEAN: GLOBAL PATTERNS AND LONG-TERM CHANGES

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Biogenic silica (BSi) or opal plays a major role in the oceans' carbon cycle and is a potential proxy for paleoproductivity. Recent studies have stressed the role of diatoms as key players in the surface ocean and an increased diatom flux during glacial times could have reduced CO_2 in ocean and atmosphere significantly. However, the relationship between BSi and organic carbon fluxes (Si:C ratio) changes seasonally, interannually and regionally. Flux data from more than 30 sites from all oceans show a pattern of increasing Si:C ratios with increasing Si availability (relative to N and P) of the source waters, along the path of the oceans' conveyor belt. With respect to the export fluxes, the Atlantic is a "carbonate ocean", the Pacific/Southern Ocean are "silicate oceans" and the Indian Ocean is in-between. These inter-ocean differences in the BSi fluxes can be recognized in the deeper water column. Due to almost constant BSi fluxes below the surface layer, the Si:C ratios rise considerably with depth. Dissolution at the sediment surface is spatially variable but may perhaps only modulate burial rates. Long-term variations in opal versus carbonate fluxes can be observed, i.e. in the Sargasso Sea, most likely reflecting changes in the plankton community structure.

Talk

GEOCHEMICAL PROXIES FOR PALEOPRODUCTIVITY: STATUS AND PROSPECT

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During the past few decades, a wide range of geochemical proxies has been proposed to assess the evolution of specific oceanic processes over geological times. The processes that are most often targeted are paleoproductivity, ocean circulation and surface water properties (temperature, salinity, nutrients, density structure), all pertinent to our understanding of the evolution of the carbon cycle.

While individual proxies target well-defined processes, most of them are also affected by secondary factors whose variability imparts large uncertainties to our interpretation of the sedimentary record. This problem is also accentuated by the fact that, in many instances, we lack a clear mechanistic or quantitative understanding of the links between proxies and related processes.

As a first step towards remedying this situation, several recent studies have highlighted the need for using a "multi-proxy" approach for paleoceanographic reconstruction. This approach facilitates the identification of biases, while providing also important information on the nature

and variability of the secondary processes that produce them. Developing quantitative algorithms for the interpretation of tracers, however, is still work in progress. Achieving success in this endeavor will require integrating paleoceanographic proxies within modern ocean process studies, and closer collaboration between paleoceanographers and oceanographers.

I will present a brief overview of the present status of several tracers that have been used to estimate paleoproductivity. In particular, I will discuss the potential and pitfalls associated with methods that use the accumulation rates of various sedimentary constituents (organic carbon, biomarkers, opal, biogenic Ba, authigenic metals), ratios of particle-reactive radioisotopes, and tracers of nutrient status. I will conclude with my personal views on future prospects for the successful development of these tracers.

Poster

IMPACT OF LATERAL PARTICLE ADVECTION AND ORGANIC MATTER DEGRADATION ON SEDIMENT ACCUMULATION AND STABLE NITROGEN ISOTOPE RATIOS IN THE CANARY ISLANDS REGION

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Three moorings along a productivity gradient in the northern Canary Islands region were deployed with sediment traps. The productivity gradient documented in satellite derived pigment concentrations is reflected by the biogenic fluxes and their stable nitrogen isotopic composition intercepted by the upper traps. However, the primary flux signal is altered during settling of the particles and in the sediments. In addition to organic matter remineralisation, the lateral transport of biogenic particles strongly affects sedimentary fluxes and leads to an eutrophic overprint on the oligotrophic flux signal at deep-sea sites located up to 800 km offshore from the upwelling influenced coastal margin. Investigations of particle accumulation and micropaleontological and geochemical properties of surface sediments reveal that despite of particle degradation and lateral transport productivity gradients in the Canary Islands region are still matched in surface sediments. Even mesoscale features like the enhanced productivity related to the Cape Ghir filament are reflected in the surface sediments.

Although the gradients are smoothed, a qualitative reconstruction of productivity gradients by the investigation of sediments is possible.

Poster

BIGSET INVESTIGATIONS OF BENTHIC BOUNDARY LAYER PROCESSES AT JGOFS SITES: REGIONAL DISTRIBUTION OF DIFFUSIVE BENTHIC NUTRIENT FLUXES

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Benthic fluxes of silicic acid and nitrate were investigated in surface sediments of the abyssal Arabian Sea within the framework of the interdisciplinary BIGSET project (Biogeochemical transports of energy and matter in the deep sea). Investigations of biogeochemical cycles of primary produced organic carbon and biogenic silica in the water column and surface sediments are necessary to understand the transfer of these components from surface waters to the deep ocean, their remineralization, and nutrient recycling. Since pore-water profiles and benthic fluxes are sensitive indicators for the input of degradable organic matter and biogenic silica into surface sediments, we investigated pore-water profiles of nitrate and silicic acid in surface sediments of the abyssal Arabian Sea. Due to the monsoon, the Arabian Sea is a region undergoing great seasonal variability comparable to ocean basins of the high northern and southern latitudes of the Atlantic or Pacific Ocean.

To meet these strong seasonal variations caused by the monsoonal regime and reflected in the regional pattern of the primary production, the benthic data presented here were obtained during four cruises (1995-1998) undertaken throughout intermonsoonal periods after the NE- and the SW-Monsoon. Five main sites located in the northern (NAST), western (WAST), central (CAST), eastern (EAST), and southern (SAST) Arabian Sea were visited. In addition, several stations located in between these main stations were investigated to get more detailed information of the spatial variability of benthic fluxes in this region.

At the main sites benthic fluxes of remineralized nutrients from the sediment into the overlying bottom water were observed to be 36-106 $mmol \cdot m^{-2} \cdot yr^{-1}$ for nitrate and 102-350 $mmol \cdot m^{-2} \cdot yr^{-1}$ for silicic acid. The benthic fluxes and the pore water composition revealed a distinct regional pattern. Highest fluxes were observed in the western and northern part of the Arabian Sea, whereas fluxes decreased towards the southeast. The regional distribution patterns of the benthic silicic acid and nitrate fluxes thus reflect the general distribution patterns build up by primary production processes. The primary production pattern, indicating a shift in the phytoplankton community towards diatoms in the northwestern part of the Arabian Sea, can be tracked down to the sediment by means of regional silicic acid distributions. Apart from this general relation, there is a distinct decoupling of particulate organic matter and biogenic opal during further particle transport through the water column and remineralization processes at the sediment-water interface which differs regionally. These two proxies thus have to be treated separately in budget calculations and for reconstruction of paleoproduction and paleoclimate.

Apart from the station WAST, no significant temporal variability was found in the benthic nutrient fluxes. These short-time variabilities are restricted to this location, thus steady-state conditions regarding benthic biogeochemical processes are assumed to be valid for all other investigated stations in the Arabian Sea.

Results of the BIGSET investigations in the Arabian Sea will appear in autumn 2000 in Deep Sea Research Part II: 'Biogeochemistry of the deep Arabian Sea', No. 47/13.

Poster

B I G S E T INVESTIGATIONS OF BENTHIC BOUNDARY LAYER PROCESSES AT JGOFS SITES : DISTRIBUTION, BIOMASS, AND DIVERSITY OF BENTHIC FORAMINIFERA IN RELATION TO SEDIMENT GEOCHEMISTRY IN THE ARABIAN SEA

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The distribution, biomass, and diversity of living (Rose Bengalstained) deep-sea benthic foraminifera (>30 μm) have been investigated from multicorer samples from seven stations in the Arabian Sea during the intermonsoonal periods in March and September /October, 1995. Water depths of the stations ranged between 1916 m and 4425 m. The distribution of benthic foraminifera has been compared with dissolved oxygen, calcium carbonate, organic carboncontent, ammonium concentration, chloroplastic pigment equivalents, sand content, pore water content of the sediment, and organic carbon flux to explain the foraminiferal patterns and depositional environment.

A total of six species-communities comprising 178 living species were identified by principal component analysis. The seasonal comparison showsthat abundanceand biomass were higher at the western stations during the Spring Intermonsoon than during the Fall Intermonsoon. The regional comparison indicates a distinct gradient in abundance, biomass, and diversity fromWest to East, and for biomass from North to South. Highest values have been recorded in the western part of the Arabian Sea, where the influence of coastal and offshore upwelling induced high carbon fluxes.

Estimated total biomass of living benthic foraminifera integrated for the upper 5 cm of the sediment ranged between 11 mg $C_{org}m^{-2}$ at the southern station and 420 mg $C_{org}m^{-2}$ at the western station. Foraminifera in the size range from 30 to 125 μm, so-called microforaminifera,

contribute between 20% and 65% to the standing stock, but only 3% to 28% to the biomass of the fauna. Highest values were found in the central and southern Arabian Sea indicating their large faunal part in oligotrophic deep-sea areas.

The overall abundance of benthic foraminifera is positively correlated with oxygen content and pore volume and partly with carbon content and chloroplastic pigment equivalents of the sediment. The distributional patterns of the communities seem to be controlled by sand fraction, dissolved oxygen, calcium carbonate and organic carbon content of the sediment, but the critical variables are of different significance for each community.

Poster

BACTERIAL C-DEMAND (MINERALIZATION) IN THE APHOTIC DEPTHS OF THE ARABIAN SEA EXCEEDS MEASURED C-FLUXES FROM THE EUPHOTIC ZONE

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In the deep ocean the biological C-pump is counteracted by bacterial degradation of settling POC. By this process parts of settling POC are mineralised to CO_2 or kept into suspension. Thus less C enters the sea bed as suggested by initial POC fallout (C-flux) from the euphotic zone. The effectiveness of this process depends on growth, respiration and the hydrolytic capacities of bacteria and - to a minor extent - also on the grazing activities of zooplankton.

Bacterial C-demand (^{3}H-methylthymidin or ^{3}H-leucine incorporation) and hydrolytic enzyme activities were measured together with settling and suspended POC during the SW-monsoon process study of the German JGOFS Arabian Sea program. Depth profiles of these variables were determined at sediment trap stations along the cruise track from the equator to the upwelling regions off Oman. Drifting sediment traps were positioned at 115 m depth. Sedimentation rates were between 3.8 and 18.9 mg C m^{-2} d^{-1} were low, corresponding to 0.2 - 1.7 % of primary production. Suspended POC ranged from 51 - 188 mg C m^{-3} at above 115 m and was between 7.6 - 24.5 mg C m^{-3} at greatest depth. Integrated suspended POC below 115 m summed up to 155 g C m^{-2} at 4400 m. Bacterial C-demand (incorporation plus respiration) below 115 m was between 91 - 169 mg C m^{-2} d^{-1}.

The C-supply from settling POC covered bacterial C-demands in the meso- and bathypelagic zone by only 3.5 - 11.3 %. Suspended POC below 115 m (even if approximately corrected by vital POC) exceeded bacterial C-demands by far. Reduction of this pool by ~ 0.1 % d^{-1} can be regarded as a substantial contribution of bacteria to POC conversion in the water column. Increasing enzyme activities per cell in the deep indicated a high hydrolytic effort of bacteria under C-limitation. Potential turnover times of integrated suspended POC were 16 - 88 d in the upper layer (0 - 115 m) and ~ 1000 d below (115 m to greatest depth). Corresponding turnover times for PON, derived from protein hydrolysis, were 21 - 154 d and 357 - 526 d, respectively. Potential turnover times of suspended POC per m^3 in the deep (3800 m) were 10.9 y and 6.2 y for

its PON constituents. Potential contributions of settling and suspended POM (including TEP) to the bacterial C-supply are discussed in a conceptional model and by a review of corresponding statements from the literature. A mismatch between POC-flux and bacterial C-demand below the euphotic zone has also been observed by other investigators. It seems that this mismatch is particularly pronounced in the Arabian Sea. However, POC sedimentation rates in the Arabian Sea are extremely variable and not all periods are covered by simultaneously conducted measurements of bacterial C-demands.

Conclusion: Bacterial C-mineralization in the water column below the euphotic zone is higher than suggested by sediment trap POC-flux measurements. Since suspended POC is the intermediate semi-labile C-pool between (rare) utilisable settling POC and the refractory huge DOC pool it is hypothesised that suspended POC rather than settling POC is the most important source for the supply of bacterial C-demand (minralization) in the deep of the Arabian Sea.

Poster

ANNUAL NET CARBON CONSUMPTION IN THE ATLANTIC SECTOR OF THE SOUTHERN OCEAN

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Using phosphate and nitrate, chemical mass balances were constructed for the surface layers of the Weddell Sea and the southern Antarctic Circumpolar Current (ACC). Due to the specific nature of the Weddell Sea hydrography, where the surface layer is formed from the underlying Warm Deep Water layer through upwelling, the net biological consumption of nutrients can be estimated by comparing the concentrations in both water masses. Data from different sub-regions and different years hint that spatial and interannual variability of the net nutrient consumptions is very small. Nutrient consumptions were scaled to carbon consumptions using canonical redfield ratios. Redfield ratios between carbon and nitrate/phosphate were checked for validity using our in situ data. For the offshore Weddell Gyre a robust estimate of the annual carbon consumption, which is identical with the export production, amounts to 20 g C m^{-2} yr^{-1}. This is in the range of previous estimations using different methods.

The surface layer of the southern ACC is made up of upwelled Upper Circumpolar Deep Water and northward flowing Antarctic Surface Water from the Weddell Sea. A chemical mass balance of the surface layer using nitrate and phosphate yields both the fractions of these water masses, and the net nitrate and phosphate utilizations due to biological activity. It follows that the surface layer is formed from 90% upwelled deep water and 10% northward flowing surface water from the Weddell Sea. Nitrate and phosphate utilizations were converted to carbon utilizations with redfield ratios. Locally collected nutrient data suggest that the canonical redfield ratios are indeed

valid in this area. The annual net carbon utilization, approximately identical with the export production, for the southern ACC amounts to 76 ± 22 g C m^{-2} yr^{-1}.

Being an open ocean region, the southern ACC sustains a much higher export production than the marginal ice zone in the Weddell Gyre. This is surprising, as the open ocean is usually considered as a biologically poor region. The advantage of carbon consumption estimates calculated in this study using chemical mass balances is that they integrate over a longer period of time and a larger geographic area. Analogously silicate consumptions were estimated. We found that the silicate to carbon export ratios are very high, both in the Weddell Gyre and in the southern ACC, which suggests that high ratios are the rule rather than the exception in the Antarctic Ocean.

Poster

BIOGEOCHEMISTRY OF SETTLING PARTICLES IN TROPICAL MARINE REGIONS AFFECTED BY RIVER INPUTS

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River inputs of nutrients and particulate matter exert control on the production and sedimentation of organic matter (OM) in tropical marine regions which receive 90 % of water and 75 % of sediment discharged in the ocean, annually. We analysed settling particles from two tropical marine regions affected by the input of large rivers for bulk constituents, amino acid, carbohydrate and stable carbon and nitrogen isotope composition. Particle flux studies were performed in the the northern Bay of Bengal and the South Atlantic off eastern Brazil. The respective major rivers are the Ganges-Brahmaputra and the São Francisco.

Particle flux to the deep northern Bay of Bengal sampled over one year from October 1987 to October1988 revealed a distinct maximum related to the high discharge period of the Ganges-Brahmaputra river during SW-Monsoon (June - September), when precipitation over surrounding landmasses was at its peak. During this period, lithogenic material contributed up to 70 % to the total flux. At the same time, enhanced marine productivity caused elevated fluxes of OM and biogenic opal. $\delta^{13}C_{org}$ values of settling particles varied between –21.5 and -23.5 ‰ with heaviest values occuring during the peak flux period indicating an increased contribution of marine OM.

Off eastern Brazil peak fluxes of biogenic as well as of lithogenic matter coincided with the high discharge period of the São Francisco river. Their fluxes and composition indicate two phases of OM deposition. First the fluvial input of nutrients triggered a bloom of non-biomineralizing plankton which led to increased fluxes of fresh autochthonous OM in late February (phase I). Subsequently suspended sediment derived from the river and/or shelf erosion increased fluxes of refractory OM associated with lithogenics during the total flux maximum in March 1995 (phase II). $\delta^{13}C_{org}$ was in the range of marine plankton and displayed little temporal variability (-21.0 ‰ to -21.8 ‰) suggesting that major portion of the settling OM was of marine origin throughout the

whole sampling period. Despite a generally high seasonality of riverine inputs and related biogeochemical fluxes it appears that transfer of terrestrial carbon to the deep sea by settling particles is small.

Poster

ORGANIC PARTICLES IN SEDIMENT TRAPS: SUBSTANTIAL LOSSES TO THE DISSOLVED PHASE.

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We present results from various time-series traps in which the solubilized organic matter could be divided into fractions derived from swimmers and from the passive flux, using multivariate statistics. The larger share of the dissolved organic matter in the traps originated from swimmers, but also the contribution from passively trapped material was substantial, especially in in a shallow trap (135m). In this case, accounting for the solubilized organic carbon attributable to the passively trapped material yielded a vertical organic carbon flux 2.7 times larger than the conventional estimate which is based on recovered particles only. In the case of organic nitrogen, an even more than 6 times larger flux was obtained. Solubilization was fast, significant already after a few days. The share of the solubilized fraction of the passive flux is less important in deep traps, decreasing with depth, resuts from the North Atlantic are: 500m: 40% of the N flux; 1000m: 20%, 2000 and 3000m: 2% of C-fluxes. There is probably a large influence exerted by the preservative used ($HgCl_2$ in the shallow trap, formalin in the 500m trap and azide in all others).

Poster

A MULTIELEMENT (CARBON, NITROGEN, OXYGEN) BUDGET FOR THE JGOFS TIME SERIES STATION BIOTRANS (47°N, 20°W) IN THE NORTHEAST ATLANTIC

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Our synthesis is based on data from decade long sampling at the JGOFS Biotrans-NABE-47 Site (47°N, 20°W) in the Northeast Atlantic. New production and export from the winter mixed layer depth as well as the respective integrated remineralization rates based on nitrogen, carbon and oxygen are estimated using independent approaches. New production, as estimates from seasonal

changes in nitrate distribution, amounted to a drawdown of 620 mmol N m^{-2} yr^{-1}. The quotient of ΔDIC (dissolved inorganic carbon) and ΔNO_3 was close to the Redfield ratio (6.4 to 7.7) between March and the end of the spring bloom. During summer (June to August), an additional drawdown of DIC was observed which is equivalent to about 50 % of the spring-bloom drawdown, but not accompanied by any further nitrate uptake. During the growth season export of biogenic matter from the euphotic zone is due to the sinking of large particles (< 50 %), convective export of suspended particles (30 - 50%) and convective export of DOC (about 10 %). Organic carbon (DOC and POC) which accumulated during oligotrophic summer monthes is exported from the euphotic zone during autum and winter by convective mixing. The overall C : N ratio of remineralisation in the upper 400 m (winter mixed layer depth) which was estimated from seasonal budgets of oxygen and nitrate, is not significantly different from the Redfield ratio. Export from the winter mixed layer accounts for only 5 to 7 % of new production and has a mean C:N ratio of about 7.2. A small additional diffusive export of dissolved organic carbon is observed.

Poster

FIVE YEARS OF DEEP-SEA ZOOPLANKTON RESEARCH IN THE GERMAN JGOFS-INDIAN OCEAN PROJECT: RESULTS AND FUTURE PERSPECTIVES

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The main goal of the deep-sea zooplankton research in the German JGOFS-Indian Ocean project is to investigate the pathways of carbon within the pelagic deep-sea community. Until now, we participated on three cruises to Arabian Sea during the autumn intermonsoon in October 1995 (Meteor 33/1), the spring intermonsoon in April 1997 (Sonne 118), and the NE monsoon in February 1998 (Sonne 129). Zooplankton was sampled using a $1m^2$-MOCNESS and a $1m^2$-Double-MOCNESS with 9 or 20 nets, respectively, with a mesh aperture of 333 µm.

The analysis of the material resulted in:

1. A description of the temporal and spatial zooplankton distribution in the deep-sea of the Arabian Sea (Koppelmann and Weikert 1997, Koppelmann et al. subm.)
2. A calculation of the energetic carbon requirements of the bathypelagic zooplankton in relation to the input measured by sediment traps (Koppelmann and Weikert 1999, Koppelmann et al. 2000).
3. A description of the trophic structure and organic matter flux within the deep-sea zooplankton calculated by means of stable isotope analyses (Koppelmann and Weikert in press).
4. A description of the distribution of characteristic zooplankton taxa in the Arabian Sea (Fabian et al. subm.)

Future objectives of a national and international synthesis are (i) to define the fine-taxonomic structure of zooplankton and (ii) to estimate its significance for the carbon flux. Detailed questions which rely on an internationally based data set are:

- Which are the significant zooplankton taxa in the oxygen minimum zone (OMZ) of the open Arabian Sea?
  -- Are there plankton aggregations in the upper and lower boundary of the OMZ?
  -- Do these taxa undergo diel and/or ontogenetical migrations?
  -- How much carbon is transferred by this biota?
- Which are the main contributors to the zooplankton carbon flux in the bathypelagic zone?
  -- Why is the trophic level of zooplankton below 2500 m depth stable or even decreasing?
  -- How much carbon is stored and transferred by the near-bottom zooplankton?
  -- How are these rates related to the activity of the benthic community?

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Poster

POREWATER DISSOLVED ORGANIC CARBON (DOC) FLUXES TO THE DEEP-SEA: ARABIAN SEA VS. NE ATLANTIC OCEAN

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Dissolved organic carbon (DOC) is by far the largest pool of organic carbon in seawater. DOC fluxes from sediment pore water could be one of its source. However, information on the quantity and quality of pore water DOC is scarce. Within the frame work of BIGSET, pore water, sediment, and sediment trap samples from the NE Atlantic and the Arabian Sea were analysed for DOC and particulate organic carbon (POC).The POC fluxes into the deep NE Atlantic are lower than those into the deep Arabian Sea. The pore water DOC flux into the deep Arabian Sea accounts for 12-28 % of the decomposed POC. In the NE Atlantic less than 22% of POC decomposed at the sediment water interface escapes as DOC into the deep-sea. Moreover, the DOC flux at the stations in the Arabian Sea are characterized by significant spatial variations, whereas the Atlantic sites show considerably temporal distinctions. Our data further suggest that

not the quantity but the quality of POC as derived from analysis of particulate amino acids mainly controls the pore water DOC concentration. This suggests that porwater DOC leaving the sediments could serve as an important energy supply for micro-organisms living in the benthic boundary layer (BBL).

Talk

THE FORMATION AND DESTRUCTION OF PARTICLES

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From the perspective of biogeochemical cycling, the formation of particles represents a massive change in the "behaviour" of the chemical components whether they derive from the dissolved phase or from the seabed. The effect of particle formation is to expose the material to a wholly different range of processes including adsorption of surface-active chemicals and feeding by planktonic organisms. Particle formation also facilitates the development of microenvironments with very different characteristics to that of the surrounding water. In comparison with the dissolved phase physical displacement is no longer mediated solely by diffusion or advection; the addition of gravitational settling causes downward movements into very different water masses and physical regimes over short time scales (less than a day).

Although the temptation is to regard these physical structures as having a degree of persistence, it is likely that the vast majority of particles have lifetimes of only a few hours and at the end of that time they are either incorporated into a larger particle, broken up or even dissolved. Interactions with the biosphere from bacteria to mesozooplankton are thought to be crucial in controlling these phase changes although the relative importance of the different biological components is far from certain. Whatever the mechanisms, exchanges between the dissolved and particulate phases and between the different particulate size classes are likely to be very rapid and to have major implications for the fate of the compounds contained therein.

Inanimate particles range in size from the submicron colloids to macroscopic marine snow particles (up to several centimetres in diameter) with a very wide range of physical, biotic, microscopic and chemical characteristics. These properties affect to a very large extent "export" and "deep ocean fluxes", topics that are the focus of this session and some of the significant features of these characteristics will be discussed. The data used to compile vertical profiles of particle flux have very large uncertainties particularly in the upper part of the water column but, such as they are, they imply substantial decrease in flux with depth within the upper kilometre. It is in this part of the water column where most particles are formed from the dissolved phase and this, together with their destruction occurs at rates that are orders of magnitude higher than elsewhere. Resuspension from the seabed also generates a large particulate pool but although the characteristics of the particles and the mechanisms of generation are very different from that in the upper ocean, the factors that control their subsequent modification and removal have some features in common.

This presentation will be a personal perspective on the key advances that have taken place over the past decade and the implications of these advances for our understanding of export and deep ocean flux. The lacunae in our understanding are still large and serious but some of the current developments offer hope for a much deeper grasp of the factors that control the formation and destruction of particles in the sea.

Talk

THE ROLE OF THE COASTAL ZONE AND THE CONTINENTAL MARGINS IN THE TRANSFER OF MATERIALS INCLUDING C, N, AND P

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The world's coastal zones form a long narrow boundary between land and ocean that is highly valued by human societies. The Land-Ocean Interactions in the Coastal Zone (LOICZ) core project of the International Geosphere-Biosphere Program (IGBP) on Global Change studies this relatively small but highly productive, dynamic and sensitive area.

Major questions that LOICZ addresses on a global scale are:

- Is the coastal zone a sink or source of CO_2?
- What are the mass balances of carbon, nitrogen and phosphorus in the coastal zone?
- How are humans altering these mass balances, and what are the consequences?
- How do changes in land use, climate and sea level alter the fluxes and retention of water and particulate matter in the coastal zone, and affect coastal morphodynamics?
- What is the role of the coastal zone in trace gas (e.g., DMS, NO_X) emissions?
- How can knowledge of the processes and impacts of biogeochemical and socio-economic changes be applied to improve integrated management of the coastal environment?

The focus of LOICZ research is on horizontal material fluxes and scaling of processes through environmental and socio-economic science. To answer the major questions, the nutrient transfer processes across the continetal margins also need to be studied. LOICZ and JGOFS established a Continental Margins Task Team (CMTT) to coordinate these studies.

A definition of continental margins is, "those provinces of continents and of the ocean which are associated with the boundary between the oceans and the coastal zone". Although continental margins occupy less than 10% of the total sea surface, they are disproportionately important for the following reasons:

- They are regions of active biogeochemical interactions between land and the open sea; they provide a pathway for receiving, transferring and transporting large amounts of terrigenous natural and anthropogenic materials from land to the open sea. The flux of this terrestrial material, its spatial and temporal variation, and its ultimate fate all need to be understood before we can construct overall budgets of carbon, nitrogen and phosphorus in the ocean.

- The rate of biological production per unit area of the continental margin can be several times higher than in the open ocean, due to nutrient inputs from land, coastal upwelling, and so forth. In addition, the growth of various types of marine organisms in shallow waters apparently presently accounts for about half of the calcium carbonate production in the marine environment.

- The physical and biogeochemical processes occurring in the margins make these regions important for intense air-sea exchange of CO_2, N_2, N_2O, CH_4, DMS and other gases

- The high biological productivity, combined with the shallow water depths of the margins and terrigenous inputs of organic matter, makes this region the site of high organic matter deposition and associated benthic remineralisation. It has been estimated that up to 50% of the annual primary production of continental margins may reach the sea floor, where much of it is remineralised in a redox environment

- The sediment accumulation rates on margins can be orders of magnitude higher than in open ocean regions. Therefore these sediments may locally contain high resolution records (especially in basins with anoxic bottom water) of processes that have occurred at the margins in response to variability of environmental conditions.

- Development of realistic global scale models for the oceanic carbon-nitrogen-phosphorus cycles requires knowledge of fluxes across various ocean boundaries. Therefore a good understanding of the fluxes between the margin and the open ocean is crucial to model development.

- Several important commercial and subsistence marine fisheries are based at the continental margins, where biological production tends to be much greater than in the open ocean. Exploitation of marine organisms by humans results in the removal of biomass from the sea, destroys specific habitats like deep water coral reefs and also may impact the functioning of the marine ecosystem

The recent findings of LOICZ and the CMTT will be presented.

Poster

AN ATLANTIC DATA BASE FOR EXCHANGE PROCESSES AT THE DEEP SEA FLOOR (ADEPD): RESULTS

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Aim of the ADEPD project was to build up a joint data base for deep sea biological and geochemical data from a variety of sources and to conduct a preliminary geographical analysis of these data. Emphasis was on the North Atlantic, since from this area most data are available and it is the most perturbed deep sea region due to human activities. More than 114,000 published and unpublished data sets were collected in the last two years. The data are now archived in the data information system PANGAEA which ensures long term data stewardship and public access to the original data. A new and very simple approach to the data base via the world wide web was implemented. Now for the first time a large deep sea data base is easily accessible for the general public on: (under data, projects, ADEPD).

Evaluation of the data collection showed that data are clustered in some well investigated areas of the Atlantic, but large regions are devoid of data like the Mid Atlantic Ridge, parts of the South Atlantic and Southern Ocean. In particular biological data from the deep sea are much more scarce than geochemical ones, since many biological data from past investigations are not accessible in a suitable form at present. Most deep sea research projects did not carry out geochemical and biological studies at the same locations. Therefore, statistical comparisons between biological and geochemical data are very difficult despite the high total amount of data gathered. Different methods employed for the determination of one variable further complicate the matter. One of the major achievements of ADEP was to convert different measurements to common units. This allowed to investigate relationships between different chemical measurements, groups of organisms and turnover rates.

Two very different approaches to estimate the total turnover of organic carbon or oxygen (respiration) at the deep sea floor gave very similar results. Regional differences in both assessments point to methodological shortcomings by one or the other method and to gaps in data coverage. While estimates agreed well in central Atlantic regions, fairly large discrepancies were found at the continental margins. This indicates that there is still insufficient knowledge about transport processes and biological turnover of organic carbon along continental margins.

The following recommendations can be given on the basis of the ADEPD results:

- It is most important to secure deep sea biological data from so far inaccessible sources and to collate them in a data information system which guarantees long-term stewardship and public access.
- Biological and geochemical studies were mostly carried out separately which seems to be a systematic, scientific pattern and poses a problem in deep sea research. Interdisciplinary studies are essential to better understand of deep sea processes.
- The largest differences in estimates of oxygen fluxes at the sea floor are found at continental margins which export large amounts of organic carbon to the deep sea. The knowledge of transport and biological utilization at the continental margins need further attention.

- The data analysis carried out in ADEPD represents only a preliminary approach. More sophisticated statistical analyses promise significant scientific advances.

Poster

VERTICAL FLUX PATTERNS IN THE LAPTEV SEA AND OVER THE YERMAK PLATEAU

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During two "Polarstern" expeditions, fluxes of organic carbon and other particulate matter as well as biomarker composition of particulate material were measured at shallow depth by short-term deployments of sediment traps attached to ice floes in the Laptev Sea and in the area of the Yermak Plateau. In addition, two long-term deployments were carried out: one from September '95 - August '96 with two multi-sampling-traps (150 m below surface, 150 m above bottom) on the western Lomonosov Ridge and, another one from July 7 - August 3 '97 with one multi-sampling-trap (100 m above bottom) on the Yermak Plateau.

Sedimentation rates and composition of sedimenting particulate organic carbon over the Yermak Plateau were very similar to sedimentation rates measured in the Laptev Sea during summer. Exceptions were the stations influenced by the Lena river outflow. Here higher flux rates were measured. Accumulation of particles was most likely favored by the strong pycnocline at 20-30 m depth between marine water and overlying river plume. Biomarkers showed a more terrigenous character of the sedimenting organic matter for all mooring sites increasing with depth.

West of the Lomonosov Ridge vertical flux of particulate organic carbon in the water column at 25 m depth (mean 200 mgC m^{-2} d^{-1}) often exceeded that found at 5 m depth (mean 113 mgC m^{-2} d^{-1}) close to the undersurface of the sea ice. At 75 m depth, POC-flux was low at all sites (mean 20 mgC m^{-2} d^{-1}). Sedimentation rates above the Yermak Plateau were lower (mean 38 mgC $m^{-2}d^{-1}$) than in the Laptev Sea. The carbon flux in the long-term deployed traps on the eastern Lomonosov Ridge showed higher values from mid July until end of October (4 -21 mgC m^{-2} d^{-1}). During all other months sedimentation of particulate organic carbon was fairly low (0,2 - 4 mgC m^{-2} d^{-1}). The flux in the long-term deployed traps above the Yermak Plateau ranged from about 2 - 8 mgC m^{-2} d^{-1}.

Poster

VERTICAL DISTRIBUTION PROFILES OF PARTICULATE MATTER IN THE OCEAN OBTAINED WITH A DEEP-SEA CAMERA SYSTEM AND DIGITAL IMAGE ANALYSIS

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Most studies and calculations on export rates of particulate matter are based upon data obtained with sediment traps. The direct measurement of particle abundance, or studies on the "shape" of marine aggregates in the water column with this technique, is not possible. Therefore, estimations about the efficiency and processes influencing the *biological pump* are difficult. The deep-sea camera system *ParCa* provides the *in-situ* measurement of particle abundance, size distribution, volumina and turbidity. These parameters were extracted with aid of an *image analysis software* from the digitized pictures. Particle profiles have been taken on four different locations in the tropical and subtropical Atlantic.

The profiles show a large variability in particle abundance at the different locations, especially in the upper water column down to 500m. So far, there seems to be no correlation between the grain size distribution and the particle abundance. The calculation of the volumina show that the export of particulate matter is mainly driven by particles >0.5mm, known as *marine snow aggregates*. Another useful method for measuring the turbidity, apart from the *backscatter*, is the "*mean gray value*" of the digitized pictures. Both methods lead to similar results and a correlation between particle abundance and turbidity was found.

The distribution of particulate matter in the water column is dependent on several different factors, such as density discontinuities, currents, turbidity or the primary production. It is supposed, that not only one factor is responsible for the distribution of particulate matter in the ocean, but a combination of the mentioned factors.

Although optical methods have several advantages, they give no evidence about the composition of the particulate matter, like the porosity or the density. Quantifications of export rates are especially difficult for example, if material is laterally advected into a region. These transport mechanisms and factors responsible for the distribution of particulate matter in the water column and their role concerning the *biological pump*, are not sufficiently understood.

A solution could be the collection of high resolution data sets with known measurement and sampling techniques (Traps, Camera system, CTD etc) in oceanographic key regions. In addition, the deployment of a new system for *in-situ* sampling of *marine snow aggregates*, could close the gap between sediment traps and camera system. This system, based on a common *Remotely Operated Vehicle* (ROV), would be able to collect marine aggregates in the water column. Furthermore, *in-situ* studies on aggregation of particulate matter and the measurement of settling velocities, could be achieved.

Poster

DECOMPOSITION OF DIATOM FRUSTULES: COMPARISON OF SUSPENDED AND AGGREGATED MATERIAL

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Silica dissolution rates of aggregated diatom cells were compared to those of cells dispersed in the surrounding seawater (SSW) during conditions mimicking sedimentation below the euphotic zone. Changes in the concentrations of biogenic silica, silicic acid, cell numbers, chl. *a* and transparent exopolymer particles (TEP) were monitored within aggregates and in the SSW during two 42-day experiments. Whereas dissolution rates of dispersed cells were high (0.003 h^{-1}) resulting in the loss of about 50% of cells during the experiment, dissolution rates of aggregated cells were negligible during most of the 42-day study period. Initially, pore water concentrations of silicic acid in the aggregates increased to saturation concentration, suggesting that during the first hours to days some dissolution of aggregated diatoms occurred. Thereafter silicic acid concentrations in the pore water of aggregates remained high, and no further dissolution of cells was observed. This result implies that the loss of solutes out of sinking diatom aggregates is extremely small with an apparent diffusion coefficient that is 4-5 orders of magnitude smaller than molecular diffusion in seawater. Furthermore, these results suggest that dissolution rates of diatom frustules below the euphotic zone are primarily controlled by processes impacting formation and fragmentation of aggregates rather than by physical or chemical processes impacting dissolution directly. Findings of the extremely low dissolution of aggregated cells are consistent with observations that the majority of silica dissolution occurs within the upper 200 m, and that sedimentation rates of diatom frustules generally do not decrease significantly with depth.

Poster

BIGSET INVESTIGATIONS OF BENTHIC BOUNDARY LAYER PROCESSES AT JGOFS SITES: BIOGEOCHEMICAL CONTROL AND FEEDBACKS ON BENTHIC PROCESSES

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BIGSET (Biogeochemical transports of energy and matter in the deep sea) is a collaborative programme of eight institutions within the German research focus "Deep Sea Research" sponsored by the Ministry of Education and Research. Investigations focus on the benthic boundary layer (BBL) a zone extending from a couple of hundred metres above the sediment to about 5m into the sediment. The overall objective is to identify, quantify and model the principal

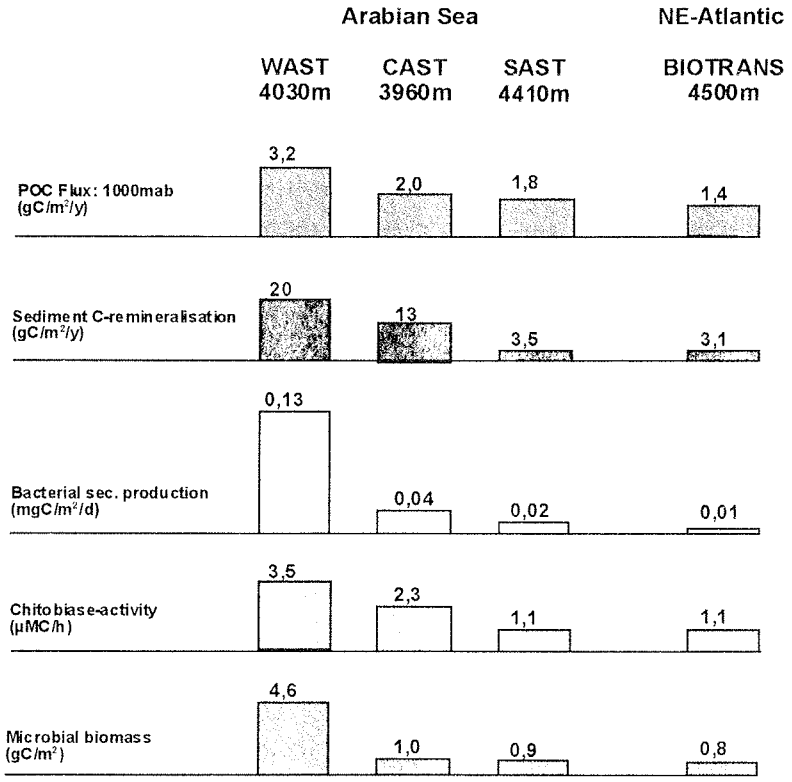
processes within the abyssal BBL which intercede between the incoming material flux and its incorporation into the permanent sedimentary record. A major objective is the parameterisation and quantification of the bentho-pelagic coupling to ascertain the net fluxes of inorganic and organic matter, especially carbon compounds and opal, on different temporal and spatial scales.

BIGSET investigations were carried out at sites investigated by JGOFS process studies: the Northeast Atlantic (BIOTRANS) and the Arabian Sea. BIOTRANS has been previously surveyed by the BIO-C-FLUX project. Both study sites are characterised by strong temporal variations in export fluxes from the upper mixed layer. The distribution of the five core stations NAST, WAST, CAST, EAST and SAST across the basin of the Arabian Sea provided a spatial coverage of the entire basin between 5°N - 20°N and 60°E - 68°E.

We expected that the trophic gradient along a spatially varying range of POC deposition in the Arabian Sea would leave its imprint on the biogeochemistry of the deep-sea benthos and we also supposed that the distinct biannual monsoon patterns could be detected.

A spatial gradient, very similar to that of surface water productivity estimated from satellite images, was found for a number of abyssal benthic element concentrations, turnover rates and various biochemical parameters. The station situated in the western Arabian Sea (WAST) closest to the upwelling region off Oman is clearly the most eutrophic region. The high rain rates of particulate organic carbon (POC) measured here by sediment traps are reflected by high concentrations of chlorophyll a inventories in the sediment. This station has significantly higher biomasses of macrofauna, meiofauna (nematodes) and bacteria compared to the other stations. Overall high benthic remineralisation rates measured by landers are comparable to rates found on upper continental slopes at upwelling regions. High bacterial production rates and activities of extra-cellular enzymes give further evidence of unusually high turnover rates. Benthic carbon consumption estimated from respiration measurements by benthic landers and from bacterial production are higher than the POC flux determined by the sediment traps. There is evidence from these and a number of other measurements that lateral input from the continental shelf increases the amount of organic matter consumed and deposited at this location. At the northern station (NAST) elevated values were found for many variables, but most were significantly lower than at WAST. The stations in the central (CAST) and eastern (EAST) Arabian Sea were intermediate and fairly similar. The southern station SAST is the most oligotrophic region of the investigated area, but it still bears some signs of monsoonal influences. Here some variables showed higher values than at other abyssal sites such as BIOTRANS (NE-Atlantic 47.30°N 20°W) which is influenced by mass sedimentation events after the spring phytoplankton bloom.

Although pronounced seasonal fluctuations of particle fluxes occur in the Arabian Sea, we could detect only a few significant temporal changes of benthic processes that can be linked to the monsoon cycle. This is partly due to the high variability in the benthic data but also perhaps due to the timing of our investigations. Apparently our investigations did not always hit the peak particle pulses which can vary more than one month in comparison to the multi-year average. Unexpectedly, most parameters describing biomass, metabolic activity or degradation rates exhibited an increase after the NE-monsoon. The effect is more pronounced at NAST and CAST and less distinct at WAST and EAST. It indicates that the impact of the NE-monsoon on the carbon cycling in the Arabian Sea was so far greatly underestimated.



The results from the BIOTRANS time series station give further insight to the extent of the pelago-benthic coupling in the abyssal open ocean in which the magnitude of POM influx determines the amplitude and duration of the benthic response. First in situ enrichment experiments demonstrate the fast response of the microbial community to detritus enrichment and give evidence to significant temporal variation in benthic carbon turnover.

Results of the BIGSET investigations in the Arabian Sea will appear in autumn 2000 in Deep-Sea Research Part II: "Biogeochemistry of the deep Arabian Sea", No. 47/13.

Talk

THE MONSOON DRIVEN ORGANIC CARBON PUMP

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Photosynthesis of organic matter and its subsequent transport into the deep sea links the marine plankton to the global climate via the so named biological organic carbon pump. The JGOFS Process study in the Arabian Sea aims to elucidate possible responses of this pump to the rising atmospheric CO_2 concentration and the associated global warming. The Arabian Sea is strongly influenced by summer heating and winter cooling of the Asian landmass. This leads to moderate NE winds (NE monsoon) during the boreal winter and the development of a strong low level Jet

(Findlater Jet) during summer (SW monsoon). Long-term sediment trap experiments in Arabian Sea have indicated that the organic carbon transport is controlled by variations in the depth of the mixed layer and the euphotic zone except in regions influenced by upwelling of nutrient enriched subsurface waters. This occurs during the SW monsoon along the Arabian coast and its velocity is related to the intensity of the Findlater Jet. Monsoon induced changes in the depth of the mixed layer and of the euphotic zone as well as upwelling result in three distinct blooms dominated by non-siliceous phytoplankton at the beginning of the NE monsoon (autumn), by diatoms at the end of the NE monsoon (spring) and also by diatoms during the SW monsoon. Changes in the intensity of the Findlater Jet could account for the natural variations of the mean annual organic carbon fluxes during the last 10,000 years as deciphered from the sedimentary record. Here we relate the mean annual organic carbon fluxes measured in the deep Arabian Sea to the primary production rates derived by different algorithms from CSZC-data considering Suess-types of models describing the water column decomposition of organic carbon. One of the major differences between the algorithms is the way in which they treat temperature effects on primary production. To integrate temperature effects into our study we compiled sediment trap data from different regions. They reveal the best correlation with those productivity algorithms which include an exponential increase of phytoplankton growth rates with increasing temperatures. This would imply that increasing temperatures, for example due to global warming, could increase the primary production. Since the export of organic matter from the euphotic zone is assumed to be balanced by nutrients mainly entrained from the subsurface into the surface layer, a temperature related increase in primary production could probably be caused by an increase in the regenerated production. This will not effect the export of organic matter and thus the biological carbon sequestering in the deep sea.

Poster

TEMPORAL VARIABILITY IN EXPORT PRODUCTION IN THE SE PACIFIC OCEAN: EVIDENCE FROM SILICEOUS PLANKTON FLUXES

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Flux of siliceous plankton and taxonomic composition of diatom and silicoflagellate assemblages were determined from sediment trap samples in coastal upwelling-influenced waters off northern Chile (30°S, 73°W, CH site) under "normal" or non-El Niño (1993-94) and El Niño conditions (1997-98). During the El Niño year the export of particulates is markedly lower: on an annual basis, total mass flux diminished by 60%, and diatom and silicoflagellate export by 75%. The flux of siliceous primary producers (diatoms and silicoflagellates) appears more strongly reduced than that of siliceous secondary producers (radiolarians). Positively anomalous SST in 1997-98 probably made mixing of the water column more difficult, resulting in upwelling of warmer, nutrient-poorer waters, and provinding fewer nutrients to the mixed zone than in an average year. Despite of the strong diminution of the flux of particulates in 1997-98, the seasonal pattern of events stimulating upwelling and the seasonal succession of siliceous organisms remain

unchanged, with diatoms numerically dominating the biogenic opal flux. The period of major export of biogenic opal and siliceous phytoplankton is rectricted to a very short time interval of 3-5 weeks in winter, when upwelling favorable winds dominate and highest phytoplankton pigment concentrations are obseved. This shows that the export of siliceous microorganisms is primarily controlled by the seasonal cycle of productivity. Major components of the diatom flora maintain much of their regular seasonal cycle of flux maxima (in winter) and minima under "normal" and El Niño conditions. Neritic resting spores of *Chaetoceros* dominate the diatom flux, mirroring the offshore influence of coastal-upwelled waters at the trap site. Pelagic *Fragilariopsis doliolus*, members of the Rhizosoleniaceae and *Azpeitia* spp. occur as secondary components, and reflect the intermingling of open-ocean Subtropical Surface waters. *Dictyocha messanensis* dominates the silicoflagellate assemblage almost year-around, while *Distephanus pulchra* delivers ca. 60% of its annual production in less than three weeks during the winter peak.

Poster

EXPORT PRODUCTION AND SHALLOW MINERALIZATION IN THE WEDDELL GYRE: ^{234}TH RESULTS COMPARED WITH BUDGET CALCULATIONS OF NUTRIENTS AND CO_2

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In the Antarctic Circumpolar Current (ACC), the region influenced by the southern Polar Front is characterized by relatively high productivity. This is mirrored by strong depletions of ^{234}Th in the surface water, a good tracer of export production, and by high accumulation rates in the underlying sediments. Further south, in the Weddell Sea, satellite observations, sediment accumulation rates, trap deployments, and phytoplankton distribution are all indicative of very low export fluxes. In these apparently low-productivity water masses we had expected ^{234}Th to be close to equilibrium with its parent ^{238}U. But in a series of high-resolution transects of ^{234}Th / ^{238}U across the ACC, ^{234}Th was depleted by 10-15 % throughout the clear Weddell Gyre, only to reach equilibrium in ice-covered regions of the Coastal Current. Vertical profiles showed that the depletion was limited to the upper mixed layer, and was balanced by an enrichment of similar magnitude in the layer of 100-250m depth. This implies that the export below 250m is negligible. Inverse modelling of nutrient distributions and calculations based on TCO_2 and oxygen sections strongly support this unexpectedly high export coupled with an unusually shallow mineralization. A CO_2 budget for the Weddell Sea implies a net downward export of organic carbon from the surface mixed layer, and a CO_2 enrichment of the underlying Warm Deep Water (approx. 200-700 m) which mixes in part eventually into Antarctic Bottom Water (AABW).

This blue ocean, characterized by upwelling of CO_2-enriched deep waters, supports sufficient productivity to be a net sink for CO_2 to abyssal depths. No record of this export is stored in the underlying sediment.

Poster

INVESTIGATIONS OF BENTHIC-PELAGIC COUPLING MECHANISMS VIA MASS BALANCES OF MARINE ORGANIC CARBON FLUXES IN BIOGEOGRAPHICAL PROVINCES USING GIS

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The marine organic carbon cycle was calculated for three different regions in the Atlantic Ocean. Supported by a Geographic Information System (GIS) a new method of spatial modelling was established to enhance detailed resolution, but still keeping the possibility for a basin wide calculation. For a realistic estimation of the world wide marine carbon cycle it is important to account regional aspects because of the high variability of oceanic regions. Therefore, summing up more realistic regional budgets may cause a considerable revision of existing global estimations.

In this study, the investigated regions are characteristic for three different marine regimes, which are: the northern North Atlantic with its subpolar climate and deep water formation, the northern West Atlantic with the Gulf Stream and the oligotrophic Sargasso Sea, and the equatorial East Atlantic with its equatorial and coastal upwelling.

The flux of organic carbon from the photic zone to the deep sea and its degradation at the seafloor was modelled and extrapolated by detailed empirical analyses of representative data sets for each region. For a spatial extrapolation three representative master parameters were defined: Primary Production (PP in g C m^{-2} a^{-1}) at the sea surface, organic carbon flux (F_{Corg} in g C m^{-2} a^{-1}) at the seafloor and the corresponding water depth (z in meters). Organic carbon fluxes at the seafloor were determined by oxygen demand measurements in surface sediments. For each of the regions, available data were collected and a final representative methodically homogenous data set of oxygen fluxes was installed in order to estimate the amount of organic carbon flux at the sediment-water interface. In contrast to these locally limited one-dimensional data, PP at the sea surface derived from satellite imagery and water depth were chosen as two-dimensional highly resolved spatial data sets.

Due to the continuous degradation of organic matter in the water column empirical relationships were established for each region by a non-linear regression method. The flux of organic carbon at the seafloor that passes the sediment-water interface was expressed by the product of PP as the initial gross amount of organic carbon at the sea surface and the corresponding water depth: $F_{Corg} = PP^{b} * z^{-c}$. The quality of this approach was proven by correlation coefficients between 0.89 and 0.96 as well as convincing results obtained by tests of the final regressions with independent data sets. With the help of these regional relationships the spatial distribution of organic carbon flux that reaches the sediment-water interface could be extrapolated for each region. Subsequently, the two gridded spatial data sets of PP by Antoine et al. (1996) and water depth by ETOPO5 (1988), both reflecting the natural distribution, enabled a cell-by-cell-calculation with an adequate resolution of 9.3 * 9.3 km. Equal area projections and overlay-techniques enabled exact planimetric analyses and mass balance calculations of each data set.

In order to investigate the benthic-pelagic coupling of the marine organic carbon cycle in each region the gridded flux data sets were divided by GIS-techniques into different zones: biogeographical provinces, morphological structures such as basins or slopes, and depth-dependent zones. Specifically, the northern North Atlantic reveals benthic remineralisation fluxes half as high as the two other regions and also smaller Export Ratios with a spatial variation of 1.7 to 2.0 % at 1000m water depth. The biogeographic provinces of the Gulf Stream and the Sargasso Sea in the northern West Atlantic are divided by different Export Ratios of 3 and 6 % at 1000 m water depth. Compared with global calculations, fluxes twice as high at the continental upper northeast American slope could be distinguished from extremely low fluxes in the deep sea. In contrast to the other regions, the equatorial East Atlantic shows significantly higher benthic fluxes with a constant high level throughout down to the abyssal plain due to the equatorial upwelling and high PP. Thus, local variability and specific dynamics are captured and adequately calculated both depth dependent and on a small regional scale. This partitioning shows a significant reflection of the biogeographical provinces of the sea surface from the benthic point of view. In contrast to global approaches, all three regions show different depth-related benthic remineralisation and specific regional distribution patterns.

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Talk

PELAGIC CALCAREOUS PARTICLE FLUX

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The oceanic carbonate system is intimately related to both atmospheric CO_2 and the global carbon cycle and therefore is of great interest to climatologists. Planktic foraminifers, as a component of the marine carbon turnover and the vertical flux, are of major interest for paleoclimatologists, because their tests carry fossil information on climates since the mid Cretaceous. Planktic foraminifers are only a small part of the marine zooplankton, but are major contributors to the vertical $CaCO_3$ flux rates, and cause a substantial portion of $CaCO_3$ and related CO_2 burial in deep-sea sediments.

Multinet plankton and sediment trap samples from the eastern North Atlantic Ocean and the Arabian Sea, collected during cruises of the German JGOFS, have been analyzed to assess the contribution of planktic foraminifers and coccolithophorids with respect to the global ocean

carbonate budget. Both oceanic regions cover a wide range of physical, chemical and biological characteristics of the tropical and temperate world oceans, and are well suited to differential and comparative analysis of oceanic properties. Sediment trap data from various sites of the world oceans were used for calibration and comparative monitoring.

The most detailed record on planktic foraminiferal population dynamics and carbonate flux is available from the eastern North Atlantic BIOTRANS station at 47°N, 20°W. Two maxima in flux rates occur in spring and fall at 100-200 m water depth with lows during winter and summer. Maximum test export from the mixed layer during April and May can be followed through the water column and reaches a depth of 2500 m between June and September. The most drastic decrease in flux rates occurs between 100 and 700 m depth occurs above the calcite lysoclines (Figure 1). Bacterial decay and predation are not the cause of the decreasing planktic foraminiferal $CaCO_3$ mass. The planktic foraminiferal flux patterns observed at BIOTRANS and the Arabian Sea are most likely controlled by population dynamics and the settling velocity of tests.

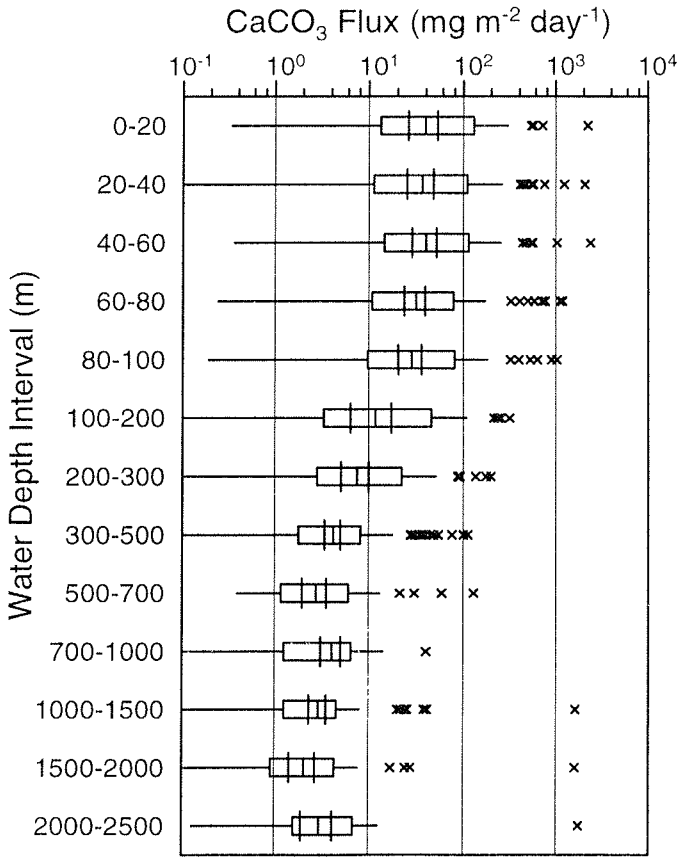

Figure 1:
Boxplots of the planktic foraminiferal $CaCO_3$ flux including multinet data obtained from the North Atlantic, Arabian Sea, and the Caribbean (n = 1817). The flux is similar for different depth intervals within the upper 100 m of the water column, and decreases significantly between 100 and 700 m. Below 700 m no significant change in flux rates has been observed.
Outlayers are marked by crosses.

The majority of planktic foraminifers live in the upper 100 m of the world ocean, and the 100 m level can be regarded as the initial flux level. The most prominent decrease in calcareous particles occurs between 100 and 700 m water depth. Within the upper 700 m, planktic foraminiferal flux decreases by about one order of magnitude, and no significant decrease is observed below. However, frequent variations in the vertical flux occur between 500 m and 1000 m water depth on various temporal and spatial scales. $CaCO_3$ flux rates may vary within two orders of magnitude, within the same depth horizon at different locations of the ocean. Below 700 m flux rates decrease asymptotically, and about 1 % of the planktic foraminiferal $CaCO_3$ reaches the sediment surface. Better preservation of tests in the Arabian Sea than in the Atlantic is caused by higher settling velocity that can be traced during high-productivity in the SW monsoon, and is also suggested to be due to reduced degradation within the prominent oxygen minimum zone.

Poster

MODERN COCCOLITHOPHORE SEDIMENTATION IN THE CANARY ISLANDS REGION: SEASONAL VARIATION, SPECIES COMPOSITION AND COCCOLITH-CARBONATE FLUXES

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Coccolithophores as one of the main primary producers in the surface waters of the Canary Islands region, were investigated to quantify coccolith and coccolith-carbonate export fluxes and to determine seasonal trends in species composition. Coccolithophore flux variations in sediment traps at three mooring locations along an E-W transect at approx. 29° N from the NW African shelf region to the open ocean were recorded from late December to September 1997. The particle traps were deployed at different depths between 700 m and 3800 m below sea surface.

In general, total coccolith fluxes were characterized by a strong seasonality. At the upper trap level, maximum coccolith flux values were reached simultaneously in all three traps at the beginning of Febuary 1997. While total coccolith flux rates and fluxes of different species at the two oceanic sites LP (La Palma) and ESTOC (European Station for Time-Series in the Ocean, Canary Islands) were comparable, fluxes increased significantly towards the shallower site EBC (Eastern Boundary Current). At the deeper trap level, the sedimentation pattern appeared similar to the trend observed in the upper traps. Maximum coccolith fluxes were also reached during spring time, approx. one month after the flux peaks in the shallower traps. In addition, an increase of total coccolith fluxes with depth indicates the influence of deep lateral advection to the mooring locations. The examination of all trap samples revealed a highly diverse coccolithophore assemblage with three species (*E. huxleyi*, *F. profunda*, *G. ericsonii*) contributed significantly to the assemblage.

In all trap samples a conversion of coccolith fluxes into coccolith-carbonate fluxes based on mean species-specific carbonate masses was made. The mean contribution of coccolith-carbonate fluxes to the total carbonate fluxes in each trap was approx. 30%. The coccolith-carbonate fluxes

are dominated on the one hand by small-sized coccoliths of the dominant species *E. huxleyi*, *G. ericsonii*, and *F. profunda*, on the other hand by the larger, but less dominant species *C. leptoporus* and *U. sibogae*.

Poster

BIGSET INVESTIGATIONS OF BENTHIC BOUNDARY LAYER PROCESSES AT JGOFS SITES: INFLUENCE OF THE NEAR-BOTTOM MIXED LAYER ON ^{234}TH DYNAMICS IN THE ABYSSAL WATER COLUMN ?

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Recent work suggests that substances of global biogeochemical relevance (organic carbon, calcium carbonate) might considerably be affected by resuspension within bottom nepheloid layers (BNLs) (Rutgers van der Loeff and Boudreau, 1997; Lampitt et al., 2000). Noticibly invariable distributions of transmission, nephels and / or potential temperature directly above the abyssal seafloor have often indicated a bottom mixed layer (BML), generally exhibiting a thickness of < 100 m and being the bottommost part of abyssal BNLs. Kilometer-scale bottom topography and convergence / divergence of the flow of mesoscale eddies in the water column above the BML are suggested to be the principal control of the BML thickness (Richards, 1990). As the upper boundary of the mixed layer and the sediment-water interface restrict particle and fluid transfer across these interfaces the BML and its physical structure should affect 'biological, chemical and geological processes at or near the ocean floor and how these processes communicate with the ocean interior' (Richards, 1990). In this study the distribution of the natural particle-reactive radiotracer ^{234}Th in the near-bottom water column (cf. Bacon and Rutgers van der Loeff, 1989) and in the surface sediment at a study site in the Northeast Atlantic (Porcupine Abyssal Plain) and a simple box-modelling approach were used to investigate the influence of the BML in the abyssal near-bottom water column on ^{234}Th dynamics.

Calculated residence times suggest that the BML is a highly dynamic system with respect to particle cycling and sorptive reactions on time scales of days up to weeks (cf. Bacon and Rutgers van der Loeff, 1989; Rutgers van der Loeff and Boudreau, 1997).

Modelling results indicate that an increasing thickness of the BML might result in (1) increasing residence times of $^{234}Th_{part}$ (and particulate matter) in the BML with respect to the net fluxes across the upper and lower boundaries of the BML; (2) declining adsorption rate constants in the BML; (3) increasing desorptive fluxes in the BML causing (4) enhanced ^{234}Th decay in the BML; (5) decreasing net $^{234}Th_{part}$ (and particulate matter) fluxes from the the BML to the upper BNL above the BML and to the resuspension zone. Potential consequences for carbon cycling are discussed. It is concluded that the BML might be a decisive filter for the exchange of matter and biogeochemical information between the ocean interior and the sediment as suggested by Richards (1990).

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Poster

THE ROLE OF MESOZOOPLANKTON IN THE CARBON CYCLE OF THE ARABIAN SEA

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Developing predictive models of carbon flux and their relation to primary production requires an understanding as complete as possible of the pelagic ecosystem. The amount of biogenic material leaving surface waters is dependent on how it is partitioned by the plankton community. The species composition of the autotrophs and heterotrophs determines the amount of carbon that is either recycled in the euphotic zone or is exported to depth. Mesozooplankton (> 200 µm), through their process of ingestion and egestion, can be important in determining the size and composition of sinking particulate matter. Therefore direct grazing measurements in the surface 100 m for Salps and the dominant copepod species (*Calanoides carinatus* and *Eucalnus crassus/monarchus* and *Rhincalanus nasutus*) was carried out on the cruise SONNE-120 (12.June – 17. July 1997) in the Western Arabian See during the SW Monsoon. The ingestion rate ranged between 16 and 69 mM C m^{-2} d^{-1}, which corresponds to 23 - 92% of primary production. The estimated faecal pellet production (egestion = ingestion x 0.3), averaged 13 mM C m^{-2} d^{-1} or roughly 15% of primary production, was greater than the faecal pellet export flux measured in the sediment trap during this investigation. The trapped faecal pellets carbon (FPC) represents nearby 6% of the total particulate organic carbon flux.

Our data suggest that the grazing impact of mesozooplankton is significant in the Arabian Sea as a consequence of the high zooplankton biomass, principally of the herbivore copepods *Calanoides carinatus* and *Eucalnus crassus/monarchus* in the upwelling system. Furthermore the high differences between estimated faecal pellet production and measurement of export flux lead to the assumption that most of the produced pellets are either recycled in the euphotic zone or transported out of the upwelling area into the open ocean.
This results are compared with published data on grazing and faecal pellet production during the monsoon seasons to assess the role of mesozooplankton in the carbon cycle in the Arabian Sea.

Poster

A COMPARISON OF COCCOLITH FLUXES FROM THE WESTERN, CENTRAL, AND EASTERN ARABIAN SEA

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The coccolith export production of three mooring arrays in the western (WAST-13), central (CAST-12), and eastern (EAST-13) Arabian Sea was investigated. Traps were deployed in about 1000 and 3000 m water depth. Sampling in the central Arabian Sea was carried out from November 1995 through April 1997 while the western and eastern traps sampled between June 1997 and February 1998.

Coccolith flux of the shallow traps differed significantly from the deep ones in terms of the pattern and export production. In general the coccolith fluxes of the shallow traps were lower (mean coccolith flux 2.7 x 10^8 coccoliths m^{-2} d^{-1}). In all deep moorings the coccolith fluxes were relatively uniform in contrast to diatom fluxes which strongly prevailed at the western Arabian Sea. In general, highest coccolith fluxes were observed during the southwest monsoon. At the deep western trap the highest fluxes were observed during July/August 1997 while at the central and eastern traps the highest fluxes occurred in late September, during SW monsoon. Subsidiary high fluxes were recorded during northeast monsoon, lowest fluxes during the intermonsoon periods. Mean coccolith fluxes increased slightly from the western towards the eastern Arabian Sea. The fluxes in the deep traps ranged between 1.85 x 10^8 and 1.44 x 10^9 coccoliths m^{-2} d^{-1} at WAST, between 2.12 x 10^8 and 8.68 x 10^8 coccoliths m^{-2} d^{-1} at CAST, and between 3.73 x 10^8 1.03 x 10^9 coccoliths m^{-2} d^{-1} at EAST. Coccolithophore diversity was lowest, one sammpling interval before or during the highest coccolith fluxes occurred within the southwest monsoon period. Dominant species was *Gephyrocapsa oceanica*. Associated species like *Emiliania huxleyi*, *Calcidiscus leptoporus*, and *Umbilicosphaera sibogae* var. *sibogae* and var. *foliosa* prevailed at WAST, while *Oolithotus antillarum* was abundant at CAST, and *Umbellosphaera irregularis* and *Florisphaera profunda* were common at EAST.

The comparison of coccolith assemblages from the western to the eastern sediment traps exhibited a gradient from more turbulent towards more stratified waters, and from more eutrophic towards more oligotrophic nutrient conditions, and a deepening of the nutricline. At WAST a high positive correlation of coccolith frequency with opal and the organic matter flux occurred in contrast to EAST, where the coccolith assemblage was associated with higher lithogenic and carbonate fluxes. Increasing relative proportions of *G. oceanica* indicated maximum intensity of upwelling during southwest monsoon. The general dominance of this species is due to its adaption on eutrophic nutrient conditions, lithogenic input, turbulence, and resistance toward dissolution. An average annual coccolith calcite flux rate of 4 g m^{-2} y^{-1} is assumed for the deep traps while planktic foraminifers contributed 7.15 g m^{-2} y^{-1}.

SESSION: BIOGEOCHEMICAL CYCLES AND CLIMATE VARIABILITY

Talk

OCEAN BIOGEOCHEMISTRY USING SATELLITE OBSERVATIONS – CHALLENGES AND OPPORTUNITIES

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Satellites provide a unique platform from which to observe the world ocean. By providing a global perspective at moderately high resolution, satellites can observe mesoscale processes which are difficult to sample from ships. However, satellites present challenges as well. Clouds can obscure much of the ocean for long time periods, preventing measurements of ocean color. Complicated algorithms are required to transform the satellite data into quantities of interest to oceanographers. As we approach the end of JGOFS, there is now a full complement of satellite sensors in orbit, including ocean color, sea surface temperature, ocean topography, vector winds, and sea ice. I will review these data sets, focusing on their application to the fundamental scientific issues of JGOFS. Estimation of primary productivity from ocean color data is of particular interest, and there has been considerable progress in recent years. I will also review satellite measurements from the Southern Ocean, where ocean circulation and sea ice are especially important to biogeochemical processes. As new global ocean programs begin to emerge, there will be a new suite of satellite sensors that will provide continued coverage as well as new capabilities.

Poster

VARIATION OF LATE QUATERNARY SEDIMENTATION PROCESSES IN THE ARABIAN SEA DETECTED FROM $\delta^{15}N$

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Denitrification in the modern mid-water oxygen minimum of the Arabian Sea is the predominant control of the nitrogen isotopic budget. It enhances present $\delta^{15}N$ values of nitrate compared to other oceanic areas with the uptake of this nitrate leading to high $\delta^{15}N$ values in suspended and sinking organic matter as well as sediments. It has been shown that $\delta^{15}N$-values vary in response to ice volume changes suggesting that denitrification has been, relatively, reduced during cold stages and enhanced during warm stages such as the present. High resolution cores have, moreover, shown that millenium scale fluctuations are reflected in the $\delta^{15}N$ records which could be attributed to climatically induced productivity changes but not to ice volume changes. Water column $\delta^{15}N$ signals are further modified by early diagenesis increasing the $\delta^{15}N$ values in

response to the intensity of degradation. This leads to, generally, higher $\delta^{15}N$ values in the abyssal areas compared to the shelf and slope sediments where early diagenetic organic matter decomposition is reduced. Here we present high frequency $\delta^{15}N$ fluctuations from sediment cores in the northern and eastern Arabian Sea confirming that millenium scale fluctuations of denitrification prevail throughout the basin. Moreover, we use $\delta^{15}N$ in conjunction with bulk components and element distributions to distinguish between pelagic and turbiditic sections as well as to determine the source of turbidites in cores from the western Arabian Sea and the Indus Fan.

Poster

THE IMPACT OF IRON ON PHYTOPLANKTON BLOOM DEVELOPMENT - SIMULATIONS WITH A COUPLED OCEAN-PLANKTON MODEL

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Field measurements and laboratory experiments investigating the HNLC (High Nutrient Low Chlorophyll) areas of the equatorial Pacific and the Southern Ocean indicate that iron addition stimulates phytoplankton growth, mainly of diatoms. These findings led to the hypotheses that phytoplankton growth in HNLC areas is limited by iron deficiency. Additionally iron supply appears to affect the uptake ratio between the nutrients silicate and nitrate: The Si:N uptake ratio rises in case of iron deficiency, which is consistent with observations from the Southern Ocean where the iron concentration is low and heavily silicified diatoms are abundant.

To investigate the processes affecting the development of phytoplankton blooms and the effects of iron limitation we developed a coupled ocean-plankton model with a resolution of 6 km. In a periodic model domain, eddy resolving model runs are initialized using WOCE data from the Antarctic Polar Front and forced using a diagnostic surface energy balance.
The biological model comprises the compartments phyto-, zooplankton, the nutrients nitrate, ammonium and iron as well as silica- and nitrogen based detritus.

The frontal structure with meanders and eddies is well reproduced.
Model results indicate that phytoplankton blooms with concentrations higher than 2 µg Chl *a* /l only develop in regions of a shallow mixed layer depth. Mesoscale patterns in the distribution of mixed layer depth are reflected in the distribution of phytoplankton biomass.
Low iron concentrations are correlated with low phytoplankton biomass. Experiments neglecting iron limitation but including different Si:N uptake ratios indicate that increasing Si:N uptake ratios lead to a decrease of plankton biomass. The effect of different Si:N uptake ratios on phytoplankton biomass is significantly higher than reducing the maximum growth rate.

Poster

PALEOPRODUCTIVITY AND FE-FLUX VARIATIONS IN THE BENGUELA UPWELLING SYSTEM OF THE LAST 1.5 MA

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Detailed records of foraminiferal oxygen isotopes, mass accumulation rates of $CaCO_3$ and TOC in combination with XRF-core-scanner analyses of Ca and Fe for ODP Leg 175, Site 1082 from the Walvis Basin reveal the timing of paleoclimatic events in the northern Benguela system over the past 1.5 Ma. The most pronounced climatic changes detected in our records correspond to the Mid-Pleistocene Revolution (MPR, Berger & Jansen, 1994) and the Mid-Bruhnes carbonate maximum event (Jansen et al., 1986).

Stable oxygen isotopes have been measured on the planktonic foraminifera *Globorotalia inflata* to obtain a chronology for the last 1.5 Ma. A comparison between oxygen isotope data from Site 1082 with those from benthic foraminifera in the central equatorial deep Atlantic (ODP Site 664 after Raymo et al., 1997) show a good correspondence for glacial-interglacial cyclicity. In contrast to the benthic oxygen isotopes with a more or less constant glacial-interglacial range of isotopic values, planktonic isotope ratios at Site 1082 show a tendency to lighter values by about 1 per mil over the last 0.65 Ma.

General sedimentation rates are remarkably constant over the time period from 0.70 to Holocene, with pronounced drop from about 13.5 cm / ka before 0.70 Ma toward 10 cm / ka after 0.70 Ma, which is about 0.20 Ma after the MPR event after Berger & Jansen (1994).

In the Northern Benguela upwelling system carbonate fluxes and preservation were enhanced during interglacial intervals and show a long-term variability with maxima roughly every 400 ka.

Organic carbon accumulation taken as a paleoproductivity indicator and the input of terrigenous material by eolian transport (Fe counts measured by XRF) are also higher during interglacials compared to glacials with a pronounced amplitude in sediments older than 0.55 Ma BP. From 0.55 Ma BP to the Holocene TOC and Fe indicate an abrupt shift to a low-amplitude variability at a periodicity of 100 ka. The obtained sedimentary records indicate that the Benguela Upwelling system had been stable between 0.55 and 1.5 Ma. Since 0.55 Ma BP the upwelling intensity decreased, while warming took place in surface waters. This may have occurred in response to an increase in northern hemisphere glaciation.

Talk

A COMPARISON OF THE BIOGEOCHEMISTRY OF THE EUROPEAN TIME SERIES STATION ESTOC WITH BATS AND HOT

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The past decade has witnessed a wealth of insights into the functioning and climate-sensitivity of oceanic biogeochemistry through intensive sampling programs at key sites in the open ocean. The sampling protocol of open ocean time-series stations allows for the investigation of the seasonal as well as multi-year and decadal variability of processes that affect the biological pump and ultimately the sequestration of anthropogenic CO_2.

Here we present a five-year data record collected at the European time-series station ESTOC north of the Canary Islands. This Spanish-German collaborative project was initiated in 1994 and even though the array of standard measurements and rates are restricted for logistical reasons, the data for the first time permit a comparison between this and the more established time-series stations BATS (western subtropical Atlantic) and HOT (tropical Pacific). Differences in the biogeochemical features especially between the eastern and western subtropical biomes of the North Atlantic are manifested for example in different export ratios, a crucial parameter when relating remotely determined primary production with the net removal of CO_2 from the mixed layer.

We will discuss differences in eolian deposition, nitrogen input (both diapycnal and by dinitrogen fixation) and nutrient stoichiometry to interpret the particular biogeochemical features of the ESTOC.

Talk

CLIMATE SENSITIVITY OF BIOLOGICAL PRODUCTION IN A MODEL OF THE NORTH ATLANTIC

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An eddy-permitting coupled ecosystem-circulation model of the North Atlantic is used to investigate the sensitivity of new and primary production to interannual to decadal changes in the atmospheric forcing. In a first suite of experiments simulations are performed for high and low phases of the North Atlantic Oscillation (NAO), persisting for five years each. The resulting changes in the winter mixed layer depth along the northern margin of the subtropical gyre show a good agreement with historical data near Bermuda, where simulated export production varies by about a factor of two between phases of high and low NAO index. Another area of NAO-related variability is the biological production associated with the coastal upwelling off West Africa. Here, variations in the wind stress lead to enhanced upwelling and off-shore transport of nutrients and biomass when the NAO index is high.

A second suite of experiments employs realistic monthly and daily atmospheric forcing fields for a five-year period (1989 to 1993) during the observational phase of JGOFS in the North Atlantic. Significant interannual changes in the nutrient supply are observed, particularly along the boundary between subtropical and subpolar gyre in the eastern North Atlantic, and in the equatorial and coastal upwelling regions. In mid- and high latitudes, the variability in primary production and also in simulated stocks of phyto- and zooplankton is found to be closely related to changes in the nutrient supply in winter and early spring. These are dominated by changes in vertical mixing whereas changes in horizontal or vertical advection play a secondary role in regional averages.

Talk

PHYSICAL FORCING OF PHYTOPLANKTON GROWTH

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A primary concern of JGOFS is „to develop coupled physical and biogeochemical models of the ocean for the purposes of testing our understanding and improving our ability to predict future climate-related change" (JGOFS Science Plan, JGOFS Report No. 5, Objective 2.2). In this respect, an overview is given on JGOFS-funded and JGOFS-related modelling work carried out in collaboration by the Fachbereich Geowissenschaften at the Universität Bremen and the Institut für Meereskunde at the Universität Hamburg. This modelling work focuses on physical-biological interactions.

There is a great number of physical forcing parameters, which act on vastly different spatial and temporal scales. External variability (manifest in changes of surface wind, heat and freshwater fluxes, i.e., changes external to the ocean) causes variability of phytoplankton growth at seasonal and interannual timescales. Kühn et al. (2000) succeed in simulating two different oceanic ecosystems (ESTOC and NABE/ECOTRANS) over four consecutive years 1989-1993 with the same trophic model structure (8 compartments) and the same basic set of biological parameters. Applying a combined carbon and nitrogen cycle model (CN) model to the 10-year period 1987-1996, Pätsch et al. (this conference) show that the simulated annual net primary production as well as the CO_2 exchange with the atmosphere at the ESTOC station is clearly related to the annual minimum sea surface temperature.

Another physical forcing parameter is internal variability, generated by processes internal to the ocean. The three-dimensional Regional Ecosystem Model (REGEM) for the ESTOC area (Determann, 1998), developped in collaboration by the Fachbereich Geowissenschaften and the Institut für Meereskunde, demonstrates how eddies and turbulent mixing evolve even under "smooth" climatologic surface forcing.

The study of paleoclimates is crucial "for the purposes of testing our understanding and improving our ability to predict future climate-related change". Using the Hamburg Ocean Carbon Cycle Model (HAMOCC) to simulate the global biogeochemical tracer distributions at the Last Glacial Maximum (LGM), Matthies (2000) shows that a weakening of the large-scale circulation and changes in sea-level (resulting in a different nutrient inventory) suffice to reduce the global atmospheric CO_2 concentration by about 60 ppm (from a pre-industrial level of 281 ppm to a glacial level of 220 ppm).

The final example is taken from the highly productive shelf seas and coastal waters, where a dominant physical forcing factor is the tidal currents. Changing either phase or amplitude of the spring-neaps tidal cycle in the PHYTO_1D model (Sharples, 2000) affects the pulsed production of biomass at the sub-surface chlorophyll maxium, in phase as well as amplitude.

In conclusion, we think that the modelling efforts in the JGOFS project has reached a state that can only be improved on if biological models of intermediate complexity are embedded in 3-dimensional physical models. It is therefore highly desirable to continue the development of coupled physical-biological models at the basin scale (Oschlies and Garçon, 1998; Pätsch et al., this conference) as well as at the regional scale (Determann, 1998).

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Poster

THE TROPHIC STATUS OF THE ANCHOVY IN THE SOUTHERN CALIFORNIA BIGHT - PRELIMINARY RESULTS FROM A NITROGEN STABLE ISOTOPE STUDY

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The abundance of the Northern Anchovy undergoes dramatic variations in the Southern California Bight on a decadal time scale, as documented through the landing of fish and the occurrence of fish scales in sediments from the Santa Barbara Basin. This might be explained by a change in the abudance of prey organims associated with variations of trophic levels. These ecosystem fluctuations are possibly linked to climatic variability (El Niño). We hypothesize that the trophic level of the organism changed with its abundance and intend to use the ratio of the nitrogen isotopes ^{14}N and ^{15}N (delta ^{15}N) in anchovies as an indicator of their trophic level. We will test the hypothesis by measuring the delta ^{15}N of the scales of anchovies from historical collections and from laminated sediments from the Santa Barbara Basin.

In order to reveal, if fish scales reflect the isotopic signal of the living Northern Anchovy, a comparison between muscles and scales of Northern Anchovy was conducted and showed a significant 1 permil depletion from scales to muscles. To apply this approach further to historic food web structures, it is necessary to investigate, how large the variability of the stable isotope signal in fresh and sedimentary scales is. Results on nitrogen isotopes of scales from Northern Anchovy from historical collections showed a 1 permil variation within each catch. Time series of the delta ^{15}N of anchovy scales from historical collections and laminated sediments will be presented and discussed.

Talk

RESPONSES OF THE MARINE BIOSPHERE TO GLOBAL CHANGE

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In global assessments of potential anthropogenic CO_2 sources and sinks, the oceanic biosphere has commonly been considered to remain constant over time scales relevant to 'global change'. The 'constant oceanic biosphere' concept is based on the assumption that anthropogenic perturbations of environmental conditions determining ocean productivity are insignificant on a global scale. However, large-scale changes in surface ocean chemical equilibria and elemental cycling have occurred in the framework of 'global change' and are expected to continue and intensify in the future. One of the most prominent anthropogenic perturbations, the progressive increase in atmospheric CO_2, affects the marine biosphere in various ways: indirectly, for

instance, through rising mean global temperatures causing increased surface ocean stratification and hence mixed layer insulation, and directly through changes in seawater carbonate chemistry. By the end of this century, the expected increase in atmospheric CO_2 will give rise to an almost three-fold increase in surface water CO_2 concentrations relative to pre-industrial values (assuming IPCC's 'business as usual' scenario IS92a). This will cause CO_3^{2-} concentrations and seawater pH to drop by ca. 50% and 0.35 units, respectively. These changes are likely to have significant effects on marine primary producers.

In laboratory experiments CO_2-related changes in seawater carbonate chemistry strongly affected calcification of marine coccolithophorids. In monospecific cultures of the two dominant coccolithophorid species, *Emiliania huxleyi* and *Gephyrocapsa oceanica*, the ratio of calcification to organic matter production decreased by 23% and 50%, respectively, with pCO_2 increasing from pre-industrial levels (270 ppmv) to values expected by the year 2100 (750 ppmv). In accord with the culture data, natural phytoplankton assemblages from the Subarctic North Pacific also showed severely reduced calcification at experimentally elevated CO_2 levels. According to these results the present rise in atmospheric CO_2 slows down marine planktonic calcification with likely effects on the vertical transport of calcium carbonate to the deep sea. CO_2-related responses in calcification may also influence the physiology and ecology of calcareous phytoplankton.

Recent studies further indicate that dominant marine phytoplankton species differ in their CO_2 requirement. Whereas some species preferably use CO_2 as carbon source, others mainly draw their inorganic carbon from the large pool of HCO_3^-. Changes in surface ocean CO_2 concentrations, therefore, may influence phytoplankton species composition and succession. These effects together with possible chances in surface ocean stratification, insulation, and nutrient availability may cause shifts in the distribution and productivity of the major phytoplankton functional groups (diatoms, coccolithophorids, nitrogen-fixing cyanobacteria, and flagellates) with likely consequences for marine biogeochemical cycling.

That large-scale changes in the marine biosphere have already occurred in the natural environment is indicated by biologically-sensitive geochemical tracers. Comparison of the carbon isotope composition ($\delta^{13}C$) of suspended and sedimenting organic matter with that in the top layer of the underlying sediment reveals significant differences in $\delta^{13}C$ between recently produced and 'pre-industrial' organic matter. As carbon isotope composition of primary producers is influenced by various factors, including the CO_2 concentration, algal growth rate, and the growth limiting resource, the ultimate cause of the observed changes is presently not clear. It suggests, however, that growth conditions of phytoplankton in the present ocean differ from those at pre-industrial times. Large-scale changes in the marine biosphere are further indicated by temporal trends in deep ocean Redfield ratios. Significant shifts in deep water AOU:P and N:P ratios in the North Atlantic and in AOU:N and AOU:P ratios in the North Pacific have occurred over the past 30 to 50 years. Together these findings demonstrate that the marine biosphere is presently not in steady state. Possible consequences of the observed responses for marine biogeochemical cycling – including potential feedback to atmospheric CO_2 increase – will be discussed.

Poster

SEASONAL CHANGE IN EFFECT OF SURFACE PCO_2 AND AIR-SEA EXCHANGE IN THE ARABIAN SEA

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Recent studies on biogeochemical cycling of carbon in the Arabian Sea, by Joint Global Ocean Flux Study (JGOFS), revealed that Arabian Sea is a source of carbon dioxide to the atmosphere throughout the year. The pCO_2 in euphotic zone and the surface mixed layer can be influenced by biological production/regeneration, and physical processes such as run-off, upwelling and winter convection. Contribution from each of these may change with season. In order to examine what makes surface waters of Arabian Sea supersaturated with respect to CO_2, four processes have been identified. They are effects of biological processes, mixing, thermodynamics and fluxes. These processes show strong seasonal as well as spatial variability in the Arabian Sea. Hence, it is difficult to interpolate to the complete basin using the observed data sets to understand controlling factors of surface pCO_2 in the Arabian Sea. Therefore, based on the satellite, derived monthly averages of chlorophyll (SeaWifs), and SST data and water transports, derived using Modular Ocean Model, the effects of these processes have been quantified. The results show that significant seasonal variability is found in pCO_2 levels. During SW monsoon, coastal waters contain two contrasting regimes. pCO_2 levels of >800 µatm off the Oman, Somalia and SW coast of India driven by intense upwelling. Low levels of pCO_2 (<200 µatm) are, however, found associated with monsoonal fresh water influx. These observations are in agreement with the observed data during International JGOFS processes study. As a whole, physical and chemical processes seems to be controlling surface pCO_2 especially, mixing effect is the dominant process compared to others whereas thermodynamics effect takes dominance during fall monsoon.

Talk

THE SEDIMENTARY SIGNAL OF PAST PRODUCTIVITY

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Biogenic particles and microfossils in marine sediments provide the opportunity to reconstruct variations in the rates of production related fluxes through the water column and burial on the sea floor over geological time scales. However, it is still difficult to estimate quantitatively ancient surface ocean productivity from flux or burial rates of these sediment components. Although algorithms exist that allow calculation of rates of past primary or export productivity, e.g., from accumulation of organic matter or biogenic barium, various processes can cause trouble when applying these rather simple empirically derived relationships as single approaches. The reason is the existing gap of knowledge on past levels of decomposition or diagenic alteration in the water

column and in the sediment, and about changes in the magnitude of biogenic particle or microfossil destruction through time. Varying oxygen conditions in the ocean and the sediments, burial rate of non-biogenic detritus, and silica or inorganic carbon budgets of the ocean can affect preservation of the biogenic material produced at the surface ocean. Also changes in terrigenous input of silica, organic matter, carbonate or barium have to be considered when using these bulk parameters for estimation of past production components. Therefore these problems can be minimized to a certain degree when using a set of multiple parameters in the same environment and a more straightforward estimation of the amount of marine versus terrigenous components in the bulk sedimentary signal. This contribution will present examples for such multiple parameter approaches from the Arabian Sea, the Benguela and Peru/Chile coastal upwelling systems, as well as for the high productive zones off the Amazon and Congo River mouths, where variations in paleoproductivity have been reconstructed for the last 0.2 to 0.5 Mio years or longer. These examples should not only demonstrate how surface ocean paleoproductivity has varied in coincidence with climate changes over longer timescales, but also how fluctuations in sea-level, the input of terrigenous constituents, oceanic oxygen and nutrient conditions, as well as diagenetic processes in the sediment column, may have altered the biogenic signal in marine sediments.

Poster

THE DEEP-SEA RECORD OF THE ARABIAN MONSOON SYSTEM: VARIABILITY, INSTABILITY AND REPEATED BREAKDOWNS OF OXYGEN-MINIMUM CONDITIONS DURING THE PAST 75,000 YEARS

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In the northeastern Arabian Sea, today, an intense mid-depth oxygen-minimum zone favours the deposition of laminated (varved) sediments with high accumulation rates of up to 200cm/kyr that offer the unique opportunity to study the monsoonal climatic variability of the past on a variety of timescales i.e. of seasonal/inter-annual to centennial/millennial and long-term solar (Milankovich) frequencies.

High-resolution sediment records of the Arabian Sea show that the intensity of the OMZ and hence, surface water productivity linked to the monsoonal circulation must have been extremely variable during the last glacial/interglacial cycle, depicting a pattern of fluctuations well correlatable with those found in the Greenland ice cores of the high northern hemisphere (NH). We verify the synchrony between the two climatic systems by the presence of the ash layer of the Toba volcanic event (~70,000 years before present), matching the monsoon and ice records directly and precisely. Detailed records of planktonic foraminiferal species abundances, of alkenone paleotemperature, and of magnetic dust proxies investigated for the time interval of ~65,000 years -~75,000 years BP show that the warm spikes of the North Atlantic interstadials

correlate in very detail to equivalent periods of warmer sea surface temperatures (SST), enhanced surface water productivity and lowered dust flux in the Arabian Sea. We estimate that the SST amplitudes from interglacial to glacial, and from interstadial to stadial periods were in the range of 4.5°C-3°C and 3°C-1.5°, respectively. Moreover, almost similar to the Greenland record, climatic warming and the establishment of high-productivity conditions in the Arabian Sea occurred abruptly, within a century or less, and stadial cooling and the decline of productivity was more gradually. These findings contradict to previous estimates based on foraminiferal transfer functions, indicating SST cooling due to increased upwelling and productivity. Our alkenone SST data suggest that this cooling effect was more than counterbalanced by the generally warm climatic boundary conditions during the interstadials. Low oxygen conditions also prevailed during the last glacial maximum, from about 17,500 to 22,500 years B.P. In contrast, during six periods of the past 65,000 years, well correlatable to the North Atlantic cold Heinrich melt water spikes, both, surface water temperatures and productivity in the Arabian Sea were extremely low, each culminating in a complete breakdown of the oxygen-minimum layer.

The question arises what fundamental mechanisms trigger the monsoonal circulation and may lead to the strong fluctuations on the millenial to sub-millennial timescales. Since the intensity of the monsoons relates on the seasonal pressure gradient between the southern hemisphere (SH) and the central Asian plateaus, we suggest that the northern hemisphere (NH) summer monsoon maxima (warm SSTs) should be associated with SH SST minima (i.e. a strong thermal and thus pressure gradient between the SH and the NH). Vice versa, the weakened monsoons should be associated with a relatively warm SH-pool. This would argue for an asynchrony between the temperature fluctuations of the two hemispheres, confirming recent detailed correlations of the Arctic and Antarctic ice core records.

In a broader perspective, changes in the monsoonal intensity and circulation patterns may (1) play an important role for the transport of tropical heat and moisture toward the higher latitudes (2) effect global atmospheric levels of water vapour and other greenhouse gases directly, and via positive rebounds on vegetation cover and emissions from tropical forest soils.

Poster

MILLENNIAL-SCALE OSCILLATION OF DENITRIFICATION INTENSITY IN THE ARABIAN SEA DURING THE LATE QUATERNARY AND ITS POTENTIAL INFLUENCE ON GLOBAL CLIMATE

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The intensity of denitrification in the Arabian Sea during the last 65 kyr is reconstructed using high-resolution $\delta^{15}N$ records of three sediment cores combined with other geochemical tracers of water column oxygenation and productivity. The results suggest three distinct modes of nitrogen cycling which are closely linked to abrupt climate changes recorded in Greenland ice cores and

North Atlantic sediments. These modes occur in addition to an orbital forcing of denitrification intensity and can be termed 'modern', 'glacial', and 'Heinrich' in accordance to those used to describe millennial-scale changes in North Atlantic circulation. The 'modern' mode represents the Holocene and the interstadials. It is characterized by strong SW monsoonal upwelling in the western Arabian Sea and the advection of nutrient-rich water masses to the central and northern parts of the basin. This enhances productivity and the corresponding oxygen demand for the mineralization of the exported organic matter sinking through the water column. As a consequence, a pronounced mid-water oxygen deficiency is maintained which in turn provides the setting for intense denitrification. For the interstadials this is particularly significant beyond 35 kyr BP, i.e. during the early and middle marine oxygen isotope stage 3. During the 'glacial' mode at times of the stadials and the Last Glacial Maximum SW monsoon intensity and upwelling are substantially lower with the corresponding decreased water column degradation leading to elevated mid-water oxygen contents and reduced denitrification. During the 'Heinrich' mode at times of the Heinrich events and the Younger Dryas SW monsoon intensity and productivity in the basin are further reduced. This causes an even lower flux of organic matter through the water column and a correspondingly decreased oxygen demand for its mineralization. Moreover, ventilation of the water column is possibly improved via an inflow of thermocline waters with a higher initial oxygen content and an intensification of deep winter mixing resulting in the cessation of denitrification.

Today, the Arabian Sea and the equatorial upwelling regions of the eastern tropical Pacific are the principal regions for water column denitrification. Related to the combination of denitrification and upwelling both regions currently contribute substantially to the global oceanic emissions of N_2O into the atmosphere. Evidence available now for the Eastern Tropical North Pacific suggests that denitrification and upwelling intensity was high during the Holocene and varied in a pattern similar to the Arabian Sea during the last termination. During oxygen isotope stage 3 also millennial-scale oscillation occurs in this region and denitrification tends to be more intense during interstadials. Changes in N_2O emissions from both marine regions could thus have contributed to stadial/interstadial variations in the atmospheric concentration of this important greenhouse gas as deduced from ice cores. In addition, denitrification is the major sink for oceanic nitrate and provides a primary control for the oceanic nutrient inventory which in turn influences global primary productivity and CO_2 sequestration by the biological pump. Millennial-scale oscillation between the different denitrification modes in these marine regions therefore potentially influences global climate.

Poster

VARIATIONS IN THE BENGUELA UPWELLING FILAMENTS DOCUMENTED BY THE DIATOM FLUX

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The diatom flux data were retrieved from a two-year sediment trap experiment at the eastern edge of the Walvis Ridge (about 20°S, 9°E, 2200 water depth). Sampling time of the WR 3 trap at 1648 m water depth extended from March 1990 to March 1991, of the WR 4 trap at 1717 m water depth from April 1991 to December 1991. The data are compared with the published results of the previous time-series sediment trap at the same station.

The mooring was situated within the Benguela upwelling system and is strongly influenced by the upwelling filaments. Within the upwelling area diatoms dominate the phytoplankton assemblage and they mainly contribute to the export of opal to the ocean floor.

During the whole sampling period, the diatom flux nicely followed the opal as well as the total flux. The diatom flux of the different years varied either in the amount or in the pattern. In 1990, the pattern is the same as 1989, a bimodal one with maxima in spring and fall. However, the flux values were much lower in 1990 than in 1989. In 1991, highest numbers of diatom flux occured in austral spring and were of a similar size as in 1989. But in contrast to the two previous years, the austral fall maximum was missing and there was a smooth increase in austral winter time. The silicoflagellates showed the same flux pattern and the similar annual variation as the diatoms. Their flux numbers are about one order of magnitude lower than the diatom flux.

An important contributor to the diatom flux throughout the three years *is Thalassionema nitzschioides*. Together with *Pseudo-nitzschia* spp. it comprised the austral spring maximum, which could be related to a rather consistent upwelling event or filament during this time of the year. In contrast, the assemblage during austral fall is rather different between the years. While in 1989 the occurence of vegetative cells of Chaetoceros suggests a direct influence by coastal upwelling, the high amount of resting spores of Chaetoceros together with oceanic taxa like *Roperia tesselata* and *Rhizolenia bergonii* in 1990 might point to an influence by a more distant filament. In 1991 the missing flux peak in fall and the elevated flux in winter might be due to a more southerly position of the Angola-Benguela-Front and a reduced influence by the upwelling filaments at the trap. In addition, the occurence of some endemic Antarctic species during fall and winter in 1989 and 1991 indicate some contribution to the vertical flux by Antarctic Intermediate Water.