Global Ocean Productivity and the Fluxes of Carbon and Nutrients: Combining Observations and Models

Report of a Workshop held at the Institute for Environment & Sustainability,
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with contributions from
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Introduction

To address one of its main objectives, JGOFS has employed a large variety of different approaches to quantify marine productivity and the fluxes of carbon and nutrients in the ocean. The methods that were used differed with respect to the technology that was applied, but they also differed with respect to the viewpoint, from which the overall system was observed (Figure 1). One such approach makes use of remote-sensing observations from instruments on satellites or aircraft that can observe the system from above and detect productivity signals from the upper tens of meters of the ocean. Another includes the *in-situ* measurements and process studies that provide more or less direct observations of productivity. A third employs moored or drifting sediment traps that collect sinking material in the water column for flux estimation and composition analysis. A fourth uses radionuclide measurements for better calibration of sediment trap data. And a fifth relies on benthic studies for estimating the material flux to the sea floor.

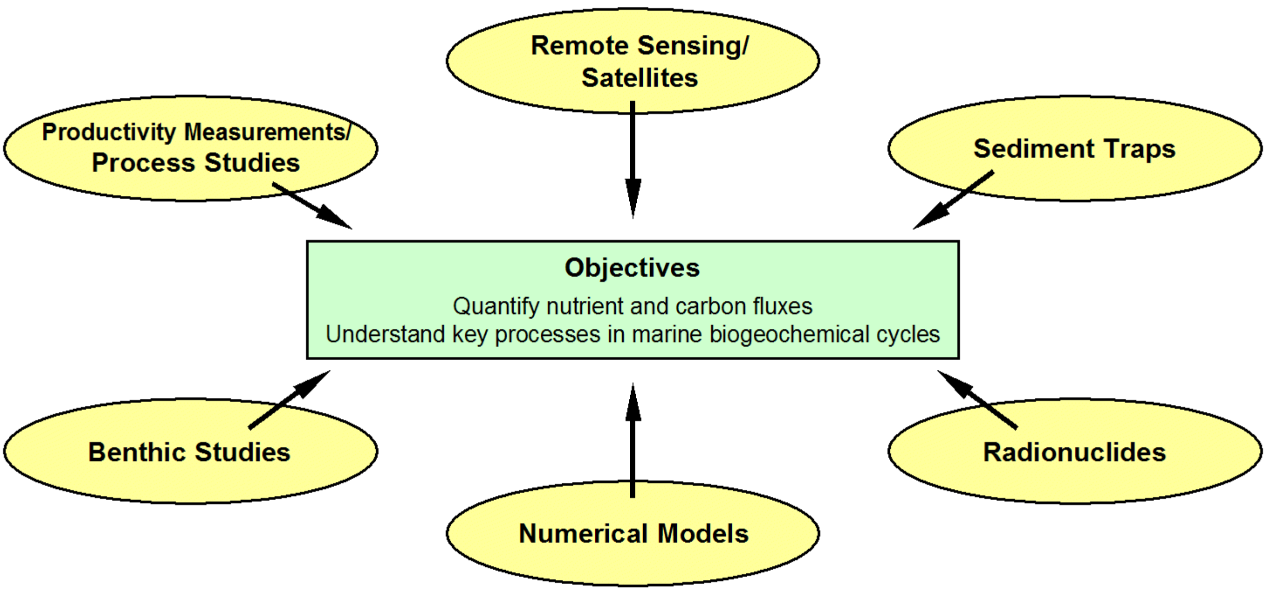

Figure 1: Schematic diagram of key research activities addressing main JGOFS objectives

In addition, there exists a wide variety of global and regional models of differing resolution and complexity. These models simulate biogeochemical processes in the ocean and yield independent estimates for property fluxes and rate constants. The range includes high-resolution regional models with complex mixed-layer dynamics and elaborate ecosystem feedback loops that can explicitly simulate physical transport phenomena and the development of blooms on small space and time scales. It also includes a number of global models with medium resolution that are used to calculate global ocean budgets and fluxes of carbon, nutrients and oxygen. Although inverse models that derive property fluxes and rate constants from available data have been less frequently used in the past, this might change in the future as more and more JGOFS data sets become publicly available.

Now with JGOFS at its final phase, there is a pressing need to compile and compare the results from the various methods and to investigate whether a consistent picture emerges. The first meeting of the JGOFS Global Synthesis Working Group (GSWG) in Amsterdam (July, 2001) indicated that significant discrepancies between different techniques and models still exist, addressing the need to conduct multi-disciplinary exercises / projects to bridge the gaps between physics and biogeochemistry, between process analyses, observations and modeling. To foster the interaction and cooperation between scientists from different research fields, the GSWG together with the JGOFS/GAIM Task Team on 3D Ocean Carbon Modeling and Analysis (JGTT) organized a workshop on: *Global Ocean Productivity and the Fluxes of Carbon and Nutrients: combining Observations and Models*, hosted in late June 2002 by the Joint Research Centre of the European Commission, Institute for Environment and Sustainability (Ispra, Italy).

Objectives

The workshop involved about 70 scientists from around the world representing all aspects of the marine carbon and nutrient cycles – modeling, process studies and experiments, as well as in situ and remote sensing observations. Specific objectives were:

1. To obtain an overview of the present state of research on global ocean productivity and fluxes of carbon and nutrients with special emphasis on comparisons between observations and models.

2. To address remaining challenges in ocean biogeochemistry and new trends in our understanding of the marine processes and their variability over time and space.

3. To explore new research strategies in ocean biogeochemistry for the next decade and foster constructive trans-disciplinary actions within the global change arena.

Questions

Key questions that were addressed at the workshop were:

- How accurate are satellite productivity algorithms?
- Are sediment trap data consistent with satellite productivity maps?
- Are benthic food supply requirements matched by measured downward fluxes?
- What controls the export and sequestration efficiency?
- How important are ocean margins for global ocean biogeochemical cycles?

- Are modeled productivity rates and fluxes consistent with observations?
- How will marine biogeochemical cycles change in the future?
- The next generation of biogeochemical models: what level of complexity is required to improve productivity and flux estimates?
- New technologies and observations: which new datasets will be available in 10 years? Are they sufficient to validate future models?

Agenda

The workshop was structured with half-day sessions on various themes. These themes were:

1. Observing ocean productivity from space
2. From primary production to export flux: factors controlling the export efficiency
3. The flux of particulate matter in the water column: magnitude and depth dependence
4. Benthic fluxes along ocean margins and in the open ocean
5. Recent evidence for changes in marine biogeochemical cycles
6. Hind- and forecasting biogeochemical fluxes with models
7. The next generation of biogeochemical models: what level of complexity is needed?
8. Future observations of biogeochemical systems: new technologies and networks

While the purpose of the first four sessions was to summarize what was achieved during JGOFS and to assess whether the results from different approaches were consistent or not, the themes 5 to 8 were more forward looking and emphasized the aspect of future changes in marine biogeochemical processes and the need for the development of new observational strategies that would provide global data coverage and near real-time data access.

Each theme was presented in three equally important parts, a plenary session with keynote presentations, a poster session, and a concluding plenary discussion. Care was taken to leave sufficient time for "unstructured" discussion, giving an opportunity for all participants to comment on the present and future strategic research within each thematic. Slightly different in scope than a formal conference, the purpose of presentations and/or posters in this workshop was to fuel and stimulate discussion. The participants were thus encouraged to present synthesis material, and/or their own perception, including provocative ideas, on oceanic biogeochemistry.

In the following, the workshop sessions are presented in more detail, and the presentations as well as the discussions are summarized. A list of participants is provided in Appendix A, and the abstracts of the key-note presentations and posters can be found in Appendix B. More information on this workshop, including electronic versions of the abstracts and of some key-note presentations are available on-line at http://www.awi-bremerhaven.de/GEO/workshops/ispra-2002/index.html.

(Disclaimer: Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of SCOR, IGBP, JRC, and the U.S. NSF.)

Acknowledgements

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Session A: Observing ocean productivity from space

This session, chaired by **T. Platt** (Bedford Institute of Oceanography, Canada), was dedicated to reviewing the various developments to estimate marine primary production using satellite data. Our ability to monitor and understand biogeochemical processes in the ocean has been significantly influenced by the use of satellite data, and particularly optical sensors. Within a few snapshots, the color of the global ocean is monitored at unprecedented resolution, providing an estimate of the distribution of surface chlorophyll concentrations and its variability with time. Recognizing that chlorophyll represents a major factor controlling the primary production in marine waters, several models were developed and implemented during the JGOFS era to determine the photosynthetic rate of the phytoplankton at regional and global scale. A first and second exercise [*Campbell et al.*, 2002] compared the performance of 12 algorithms and their ability to estimate depth-integrated daily production at 89 discrete stations distributed in various oceanic environments.

In a third inter-comparison (presentation by **M.-E Carr** and **M. Friedrichs**), 24 models (including 2 ecosystem models) were run with the same global biomass fields as derived from SeaWiFS data for 7 months of the year 1998. On a global scale, the difference between models is highly substantial, almost a factor of 2. The annual 1998 global production ranges from 35 GtC.y-1 (from 6 models) to 65 $GtC.y^{-1}$ (from 5 models). The rest of the models gave intermediate values, ca. 49 $GtC.y^{-1}$, close to the overall mean (Fig. A1). The models diverge according to basins, trophic conditions and latitude (temperature). Divergence is greater southward, and for water with T < 0°C. Uncovering the reasons behind these differences is the goal of this on-going third inter-comparison exercise.

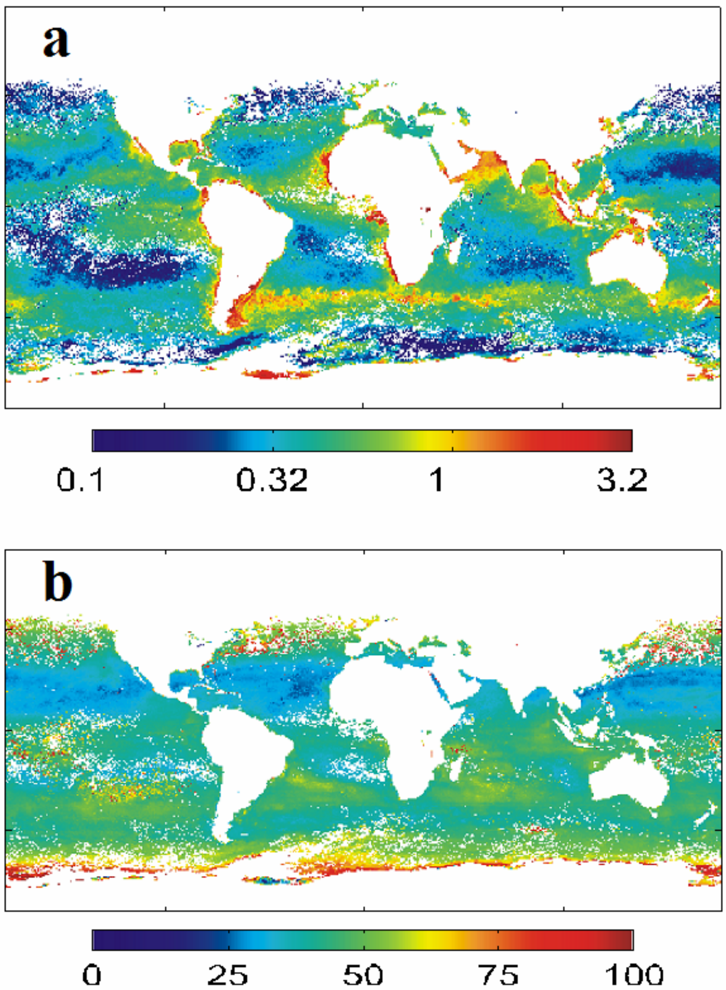

*Figure A1: **a**) all-models average global primary production for January 1998 (units are in $gC.m^{-2}.d^{-1}$); **b**) standard deviation as % of the mean (courtesy M.-E Carr)*

To achieve this goal, it is important to have first a clear understanding of the dominant variability associated with biogeochemical processes in the ocean. In **J. Yoder** and **M. Kennelly 's** presentation, 4-year time series of SeaWiFS global chlorophyll are used in an EOF analysis to quantify the major signals in phytoplankton biomass variability and to find relations in the basin-scale patterns over the global ocean. The variability in surface chlorophyll is dominated by the seasonal signal, particularly in high latitude and in the Atlantic Ocean (as compared with the Pacific). The inter-annual variability is much less significant. Globally, the variability due to the 1998 ENSO event is shown to be ca.7x less than the seasonal variations in the first 6 EOF modes. Also, the analysis highlighted a 6-month shift in the peak of chl-a concentration between subtropical and subpolar waters. On the contrary, greater inter-annual variability in the satellite-derived chlorophyll and productivity is observed at regional scales, e.g. the subarctic North Pacific (poster by **K. Sasaoka, S. Saitoh,** and **T. Saino**), with a strong signal coinciding with 1998 El-Nino and 1999 La-Nina events. The way these variations are implemented into primary production models would likely affect their outputs and contribute to their divergence.

T. Platt noted that all photosynthesis-light models have a common structure that is imposed by dimensional considerations. Basically, all these models require three sets of parameters as inputs: parameters that define the vertical structure of the phytoplankton biomass; those that determine the optical light transmission underwater; and those that determine the photosynthetic response of phytoplankton to the available light.

The subtlety in the various models arises from the methods used to assign these parameters at the global or basin scale, on a pixel-by-pixel basis. Considering that some of these parameters are not accessible from satellite, one way to implement the models is to partition the ocean into biogeographical provinces reflecting the heterogeneous nature of the ocean environment. In a poster by **M. Dowell, J. Campbell,** and **T. Moore**, the assignment of the parameters necessary for the computations of primary production is achieved following an approach based on fuzzy logic, which brings a dynamic quality to the partition of the oceans into provinces when compared to a fixed geospatial and temporal areas. From a global data set on primary production, 9 classes (Fig. A2) were differentiated on the basis the major controlling factors, i.e. chl-a, sea surface temperature (SST) and the photosynthetic active radiation (PAR). The global distribution of these classes reproduced spatially coherent and seasonally dynamic provinces, starting point for an effective assignment of the input parameter fields to primary production models.

Another source of divergence between various models stands in the degree of parameterization of the model variables. For example, simple optical models for open ocean waters (Case 1 models) usually assume a co-variance between the optical properties of phytoplankton and those of other organic and particulate matter present in the water. There is increasing evidence that the concentrations of dissolved organic matter in the open ocean, and its influence on the optical properties of the water column, maybe more important and more variable than had been hitherto supposed.

In this context, **J. Marra's** presentation described an alternative model for primary production based on phytoplankton absorption and quantum yield. The retrieval of chl-a from satellite contributing to most of the error in the calculation of primary production, the idea is to focus on the absorption coefficient of phytoplankton instead of using the photosynthetic parameters as derived from P *vs* E curves. In this way, using more accurate satellite reflectances, which depend on the inherent optical properties of the water column, one can proceed directly to productivity, avoiding the step of calculating chlorophyll.

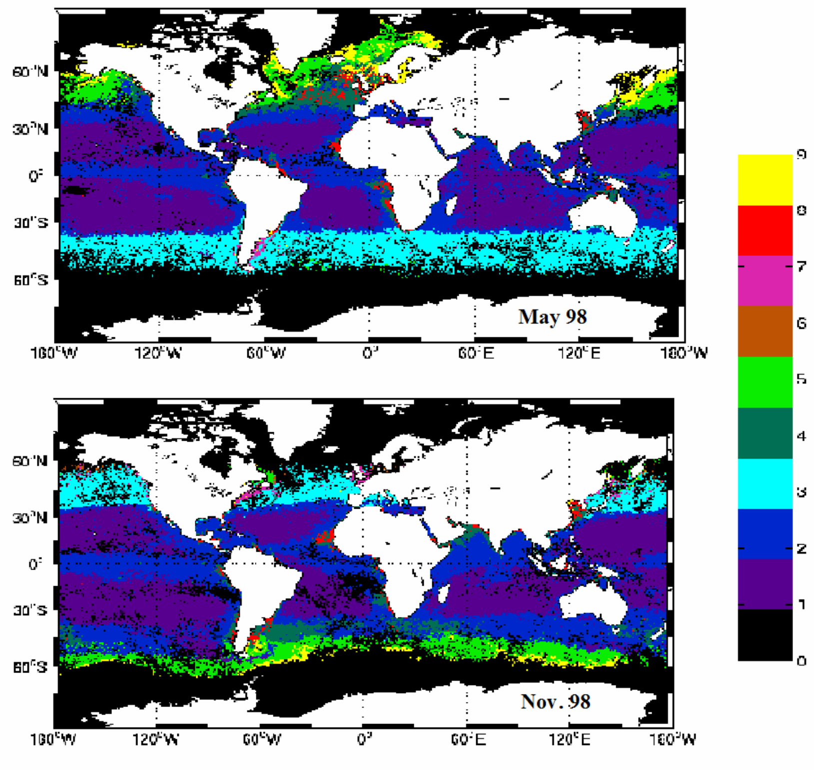

Fig. A2: Monthly (May and Nov. 98) distribution of primary production 'classes' or provinces identified through fuzzy logic analysis based on ranges of chlorophyll, SST and PAR (courtesy M.D. Dowell)

A new challenge will then be to understand how quantum yield and absorption vary with the environmental properties. Field observations conducted in different oceanic regions and at different periods demonstrate a significant relationship between the photosynthetic quantum efficiency and the chl-a to total pigment ratio (poster by **J. Aiken, G. Moore, J. Fishwick, T. Smyth, C. Omachi,** and **K. Woods**). In natural marine ecosystems, phytoplankton cells increase the fraction of chlorophyll to total pigment to sustain maximum growth rates in their changing environment. Using accurate bio-optical algorithms, the ratio of chlorophyll to total pigment can be accessible to satellite ocean colour data, and thus represents a 'dynamic' parameter of phytoplankton production.

Discrepancies between satellite-based estimates of production are aggravated in particular regions, e.g. in the Southern Ocean, due to the paucity of field measurements reducing the reliability in the input parameters and their implementation. Out of 24 production models compared (presentation by **M.-E Carr** and **M. Friedrichs),** the mean annual (1998) production rate in the Southern Ocean is 6.9 GtC.y^{-1}, but the model estimates range from 3 to 11GtC.y^{-1}. Using inverse method with a coupled global ocean circulation-biogeochemical model, **R. Schlitzer's** poster showed a significant difference between modeled and satellite–based productivity values in the Southern Ocean. In the model, the total integrated export flux of particulate organic matter (POC) necessary for the realistic simulation of nutrient data is significantly larger by a factor 2 to 5 than export estimates derived from satellite primary productivity maps (Fig. A3). The good performance of the model to provide the nutrient distribution and CFC's fields suggests possible underestimation of the upper layer primary production from satellite (see also [*Schlitzer*, 2002]). The accuracy of satellite-retrieval productivity in the Southern Ocean is likely reduced by the poor calibration of the algorithm (lack of field measurements), but also by the presence of frequent sub-surface chlorophyll patches whose potential effect on primary production may not be well parameterized within satellite algorithms.

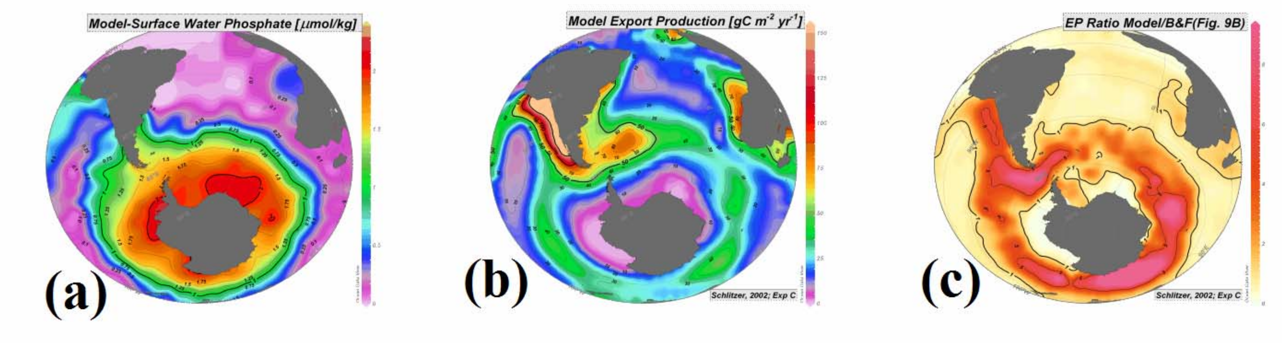

Figure A3: Southern Ocean export production. (a) model simulated surface water phosphate concentration; (b) modeled export production; (c) export production derived from satellite productivity and converted using [Eppley and Peterson, 1979] algorithm [Fig. A3(c) is adapted from [Behrenfeld and Falkowski, 1997], redrawn from [Schlitzer, 2002].

Concluding remarks and future perspectives

Satellite imagery, and particularly ocean color, is instrumental to determine the spatial and temporal variability related to the ocean carbon cycle on a wide variety of scales. Although the number of applications is constantly increasing, it is, however, necessary to extend research on primary algorithms in an attempt to reduce errors on the retrieval of surface parameters, such as phytoplankton biomass and to extend these applications to optically-complex environment, e.g. the Southern Ocean and continental margins.

Considering that multiple approaches exist to estimate daily productivity in the ocean from satellite data, consensus and coordination within the community is most beneficial to improve our knowledge on how phytoplankton physiology responds to a change of the surrounding environment. However, all models do not have the same goal and their performance on a specific target may differ on the basis on how they have been constructed to achieve this goal. Also the assignment of parameters to the models is still an issue and underlines the need for more field data, especially in extreme areas.

The increasing number of spectral bands and higher spatial resolution on recently launched and/or future ocean color sensors (MODIS, MERIS, GLI) are very promising to achieve better processing algorithms of the signal and, thus, more accurate surface parameters, while improving assessment in the time-space domain.

Session B: From primary production to export flux: factors controlling the export efficiency

This session, chaired by **E. Laws** (University of Hawaii, USA), focused on one of the primary goals within JGOFS, that is to determine and understand the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean and to evaluate the transfer of particulate organic carbon through the various biological pathways as it settles from the surface to the deep ocean. In other words, the session's debate was centered on how much do we know about the relationship between export flux and primary production, which required a review of our understanding on the magnitude, variability and controls of the carbon cycle in both the epi- and mesopelagic layers.

The development of a theoretical understanding of the mechanisms that control the transfer of organic matter from the surface waters of the ocean to the deep sea is severely constrained by a lack of observations between the base of the euphotic zone and a depth of roughly 1 km. Because of the ease with which primary production rates can be estimated with the ^{14}C-technique, developed by Steemann-Nielsen 50 years ago, there now exists a very large database of photosynthetic rates, with a significant part of it that has been collected during the JGOFS era.

According to **P.J. le B. Williams'** presentation, however, the information on photosynthetic rates (P) is not sufficient to close the carbon mass balance in the epipelagic layer of the oceans. It requires measurements or estimates of the respiration rates (R) in the euphotic layer. In comparison with photosynthesis, the information on respiration rates in the ocean is scarce, and not explicitly advocated in the JGOFS protocols, although the sensitivity of the light-and-dark bottle oxygen method has now improved to the point where both respiration and photosynthetic rates could be measured in the euphotic zone of even oligotrophic parts of the ocean.

To palliate the lack of data, statistical trends between photosynthesis and respiration from few volumetric data set have been analyzed and used to make global projection [*Duarte and Agusti*, 1998]. Significant scatter in the correlation between P and R depth integrated rates (Fig. B1) has given rise to an on going debate on whether oligotrophic areas are net heterotrophic systems. Increasing in vitro oxygen flux measurements in the upper layer of the oceans will certainly add more substance to the debate.

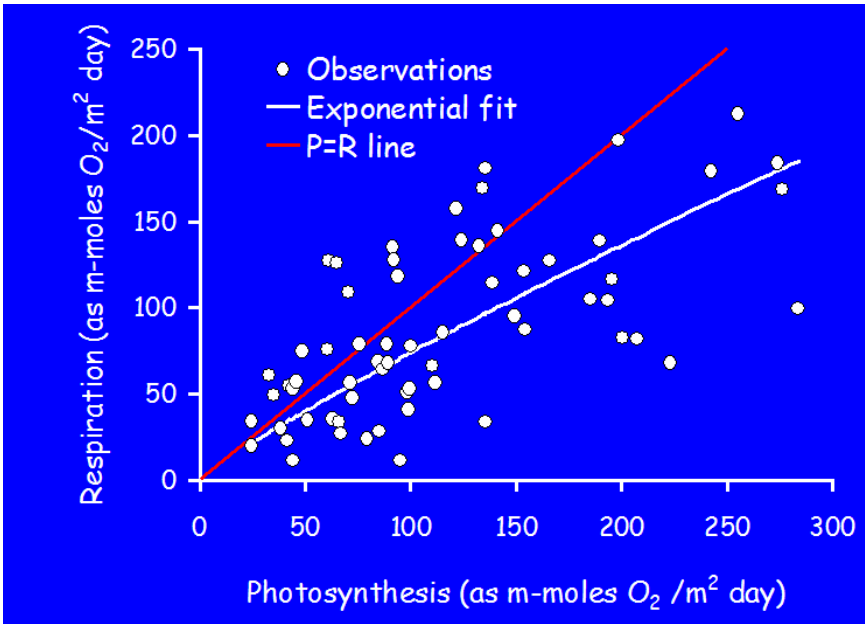

Figure B1: Epipelagic carbon balance. Respiration rates vs photosynthesis rates (courtesy P.J.Le B. Williams)

Such measurements can provide estimates of net community production, as well as estimates of export production of carbon using appropriate stoichiometric conversions and assuming that net community production and export production are in balance.

With increasing depth below the euphotic zone, direct measurements of respiration with the oxygen method become problematic, since the flux of organic carbon, the substrate for respiration, declines in a more-or-less exponential manner with depth ('Martin's curve'). Measurements of electron transport system (ETS) activity could, however, be used to infer respiration rates in the mesopelagic. Strictly speaking, ETS measurements provide information on the potential respiration. The actual respiration rates will be some fraction of the ETS number. In other words, with appropriate calibration of the method in the upper layer where both oxygen consumption and ETS measurements can be made, estimates of respiration rates can be obtained in the deeper water column where the oxygen method is too insensitive. Sensitivity issues can be circumvented to some extent with the ETS technique by simply filtering more water in regions where rates are low.

While estimates of respiration will provide a mechanism to calculate the rate of consumption of organic carbon as a function of depth within the epipelagic and mesopelagic layer, such measurements provide no information on processes. A better understanding of the relationships between the abundance and activity of organisms, and the role of community composition in carbon processes (see Fig. B2) is needed before models can predict how the transformation of carbon in the water column may vary in response to climate change. For example, a poster by **E. Laws** demonstrates that the ecological law of maximum resiliency can be applied efficiently in an ecosystem model [*Laws et al.*, 2000] to predict the heterotrophic bacterial biomass in a variety of environmental conditions. According to that model, photosynthetic rate and temperature are the primary determinants of community composition and system behavior.

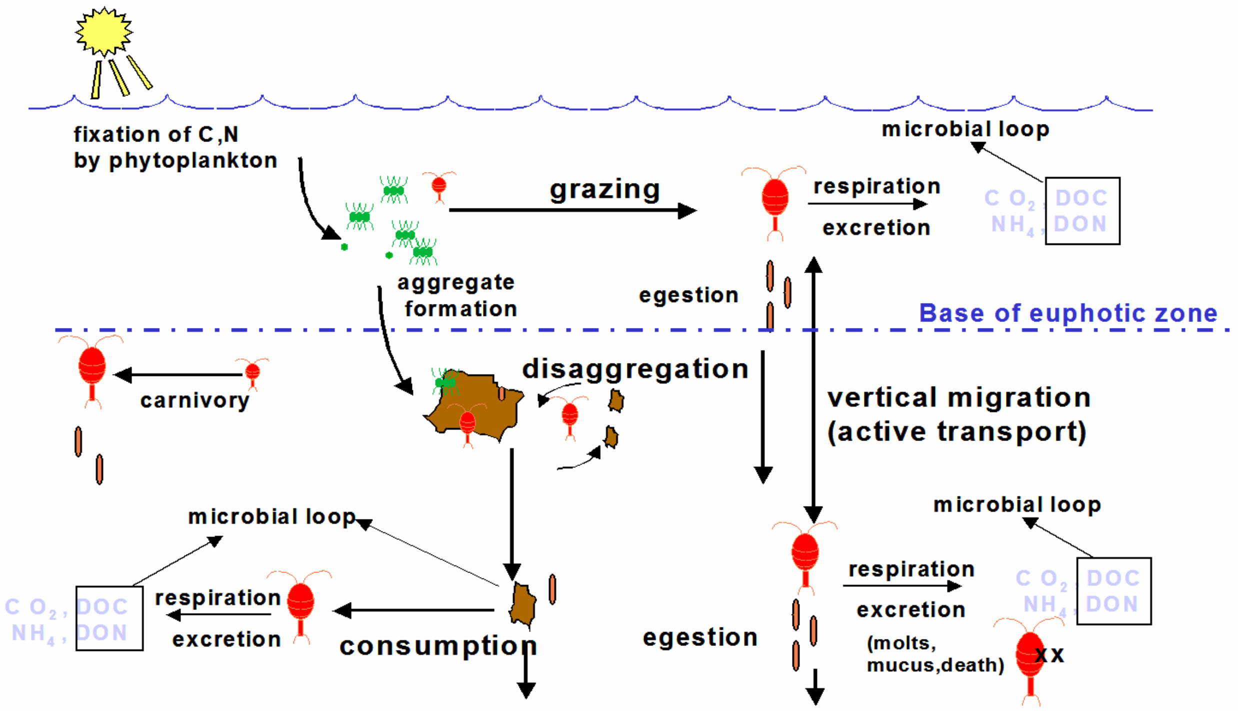

Figure B2: Particle cycling and remineralization in the epipelagic and mesopelagic layers (courtesy D. Steinberg)

A presentation by **D. Steinberg** showed that zooplankton metabolic activity can account for a significant proportion of the loss of particulate organic carbon (POC) with depth, 9 to 100% being respired and 6 to 38% being consumed. As important processes, zooplankton grazing and fecal pellet production vary with ocean basins and seasons, but can respectively account for 3-50% of the daily primary production in the euphotic zone (grazing), and 5 to more than 100% of export flux in the mesopelagic (fecal pellet production). The composition of the zooplankton community can have a dramatic effect on the rates and efficiency of this carbon processing. Salps, for example, are active filter feeders producing large fecal pellets that may sink as rapidly as 1 km per day.

The vertical migration of zooplankton represents also an efficient flux of carbon through feces production at depth (2-7% of POC flux), and primarily, through active transport of dissolved material representing 4 to 40% of the POC flux (Fig. B3). The latter will fueled the microbial loop at depth. Therefore, understanding the factors that control zooplankton community composition, hence functionality, is essential to design carbon flux models in the epipelagic and mesopelagic layers of the ocean.

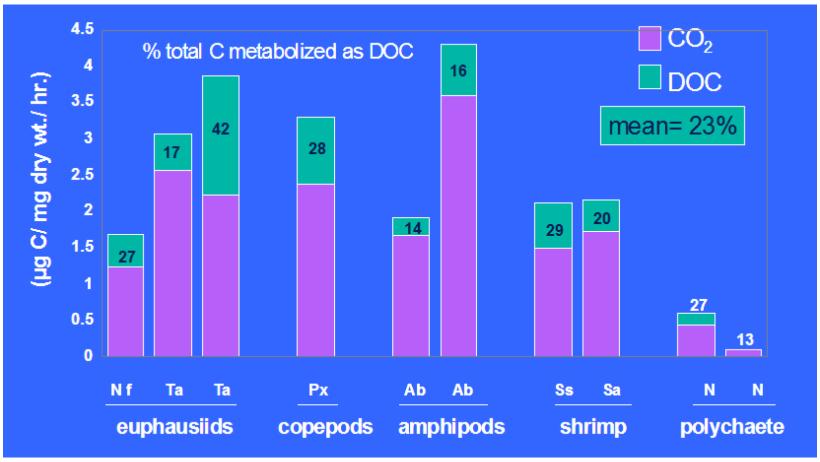

Figure B3: Transport of dissolved organic material by migrators (from [Steinberg et al., 2000])

Current understanding is that the export of organic carbon from the euphotic zone and the export efficiency is positively correlated with primary production and negatively correlated with temperature. For many years, it has been assumed that the flux of organic carbon declined in a more-or-less exponential manner with depth below 100 meters or so, and that a single constant would characterize the rate of the decline. In reality, the reliability of information on organic matter fluxes above a depth of roughly 1 km is highly questionable due to concerns with methodological artifacts (e.g. sediment traps).

A presentation by **K. Buesseler** illustrated this problem, showing that the data interpretation from shallow traps often differs from measurements using ^{234}Thorium approach. In addition, JGOFS ^{234}Th studies provide significant insights that there is no single relationship describing the carbon export:production ratio. The POC export as measured from ^{234}Th varies from less than 5% to higher than 50% of the surface primary production (as measured with the ^{14}C technique, Fig. B4)

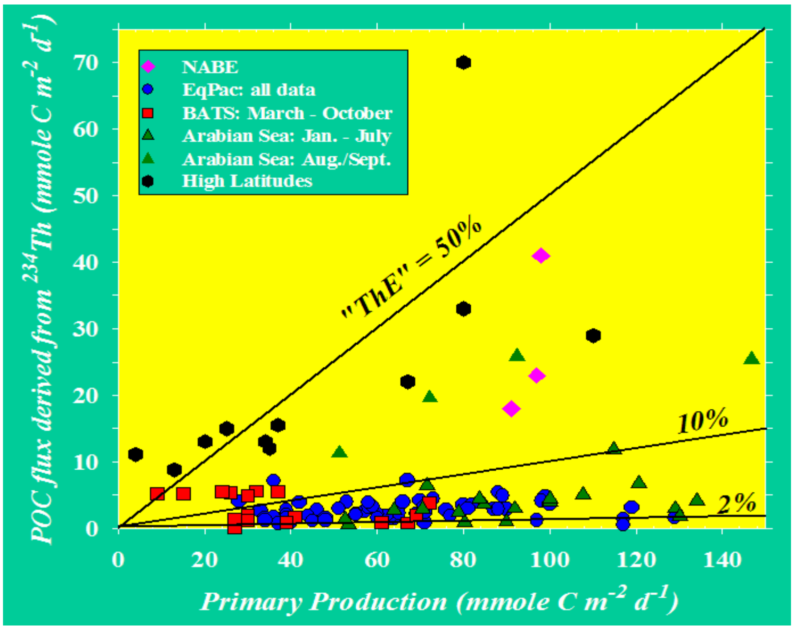

Figure B4: Particulate organic carbon flux vs upper layer primary production for different oceanic conditions. "ThE" = POC export (^{234}Th) / primary prod. (^{14}C) (from [Buesseler, 1998])

The high variability in the observed POC flux at shallow depth suggests that the export efficiency from the euphotic layer is very much tied to the structure of the food web, with diatoms being key players in many situation where export production from the upper layer is high. Using models, a poster by **L. Smith, Y. Yamanaka** and **M.J. Kishi** showed the difficulty to obtain harmonized estimates of primary production and POC flux if local characteristics of the food web (e.g. N_2 fixation, microbial food chain) and processes (e.g. differential remineralization) are not taken into account in the biological parameterization scheme. In general, however, large uncertainties remain in the estimation of shallow POC fluxes due to limited datasets and technical obstacles surrounding these measurements.

T. Trull's poster suggest the possibility to use stable carbon isotope mass balance to address issues on carbon export and to identify organisms that are mostly responsible for the transfer of organic carbon below the euphotic zone. Comparisons of phytoplankton organic-$_{13}$C compositions with the concentration of that isotope in DIC indicate that large phytoplankton cells are responsible for the majority of seasonal export in the Southern Ocean, and are more sensitive to aggregation than small sized phytoplankton.

Another difficulty is due to variable time lags observed between net community production and export production. A study conducted on either side of the Antarctic Circumpolar current (ACC) (poster by **R. Sambrotto** and **S. Green**) showed time lags ranging from non-existent period for silica in the southern region of the ACC, to almost two months for carbon and nitrogen in more northern regions. Also the dominance of diatoms south of the polar front was associated with higher export efficiency of carbon and nitrogen than the flagellate dominated regions to the north, confirming earlier statement that the floristic composition, even defined at species level, is an important state variable to model surface fluxes.

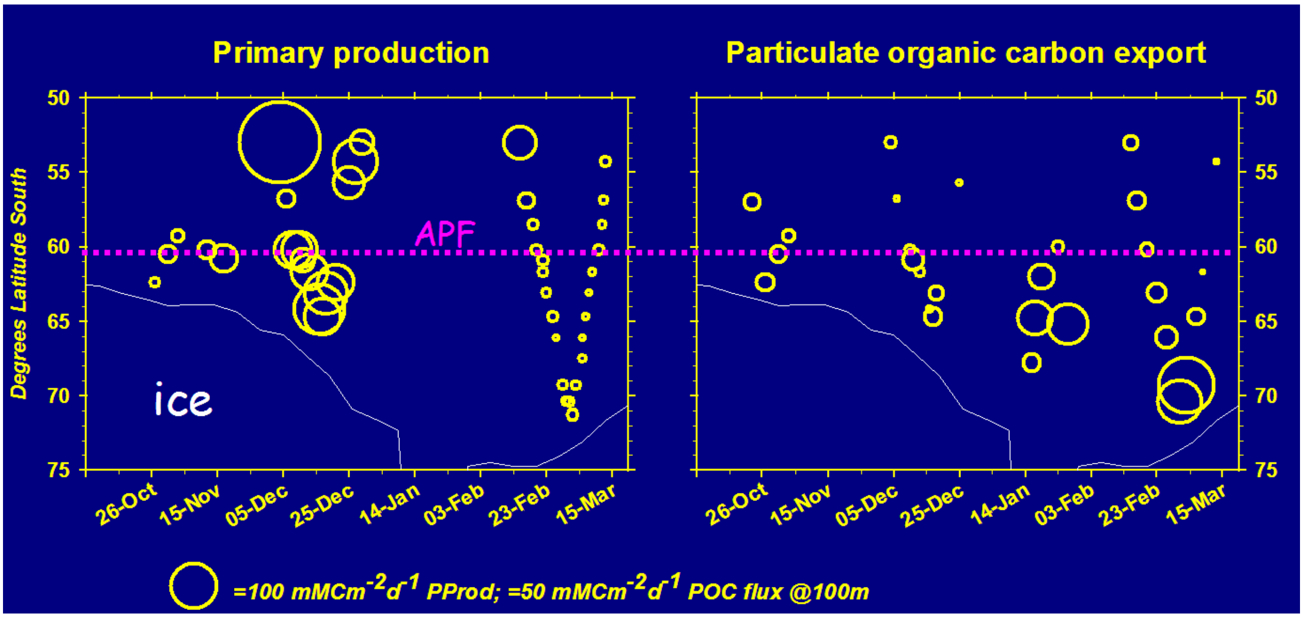

Figure B5: Latitudinal and time variability in the magnitude of primary production and POC export in the Southern Ocean (APF = Antarctic Polar Front). Primary production is highest in December, export flux increases in March south of 60° S (from [Buesseler et al., 2003]).

Concluding remarks and future perspectives

Despite significant effort made during JGOFS to quantify each step of the upper ocean carbon cycle, large uncertainties remain in the estimation of shallow POC flux budgets due to technical difficulties (e.g. sampling the mesopelagic zone), as well as limited target studies on the heterotrophic processes, particularly respiration.

Two important recommendations are that in the future much more emphasis be given to measurements of respiration using both oxygen and ETS methods in the upper water column and ETS in the mesopelagic where the oxygen method is too insensitive.

Also, a better understanding of the factors that control zooplankton community composition and, hence, functionality is required if models are to predict how the POC flux and the processing of organic carbon within the mesopelagic may vary in response to global change. Accordingly, more extensive simultaneous measurements of phyto- and zooplankton species composition, particle flux and bacterial community are necessary to narrow down the uncertainties and to address future challenge, if at all realistic, to find simple parameterization for export efficiency that works globally.

Session C: Flux of particulate matter in the water column: magnitude and depth dependence

This session, chaired by **G. Fischer** (University of Bremen, Germany), summarized our knowledge on the processes controlling the distribution of various compounds in the bathypelagic layer of the oceans, extending then the vertical dimension in the flux of particulate matter discussed in the previous session. The transfer of particulate matter below the winter mixed layer is an important issue within the JGOFS Science plan as to better understand the sequestration of carbon on long time scales and to evaluate the exchanges of matter with the seafloor.

Below the depth horizon of roughly 1 km, the flux of particulate organic carbon (POC) is highly correlated with the flux of ballast in the form of silica, calcium carbonate, and lithogenous particles. Comparisons of export production from the euphotic zone, estimated from photosynthetic rates and temperature, with POC fluxes at 1-2 km depth suggests that the biodegradability of exported POC varies substantially from one region of the ocean to another. In other words, there is no universal exponent associated with the so-called 'Martin curve'. Using a global compilation of deep-sea sediment trap data (more than 150 JGOFS mooring sites), **S.Honjo, R. François, R. Krishfield** and **S. Manganini** presented a clear division of the global ocean into an organic carbon, a carbonate, and a silicate ocean. As opposed to shallow flux measurements, deep-sea sediment traps seem to be rather well constrained, exhibiting errors in the order of 20% with respect to radionuclide techniques.

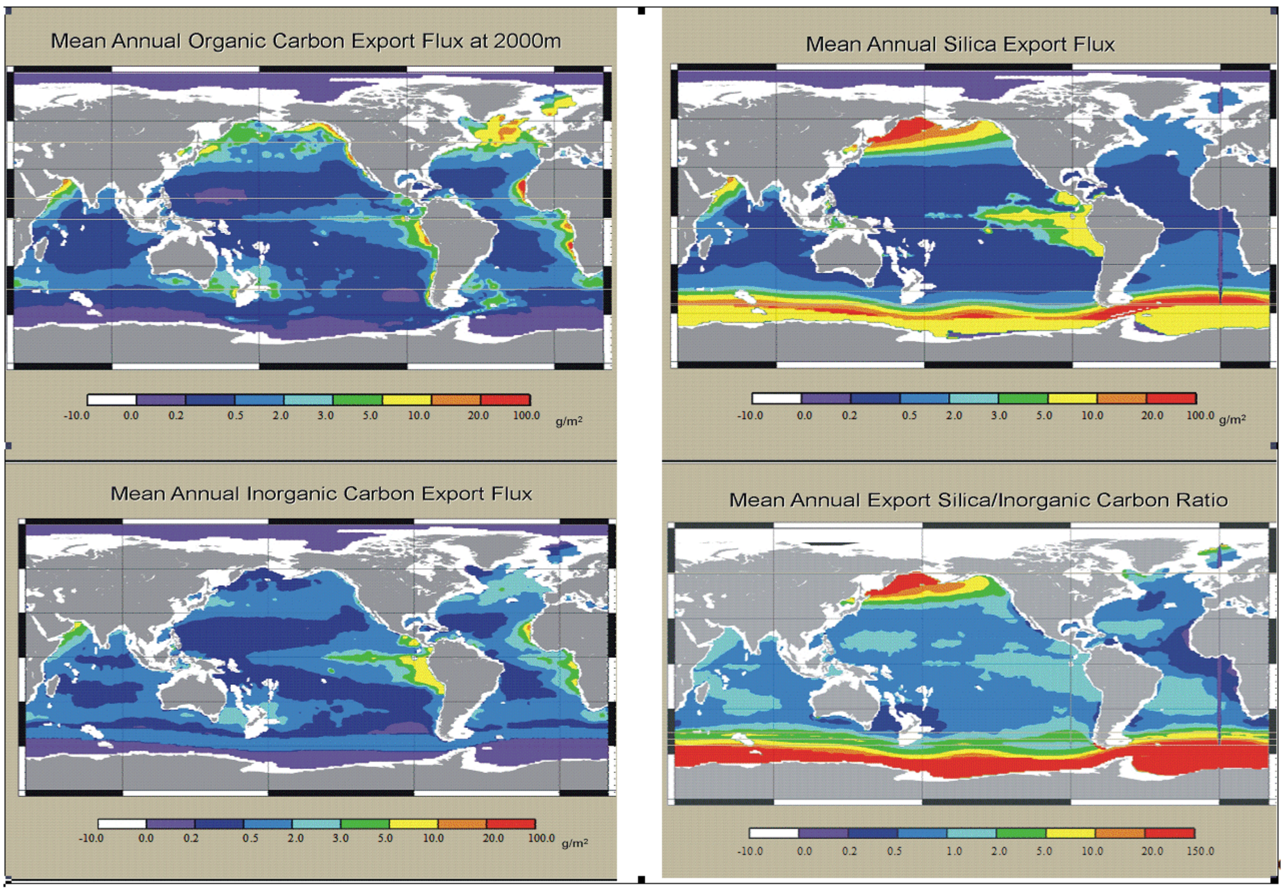

Figure C1: Mean annual export of organic carbon, inorganic carbon ($CaCO_3$), silica, and silica / inorganic carbon ratio as measured with sediment traps at 2000m depth (courtesy S. Honjo).

On average, the fluxes of organic and inorganic carbon, silica and calcium carbonate at 2000m depth are unexpectedly similar, that is 34 to 36 $Tmol.y^{-1}$, although the range of variations are rather large in time and space. The distribution of such provinces clearly indicates the important role of $CaCO_3$ to increase the transfer efficiency of organic carbon to the ocean interior (Fig. C1).

On a regional basis, a poster by **E. Malinverno, C. Corselli, P. Ziveri,** and **G.J. De Lange** indicated the importance of the carbonate flux in the oligotrophic pelagic eastern Mediterranean Sea where the upper ecosystem is dominated by several species of coccolithophorids. The data showed strong seasonal and inter-annual variations in the deep water flux of coccospheres which seem to be decoupled from that of coccoliths. These variations can be tracked back to decadal, centennial and millennial time scale in surface and core sediments.

Using a mechanistic model of POC-mineral association by [*Armstrong et al.*, 2002], a poster by **C. Klaas and D.E. Archer** showed a good prediction of deep-sea POC fluxes when using specific association coefficients with mineral fluxes of opal, calcium carbonate and lithogenic material; most of the POC export being associated to the flux of $CaCO_3$ to the deep ocean. The integration of this model to a GCM enable a regional analysis of the Si:Ca flux ratio, largely dependent on the surface temperature field.

In **R. François, S. Honjo, R. Krishfield,** and **S. Manganini's** presentation, globally distributed deep-sea sediment traps data are used to define a transfer efficiency as the ratio of the flux of carbon measured at 2000m to the export production (i.e., the flux of organic matter leaving the euphotic zone). When comparing this ratio with the flux of mineral ballast, it confirms the important role of aggregation in the transfer of carbon in the deep ocean, but also indicates the importance of the nature of the minerals. Accordingly, denser carbonates are more efficient for regulating the transfer efficiency than biogenic silica (Fig. C2). The effect of lithogenic particles is less clear. They are not considered to be dominant constituents of particle settling in the open ocean.

Using simple multiple regression model (Fig. C2), the authors have shown that ca. 85% of the variance in the transfer efficiency can be accounted for with depth, the flux of calcium carbonate, and the range of primary production in the upper layer as independent variables. The flux of the other two mineral phases (silica and clay) has negligible effect on the overall performance of the model.

$$
\begin{aligned}
T_{\mathrm{eff}} = {} & \left[\left(3.86 \times 10^{-3}\, {}^{\mathrm{ball}}\mathrm{CaCO_3}\right) - \left(0.45 \times 10^{-3}\, {}^{\mathrm{ball}}\mathrm{Opal}\right)\right. \\
& \left. - \left(1.80 \times 10^{-3}\, {}^{\mathrm{ball}}\mathrm{Lithog}\right)\right] F_{\mathrm{ballast}} + \left[52.1 Z^{-1}\right] - 0.005
\end{aligned}
$$

The lack of ballasting effect for biogenic silica can be explained by a difference in biodegradability of organic matter exported from different planktonic ecosystems. Low latitude regions are carbonate-dominated systems with complex food webs and effective microbial loops generating more refractory compounds, contributing to higher transfer efficiency to the deep sea. High latitude regions are diatom-dominated environments associated with simple food web structure releasing more labile organic matter that would be efficiently remineralized in intermediate waters, thus contributing to a lower transfer efficiency to the deep sea.

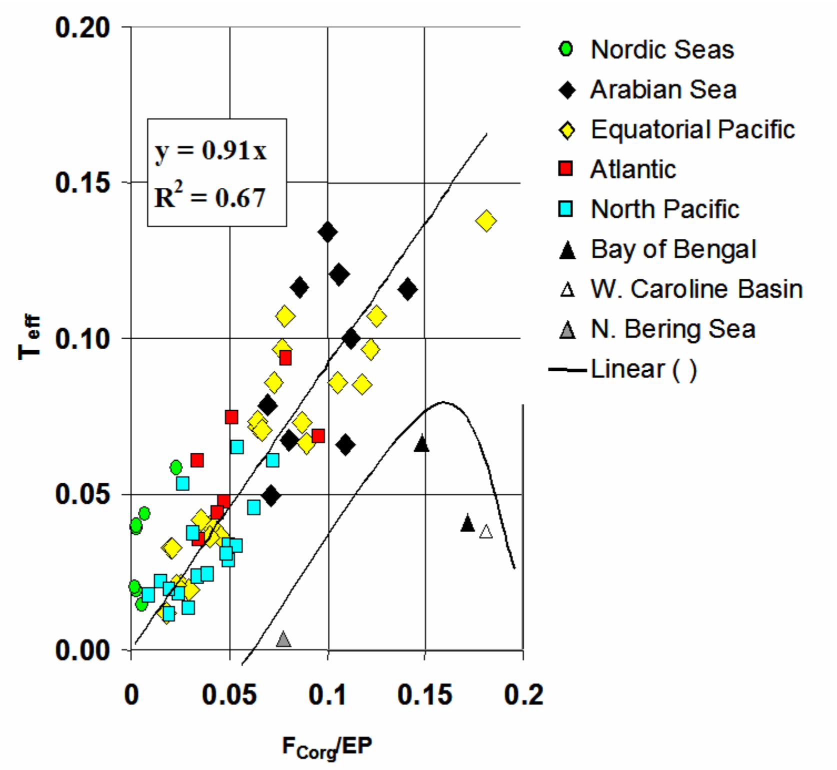

Figure C2: Linear regression between Fcorg/EP obtained by dividing organic carbon flux measured at 2000m by estimates of annual avg.export production as derived from satellite and Teff calculated with the equation above (from [Francois et al., 2002])

Such a statistical relationship is globally applicable and can be improved by adding seasonality into the model. It suggests that the b-exponent of the commonly used Martin's equation must be systematically adjusted between oceanic regions and seasons.

W. Berelson's presentation indicated that larger Martin's b-values (ca. 1.5) are associated with an efficient recycling of particulate organic carbon (POC) in the upper ocean, whereas in regions with lower b-values (ca. 0.7), more POC gets to the deep ocean. In fact, the flux of organic matter varies with depth according to both the reactivity of the constituents with its surrounding environment (e.g. temperature, heterotroph activity, inhibitors, etc.) and the inherent velocity of the particles /aggregates (e.g. carbonate vs opal, effective size, density, etc.). Within a large range of oceanic conditions, the data showed a systematic increase of the biogenic Si: Corg ratio with depth, suggesting a reactivity of POC higher than for silica. In addition, high opal contents of particles tend to reduce their settling velocity, and enhance furthermore the remineralisation of organic carbon at intermediate depths. Unbalanced situation between reactivity and settling velocity of particles can explain why opal burial to the bottom is often decoupled from POC burial. Adding iron to the ocean would increase opal-rich, slowly-sinking particles and favor rapid recycling of Corg. Thus, the effectiveness of iron fertilization for long-term sequestration of atmospheric CO2 will remain an open question until we know more about the processes occuring in the twilight zone.

Using a slightly different approach, **W. Koeve's** poster presented an estimation of an effective carbon flux in the Atlantic Ocean from the difference between the export production (as derived from particle flux data and satellite-based primary production) and the flux of particulate inorganic carbon (PIC) weighted by the ratio of released CO_2 : precipitated carbonate during $CaCO_3$

formation. The result shows a difference of about 30% between the export production (0.9 to 2.9 GtC.y-1) and the effective carbon flux at depth (0.64 to 2.2 GtC.y-1) which is controlled by the balance between remineralisation of organic carbon above the winter mixed layer and the production of $CaCO_3$.

From a regional study in the Porcupine Abyssal Plain, **R. Lampitt, K. Popova,** and **I. Totterdell** presented the benefit of using simple biogeochemical model of the upper ocean (e.g. Fasham's NPZD type) to obtain the magnitude and variations (seasonal) of the flux of particulate matter at 3000m depth. Extrapolating their study to global scale, observations of flux at 2000m obtained from sediment traps were compared with global circulation models including biogeochemistry (HadOCC and OCCAM).

Concluding remarks and future perspectives

A surprising result from recent studies and modeling exercises presented in this session is the importance of carbonate ballast to control the transport of organic carbon through the water column. This conclusion represents a major paradigm shift in the sense that opal has for decades been regarded as the substance primarily responsible for ballasting detritus as it sinks through the water column. However, we still have presently no understanding of the mechanisms underlying the significant empirical relationships between organic carbon and carbonate fluxes in the bathypelagic layer. If carbonate particles play a critical role as ballast, more information is needed about the magnitude of production of relevant carbonate producers, which include pteropods, foraminifera, and coccolihtophores. The relative importance of these different groups of calcifiers and the factors that control their abundance and activity need to be identified.

Our understanding of deep sea fluxes is mainly constrained by difficulties in evaluating formation and destruction processes and the interaction between suspended and sinking particles in the twilight zone. Reliable fluxes in the mesopelagic, or below the euphotic zone, are required to assess the decay functions of the organic carbon ('b-values') with depth. As seen in the previous session, these measurements are technically difficult. However, Neutrally Buoyant Sediment Trap (NBST, [*Buesseler et al.*, 2000]) with limited hydrodynamic bias and low swimmer flux maybe a promising tool for future studies.

Session D: Bentic fluxes along ocean margins and in the open ocean

This session, chaired by **Richard Lampitt** (Southampton Oceanography Centre, UK) summarized our present-day knowledge on fluxes of particulate organic and inorganic material to the sea floor, both in the open ocean and along ocean margins. Also covered was the role of mineral ballasts and the linkage with organic carbon fluxes. It was emphasized that the majority of nations with JGOFS programs did not include a benthic component in their science plans. Nevertheless the significance of the benthos as an environment that integrates the processes occurring in the upper waters over large space and time scales has not been lost. This environment may furthermore provide the only insights into the massive fluxes that are expected to occur across the margins of the deep ocean.

Two presentations were made that focused on benthic fluxes and these provided contrasting approaches. Increasing depth in the water column can be equated to increasing time before the water is in contact with the atmosphere and hence increasing time before the dissolved components such as carbon dioxide can exchange with the atmosphere. Remineralization of organic matter that occurs at the benthos thus generates CO_2 that will not be climatologically active for a longer period of time than that generated elsewhere. Within anthropological timescales, the benthos is thus the ultimate “sediment trap”. Almost all of the organic material that reaches the seafloor is remineralized there and the global map of remineralization [*Jahnke*, 1996] updated during **Jahnke’s** presentation (Figure D1) thus provides an alternative measure of regional variation of downward organic flux to that provided by productivity maps, sediment trap measurements or global models.

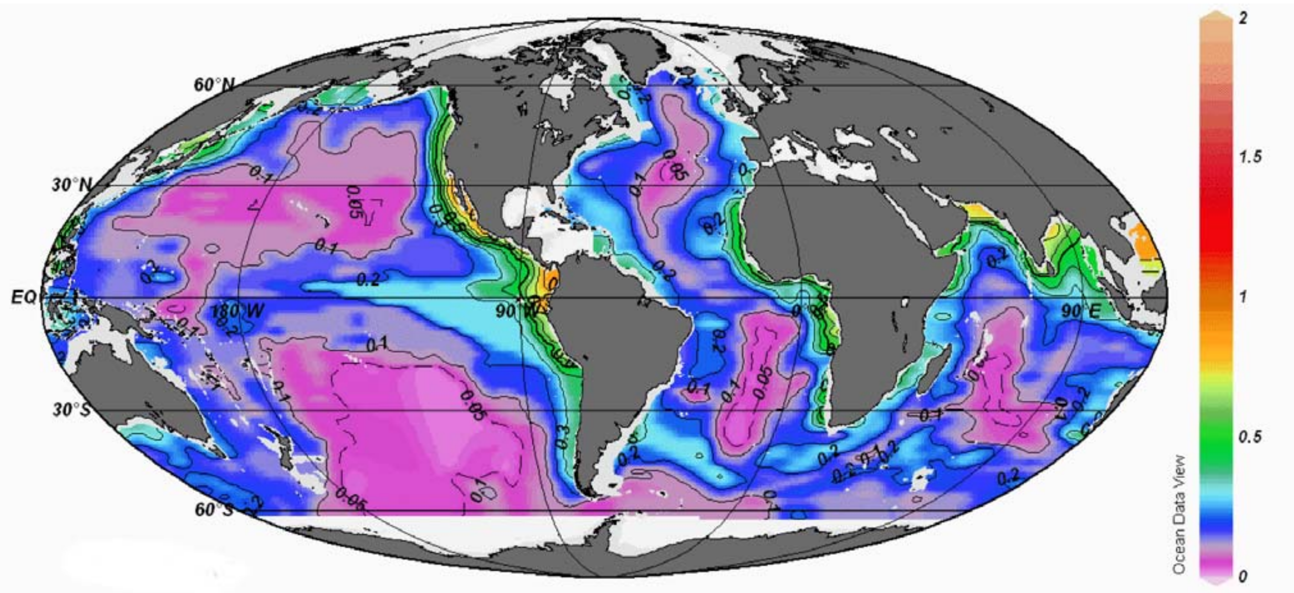

Figure D1: Benthic oxygen fluxes [mol O_2 m^{-2} yr^{-1}] (redrawn from [*Jahnke*, 1996]*)*

Although many of the regional features determined from benthic observations are similar to those found in global maps of primary production (see Figure A1), there are significant differences. The benthic results provide much greater emphasis on the importance of the margins where, it is calculated, half of the total organic flux to the deep oceans occurs. Furthermore, high latitude environments especially the North Atlantic are of much less significance than is calculated on the basis of primary production. The reasons for this disparity are still not clear but are likely to reflect variations in export efficiency (see session B) and midwater processes.

Following on this theme **Chen** calculated that about 5% of the new production that occurs on the shelf is exported to the deep seas. Chen also addressed the issue of whether the coastal seas are a net source or sink of CO_2. In this case there appears to be a range of directly opposing opinions within the community and as yet no consensus has been reached.

R. Armstrong in his presentation emphasized the role of mineral ballasts, such as biogenic carbonate and opal as well as lithogenic material, for the deep ocean fluxes of particulate organic carbon. From the analysis of sediment trap data in the equatorial Pacific and the Arabian Sea he found that below about 1000 m depth, the normalized POC fluxes (POC flux divided by total flux) were surprisingly constant, while absolute POC flux variations were large. As an alternative to the frequently used Martin formulation [*Martin et al.*, 1987] he proposes to represent the depth dependence of the POC flux as the sum of a ballast associated component (proportional to ballast flux) and an excess component, which is almost completely remineralized in the upper kilometer of the water column [*Armstrong et al.*, 2002]. Using a larger sediment trap database, **K. Klaas** and **D. Archer** confirmed the correlation between deep POC and ballast fluxes, and they determined POC loading factors for $CaCO_3$, opal and lithogenic material, respectively using multiple linear regression between the measured flux components [*Klaas and Archer*, 2002]. From their analysis it appears that $CaCO_3$ and lithogenic material are efficient ballasts for POC, while opal has a much smaller loading factor and appears less efficient.

Concluding remarks and future perspectives

Uncertainties about the role of the margins in global cycles are large but developments in coupled physical/biogeochemical models of the shelf and slope regions provide a strong framework for resolution of several of these issues. The systematic differences between surface productivity and benthic fluxes suggest that export f-ratios and transfer efficiencies of particulate material into the deep ocean vary spatially and, possibly, with time. We need more studies on magnitudes, regulations and dependencies of particle remineralization in the euphotic layer and the “twilight” zone below, in order to better predict deep ocean fluxes from surface production. Mineral ballasts appear to affect the transfer efficiency of particulate organic carbon into the deep ocean. However, the underlying mechanisms and processes have not been identified and understood yet, and the linkage between ballasts and deep POC fluxes still has to be verified in large ocean areas.

Session E: Recent evidence for changes in marine biogeochemical cycles

This session, **chaired by J. Steele** (Woods Hole Oceanographic Institution, U.S.A.) was dedicated to look at observations of inter-annual to intra-decadal variability of marine biogeochemistry and biology. Understanding this range of variability is mandatory to evaluate prognostic models that would be used in a context of climate change.

The first part was dedicated to long time series obtained in the context of marine resources surveys, both in Northern Atlantic from (**G. Beaugrand**) and in the Northern Pacific from (**S. Chiba**), while preliminary analysis of coupling-decoupling between physics, nutrients and production was discussed using a simple process based model (**M.Levy**).

In the Northern Atlantic, the Continuous Plankton Recorder (CPR) from SAFHOS (UK), operated since a half-century, provides a unique opportunity to look at variability and change of planktons (large phyto- or zoo-). In a striking manner, Figure E1 illustrates how, in the recent decades, subarctic cold species have been replaced by temperate species in the North-East Atlantic and in the North Sea [*Beaugrand et al.*, 2002]. Analysis with principal components show correlation with global warming of Northern Hemisphere while correlation with NAO is found weaker, except for some specific species as Calanus Finmarchiccus [*Fromentin and Planque*, 1996]. It has been pointed out that foodweb don't react instantaneously and locally to change in ocean physics, thus linear correlation between biological and physical proxy could be poor.

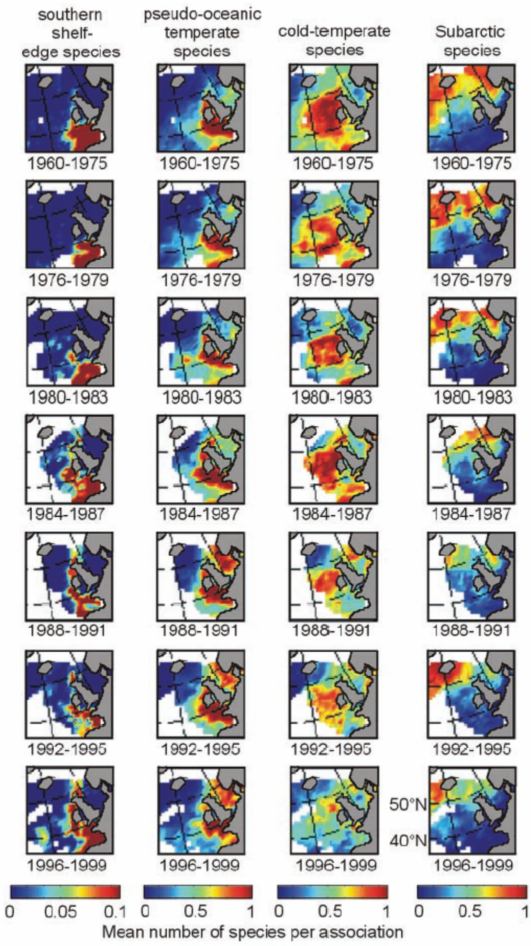

Figure E1: Changes in North Atlantic marine copepods (from [Beaugrand et al., 2002])

Insights on this coupling-decoupling paradox had been given by using a simple process based model (NPZD scheme in LOAM model, [*Visbeck et al.*, 1998]). In fact, the North Atlantic Oscillation, ie a proxy of location and strength of High and Low systems, cover a wide range of time spectra from synoptic to season, year and decade. Longer time scales tend to decouple nutrients fields changes induced by wind fields variability. As illustrated in Figure E2, patterns of primary production (PP) could be in phase with NAO for western mid-latitude or sub-arctic gyre, while there are in quadrature for the eastern basin. This decoupling near Europe is due to the lag induced by the advective transport of nutrient anomaly along the Gulf stream.

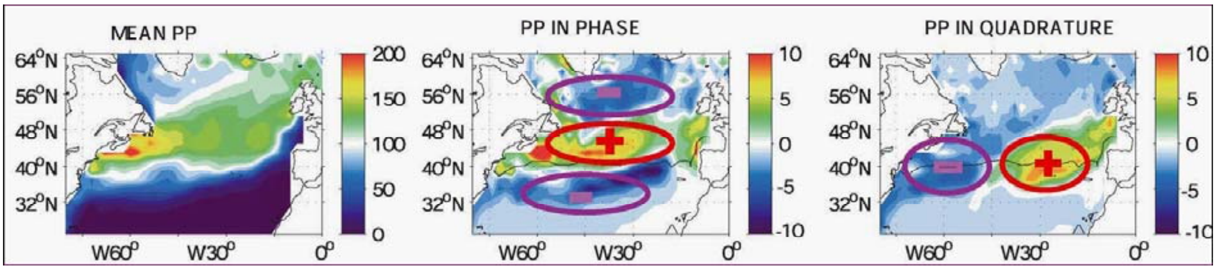

Figure E2: Simulated primary production for an idealized 8 yr NAO cycle: (a) mean, (b) 1st harmonic in phase, (c) 2nd harmonic in quadrature (courtesy M. Visbeck and M. Levy)

In the Northern Pacific, same large changes are found as illustrated in the Oyashio area (see Figure E3) where a significant decrease of nutrients is found in wintertime due to a more stratified ocean in recent decades. Also some changes in 1976 and 1988 could be identified, potentially related to phase of PDO.

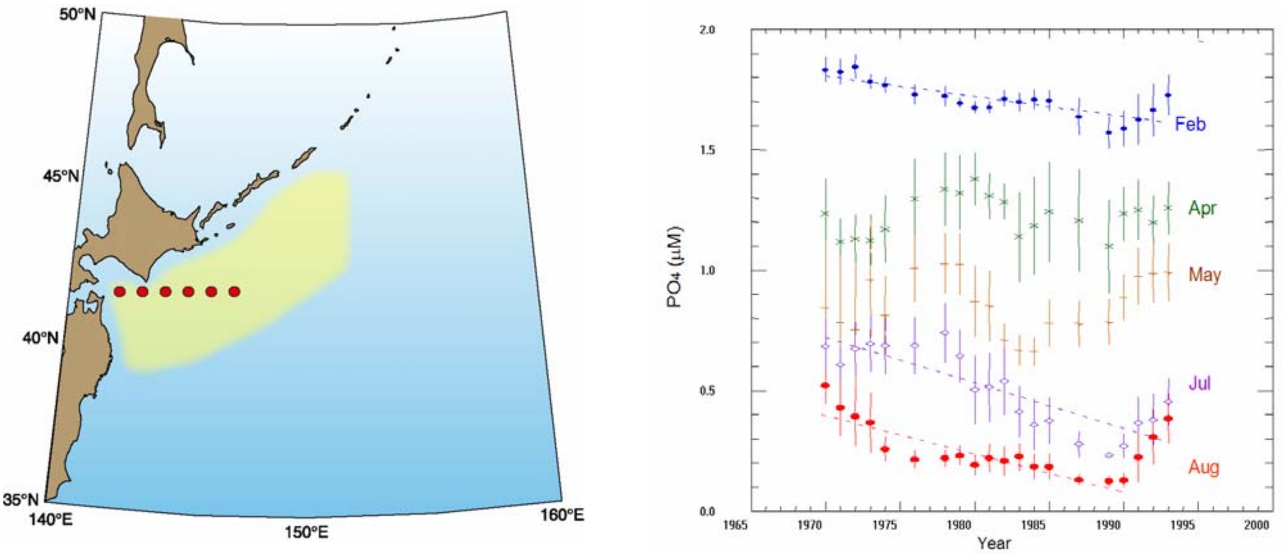

Figure E3: Impact of stratification in Oyashio waters (left) on phosphates (right), (courtesy T. Ono, adapted from [Ono et al., 2002])

Furthermore such behavior cascade in the foodweb in a non-linear way as illustrated in Figure E4. While overall primary production and chlorophyll decrease, the spring bloom starts earlier and favors the success of copepod development. Thus again a decoupling occurs here, but between nutrient and zooplankton community.

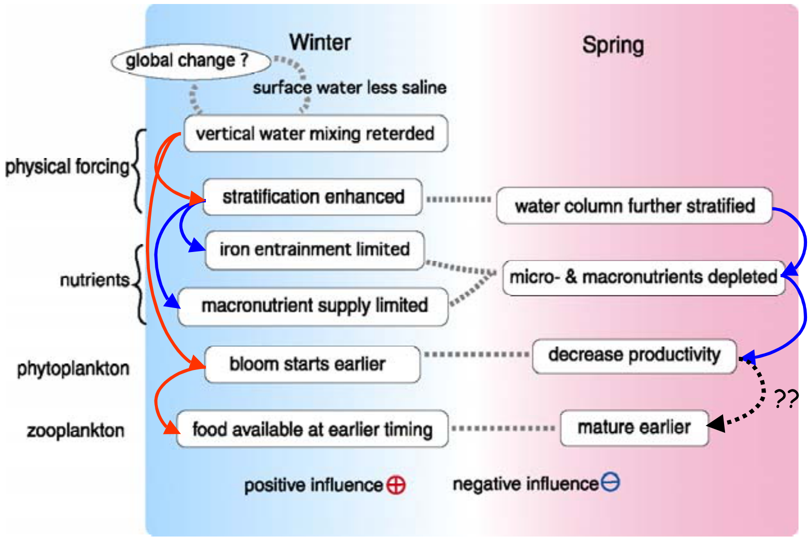

Figure E4: Sketch for non linear process through the foodweb *(courtesy S. Chiba)*

Concluding remarks and future perspectives

Overall, even if there is strong control of physics on nutrients, cascading on phytoplanktons and zoo-planktons, it is recognized that such coupling is not a linear one. It implies a good description of basic process and their time and space development. For example, stratification could reduce nutrients for life but could also reduce light limitation and favor early phytoplankton bloom (see poster **Monfray et al.**) that could increase secondary production (i.e., copepods, see Figure E4).

Redistribution by lateral transport of nutrient must be taken into account at basin scale, pleading for wide domain 3D models but including the relevant bio-geo-physical processes and their relevant scales, as remineralization of organic matter (see poster **Kawamiya** and **Kriest**). Highly crucial, it is to have the right mixture of limiting nutrients at the right place and time: in this context, the role of iron role should be tackle as soon as possible.

Evaluation of simulations on long time series is crucial at JGOFS stations (see poster **Fujii et al**). This effort must be extended at zooplankton level to use CPR, Japanese and others countries records, made along their marine resources survey. Reversely, analysis of large phyto-plankton records within the CPR would be a gold mine to interpret. Basically, both integrated model from physics to zooplankton and data-mining, dealing with intra- to inter-decadal timescale, are needed for the up-coming years for fruitful interactions. There is a strong requirement for data archives explorations (also in sedimentation records) in close cooperation with CLIVAR, GLOBEC, and PAGES.

Session F: Hind- and forecasting biogeochemical fluxes with models

This session, chaired by **S. Spall** (Hadley Centre for Climate Prediction and Research, UK), was dedicated to look at capability to represent variability and change in biogeochemistry over the past (hindcast modeling) or to bracket the scenario prediction for the future (forecast modeling). A special challenge all along is to evaluate models versus independent datasets to qualify their different skills.

First, impacts of global warming on ocean biogeochemistry was argued using prognostic model that can forecast the system under a climate scenario (**R. Matear**). It is now recognized that a significant change in ocean state is occurring with a surface heating entering the upper ocean as illustrated in Figure F1 for the Austral Ocean, both from observation or simulation.

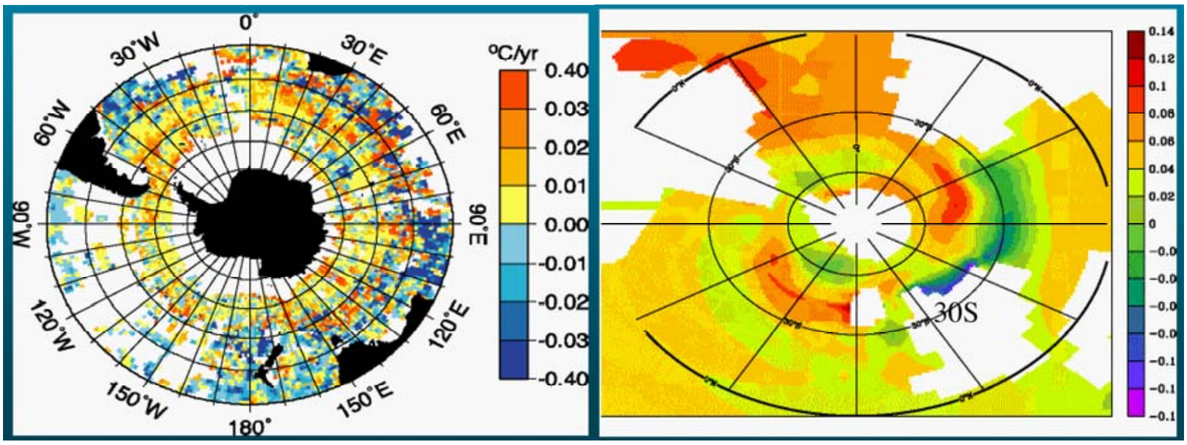

Figure F1: Present changes in temperature at intermediate depth (≈1km): a) from observation in °C/yr ([Gille, 2002]), b) from CSIRO simulation in °C/decades (courtesy R. Matear).

Furthermore change in precipitations regime tends to bring more fresh waters in mid and high latitudes structures as illustrated in Figure F2.

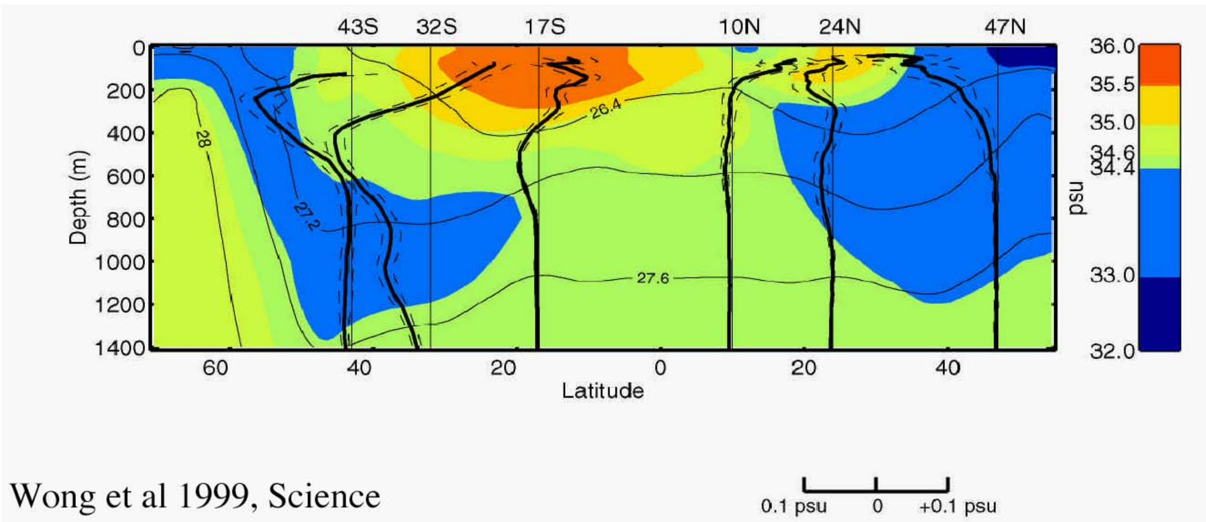

Figure F2: Salinity field (color) and change (profiles) in the Pacific (in psu): evolution of properties in mode and intermediate water masses are clearly seen ([Wong et al., 1999])

These changes in temperature and salinity combine to increase upper ocean stratification and cause a sluggish circulation of the ocean which will potentially redistribute nutrient patterns and primary production in the whole ocean ([*Sarmiento et al.*, 1998], [*Matear and Hirst*, 1999]). To retrieve and follow such climate change impacts on geochemistry or on biology is a hot topic. [*Bopp et al.*, 2001], [*Matear et al.*, 2000] and [*Plattner et al.*, 2002] have recently highlighted that dissolved oxygen levels in the ocean are sensitive to less ventilation at high latitudes, and under such conditions deep oxygen levels decline and deep nutrients such as phosphate increase (see Figure F3).

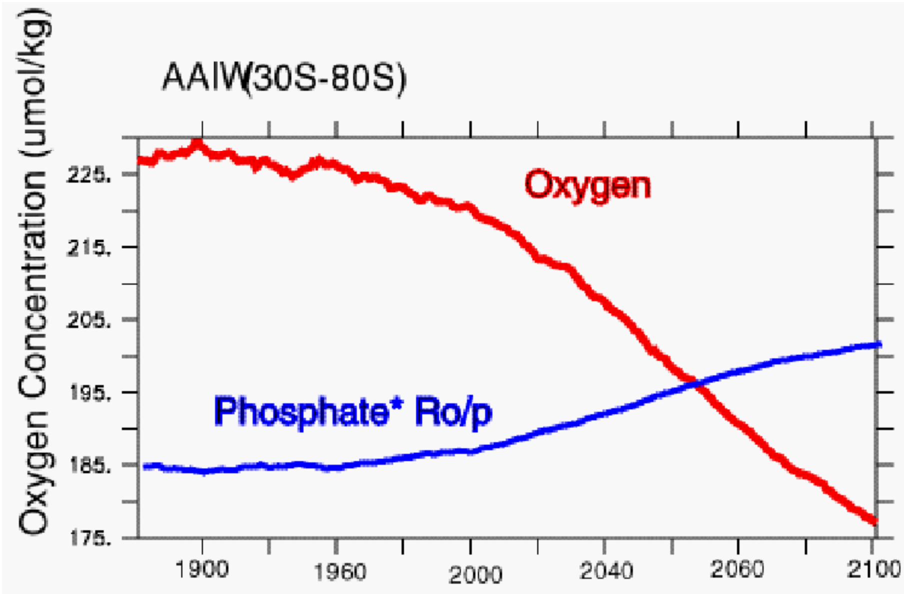

Figure F3: Estimated changes in Antarctic Intermediate Waters for oxygen and phosphate contents from the CSIRO simulation (courtesy R. Matear). *oxygen normalized*

Detecting such imprints of climate change over the intra-decadal variability in the fields of oxygen, nutrients or circulation tracers such as CFCs (see also poster **Ishida et al.**) is a crucial task to tackle with:

i) Quality controlled data mining;

ii) New systematic observing system of these variables to split short-term variability from the trend.

Second, intra-decadal to inter-decadale time variability needs, in such context of global change, to be better assessed and quantified. As meteorological reanalysis is now available over the last 50 years, it is feasible to force biogeochemical model and hindcast what happened for geochemistry and biology over the last half-century (see NOCES/OCMIP-III initiative).

On one hand, new insights on process occurring on such time scale could be studied in the modeling world, as subsidence of nutrient at the base of the mixed layer in wintertime. It seems that modulation of transport of dissolved inorganic matter (DIN) plays a stronger role than change in export production (PON). This means that physical process to isolate carbon or nutrient from the surface for years could be equal or more important than biological process. This urges to use advanced physical oceanography with finer resolution (eddy permitting and mixed-layer dynamics) that reacts in a properly way to climate modes (see also poster **Popova et al.**), as the NAO in the Northern Atlantic triggering behaviors from season to decades.

On the other hand, very few qualified long time series exist to evaluate the simulations, except some record for some planktons (as CPR or Japanese survey, see session E) but models still have problems to represent such categories (see session G). Here again data mining and careful aggregation are mandatory. Reversely, this implies that models could represent or parameterize the different observed variables in an appropriate manner.

Concluding remarks and future perspectives

It is reckoned that ocean biogeochemistry should be considered as a non steady state system, both due to:

i) natural variability occurring from seasons to decades, and tightly coupled to climate modes;
ii) global change, particularly the warming climate induced by human activities.

Evaluation of biogeochemical models by observations rise different sets of question:

i) What variables do we need to represent: oxygen, carbonates, nutrients, planktons, paleo-proxies ?
ii) What suite of tests do we need to make to qualify a forecast model? From season to decades? From glacial time to anthropocene, via holocene ?
iii) What accuracies are required for the observations?
iv) How to compare data and models in an objective way? What kind of synthetic tools could summarize the behavior of a model, in a certain space and time range?
v) What are the uncertainties of an ensemble of simulations *(as OCMIP-II&III).* How this knowledge can be translated to policy makers?

There was a general consensus to focus from season to decades over the recent past. The paleo challenge, despite interesting issue (see poster **Bopp et al.**), could not really qualify a model to forecast the next centuries. In opposite, a much better description of last century or millennium both for climate and biogeochemical variables would be very helpful. Stronger links with programs dealing with those issues as PAGES or CLIVAR are crucial. Session H discussed more in depth this observational issue.

Finally, a better physics is still strongly required and our community should have to insure a short and permanent link to advanced physical modeling developed within operational oceanography (GODAE) or within coupled ocean-atmosphere (CLIVAR-CMIP).

Last but not least, propagations of errors associated with parameterization of biogeochemical processes must be tackled. Systematic sensitivity test using ensemble method or adjoint model should be undertaken. A particular concern is devoted to fitting procedure of the various parameterization (see **Dunne**'s talk or posters **Yamanaka et al.**, **Popova et al.**, **Winguth et al.**) that could prevent the forecast capability of a model, beyond the diagnostic period where the adjustment was made.

Session G: The next generation of biogeochemical models: what level of complexity is needed ?

This session, chaired by **M. Levy** (Laboratoire d'Océanographie Dynamique et de Climatologie, France), was dedicated to look at representation of biogeochemical processes in the context of past, present and future variability or trends (see Sessions E & F). Complementary, recent field knowledges pinpoint the different key role of macro- and micro-elements to control biological production, a new generation of model is required. Despite these challenges, as introducing the iron cycle, either diagnostic or prognostic schemes should remain robust and as simple as possible.

Different approaches had been proposed to deal with multiple limiting nutrients, ranging for plankton from explicit taxonomic groups (**Le Quéré**) to size spectrum dependency (**J. Dunne**). In a more general context, paradigms had been discussed from two end members of the foodweb: the dissolved organic matter recycled by bacteria (**I. Totterdell**) and the zooplankton control via trophic structure (**J. Steele**).

From analogy with land Plant Functional Type (PFT), 5 main taxonomic groups of phyto-planktons have been proposed (**Le Quéré**'s talk, **Buitenhuis et al.**'s poster) to mimic 5 different behaviors related to the biogeochemical cycles (see Table G1). In this manner, both nutrient co-limitation controls biological activities and reversely biology impacts on key cycles (C export, DMS production, etc.) in a coherent manner. However, explicit 5 different groups challenge:

i) in one hand, how to bracket a wide range of parameters from field studies such processes as grazing or export ?

ii) in other hand, how to evaluate simulations by poor coverage of such group speciation or by indirect proxies ?

Trait	**Phyto Silicifiers**	**Phyto calcifiers**	**Phyto N2 fixers**	**Phyto DMS producers**	**Phyto Nano/ pico**	**Micro zoo**	**Meso zoo**
Max growth rate	**H**	**L**	**L**	**H**	**H**	**H**	**L**
Min survival T			**20**		**(16)**		
Affinity for light	**L**		**L**		**(H)**		
Light stress	**L**	**H**		**H**	**M/L**		
P half saturation	**75**	**4**	**75**	**19**	**19**		
Fe half saturation	**120**	**20**	**120**	**20**	**20**		
N_2 fixation			**Yes**				
DOP fixation		**Yes**					
Si utilisation	**Yes**						
food						**Small**	**Large**
CO_2 response		***Yes***					
Production of ballast						***?***	***?***

Table G1:Key marine Plant Functional Types (PFT) proposed within the Green Ocean Project (http://www.bgc-jena.mpg.de/bgc_prentice/projects/green_ocean/start.html, courtesy C. Le Quere)

An alternative approach is proposed by **J. Dunne** by simplifying the trophic status with a size spectrum dependency triggered by co-limiting nutrients following the concept of [*Armstrong*, 1999]. Figure G1 illustrates the clear dependency between size and chlorophyll concentration. Such shift from small to large species directly reduce grazing control and increase particulate export versus DOM production. In this approach, uptake of nutrients or release of dissolved matters or particulates could be either diagnose by restoring to surface nutrients values or parameterize in a semi-prognostic way.

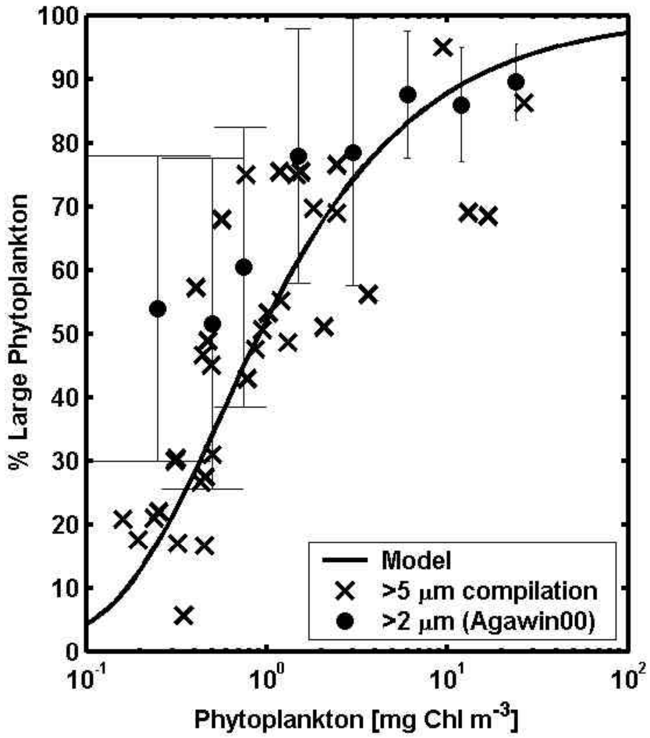

Figure G1: Rate of large phyto-plankton versus biological density, here Chlorophyll: data from [Agawin et al., 2000], model from [Dunne et al., in prep]

The role of bacteria loop and its control on DOM production and consumption is not yet clear specially to sustain life in oligotrophic gyres (**I. Totterdell**). Emphasis on continuum spectra of lifetime, depending on environment, for DOM should be envisioned.

Finally, in a broad sense, **J. Steele** addresses the problem of complexity and stability in the whole foodweb where both bottom-up and top-down controls occur. This problem is not only a numerical problem but much more intrinsic to the character of biological interactions and adaptations. A particular key point is still to be solved: the coupling between lower trophic levels, i.e. phyto-planktons acting as fuel producer, and medium trophic levels, i.e. zooplankton stages acting as grazers and fuel transmitters to upper trophic levels. As yet pointed in session E, strong non-linear processes occur with (un)likely bifurcation points where regression approach is useless. Such turning points could be reached after a long stable time period, either by top-down perturbation as over fish catching or by bottom-up propagation of climate or nutrient changes. Furthermore, we still don't know if a minimum of diversity and complexity of ecosystems favor stability or multiple stabilities.

Concluding remarks and future perspectives

Do we need more complex model is one leitmotiv for biogeochemical modelers. Also, it's recognized that a full suite of biological schemes are needed. In fact there is no universal scheme, but just biogeochemical tools that should be designed within the context of a targeted scientific question. These different schemes are yet used extensively towards better insights on biogeochemical cycles as DMS (**Spall et al.**'s poster; [*Bopp et al.*, 2003]) or carbon cycle (**Ragasakthi et al.**'s poster) or tracers (**Sasai et al.**'s poster).

Following items are key challenges to solve:

i) The role of iron with strong continental sources needs to be addressed in some way (see poster of C. Measures).

ii) The mesoscale or sub-mesoscale patterns occurring in the real ocean at few kilometers scale. At such scale, CPU is too limited thus it is crucial to found ways to implicitly take into account those processes to capture their effect on large scale ocean models.

iii) The processes in the mesopelagic layers are still poorly known as vertical migration, ballasting, aggregation/desaggregation effects (see discussions in previous sessions).

Finally, qualified, aggregated and systematic observations and data synthesis should be accomplished to evaluate new generation of models. On a longer timeframe, if first order processes are depicted, data assimilation techniques should be used in more systematic way to give a coherent picture of biological, geochemical and physical variables.

Session H: Future observations of biogeochemical systems: new technologies and Networks

This session, chaired by **N. Gruber** (University of California, Los Angeles, U.S.A.), was dedicated to new data challenges that biogeochemical research faces to get insights and constrains on a broader time frame, i.e. towards inter-annual to decadal variabilities. Thus main topics address here was:

- *i)* how to design a new observing system with new generation in-situ sensors (**J. Bishop**) and satellite capability (**S. Sathyendranath** and **T. Platt**);
- *ii)* how to recover, qualify, manage and diffuse the data, both from past long-time records as well as towards near real-time access of new acquisitions (**M. Conkright** and **Bernard Avril**).

To follow the dynamics of the ocean, the physical oceanography community is now deploying, within IGOS, CLIVAR & GODAE programs, a long term and comprehensive survey based on satellite platform, ships of opportunity, fixed mooring and autonomous buoy, profiler or glider. This array of observing network will permit for the first time a full coverage of the ocean at an unprecedented space and time resolution. Biogeochemical community faces same issue to tackle the variability of geochemical cycles and biology in the ocean. However, it required a dedicated technological investment to develop a new generation of biogeochemical sensors that could be downsized, autonomous and integrate on the new autonomous platforms. Towards this step, **J. Bishop** presented a very interesting pathway by setting-up on ARGO autonomous profiler POC concentration and flux sensors based on transmissometer. Figure H1 illustrates around station Papa a 50 days survey that allows to follow the biological blooms in the photic layers. Four others systems are also functioning successfully in Southern Ocean even in wintertime with an autonomy over a year. As illustrated by the Gardner et al.'s poster transmissometer database would help to constrain POC distribution at basin scale.

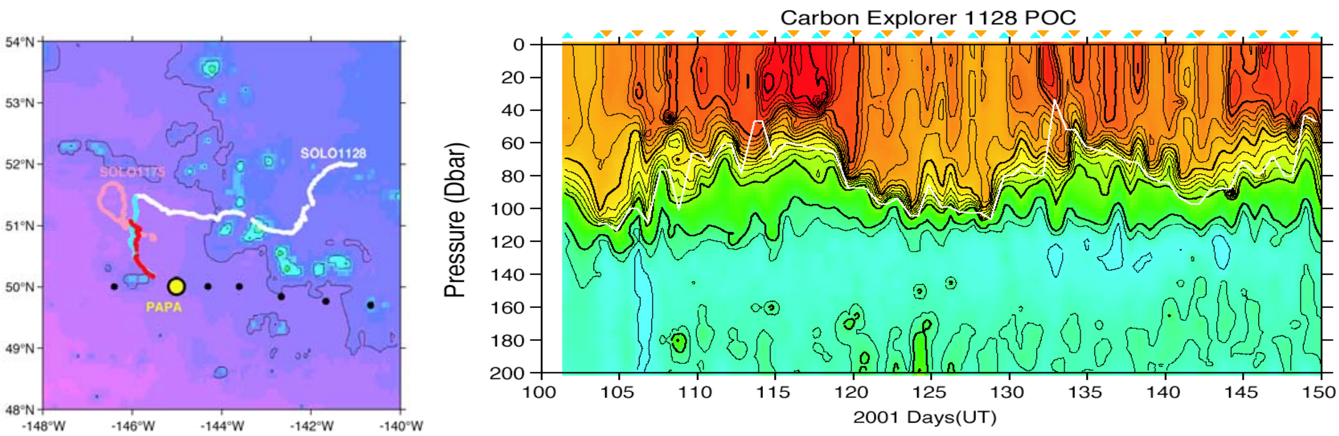

Figure H1: Carbon Explorers near Station PAPA (April to December 2001): a) trajectory superimposed over bathymetry, b) Time series of POC variability from SOLO1128. Cyan up-triangle and orange down-triangle at the top of each panel are plotted at the times of dawn and dusk profiles. From [Bishop et al., 2002].

Complementary to in-situ observation, maintaining and improve satellite survey of marine biology is a key issue that was presented by **S. Sathyendranath**. Presently, the major global-scale missions, SeaWiFS, MODIS, and now MERIS, GLI or POLDER-2 are still research missions (see IOCCG) and not operational missions. There is a great concern for the continuity of these products and our community should have to strongly support initiative as POGO (Partnership for Ocean Global Observations) or IGOS/GOOS (Global Ocean Observing System) on that way. **Dr. Sathyendranath** presented also exciting new developments with regard to the ability to detect different phytoplankton functional groups (as coccolithes, diatoms, cyano-bacteria, …), or separate chlorophyll from dissolved organic matter or suspended matter, on the basis of their different optical properties, as discussed in the SIMBIOS project. Tests, before these new products can become operational, are actually conducted. Courtesy of **H. Loisel**, Figure H2a illustrates for this report an example to discriminate particles size from backscattering properties using SeaWifs. Figure H2b shows the global distribution of *POC*, for the first time [*Loisel et al.*, 2002]. This study indicates that *POC* exhibits remarkable different seasonal variations than *Chl* and that *POC* values are more evenly distributed in space compared to the Chl ones.

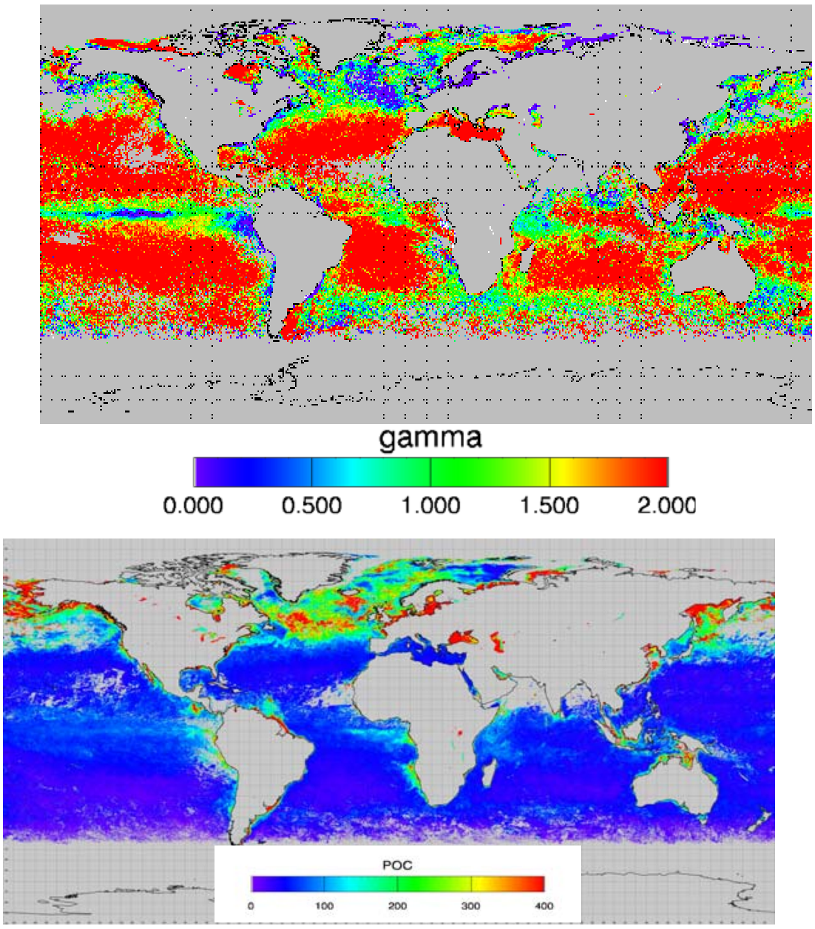

Figure H2: a) Particulate size index in June 2000, from SeaWiFS backscattering spectral dependency using. Low values (blue) correspond to large size, high values (red) correspond to small size (courtesy of H. Loisel). b) Global POC distribution in June 2001 as retrieved from SeaWiFS using Loisel et al. [GRL, 2002].

Finally, **M. Conkright** addressed a critical issue: the data management. There is a tremendous release of ocean data since the last decade as illustrated by the new World Ocean Atlas available at NODC. JGOFS available products had been also presented. But the inventory of JGOFS or related cruises is still not finished, and despite an attempt to produce a JGOFS Database for the 2003 final synthesis (see also **Dipenbroek et al.**'s on PANGEA), a lot of data are still be far to be easily accessible. The lack of a centralized international data office severely hampers the use of JGOFS data for synthesis and model validation (see also **Avril et al.**'s poster). A world integrated chemical and biological database would be a huge step to achieve and should allow analysis of inter-relationships between biogeochemical variables, as well as evaluate and constrain an hierarchy of models (see also **Andersen et al.**'s poster and **Follows et al.**'s poster).

Concluding remarks and future perspectives

The conclusions of the session can be summarized as follows :

i) Autonomous sensors and platform are undergoing rapid development. Many of them are ready for beta testing, i.e. deployment by less experienced researches. It is likely that large-scale deployments of such instruments will lead to a revolution in the manner that ocean biogeochemistry will be done, but many issues still need to be addressed. Those are in particular calibration and stability of the sensors, and the lack of sensors for many critical parameters. Extension to chemistry (oxygen, nutrient, etc.) or biology (pigments, acoustic imprints, genetics, etc.) would be highly valuable, as recommend by IGCO/GOOS (see Report N°118 for a Global Ocean Carbon Observation System). High technological projects should be favored at a high level of priority in the next decade.

ii) Many new programs/observational networks are currently being developed. These programs are often driven by the physical oceanographic/climate community. This provides many opportunities for the biogeochemical community and linkages should be sought to the maximum extent possible. At the same time, it is important to ensure that the existing and well working programs and networks, as time series stations.

iii) For satellite survey, beyond the need to insure a suite of operational satellite on ocean color, a significant effort should be devoted on new algorithms. It should characterize the lower trophic state of the ocean, as pigment/group classification, size spectra, dissolved or suspended matter specially in ocean margins.

iv) Experience with JGOFS and other large-scale programs has provided ample evidence that quality control and data management activities have to be integrated from the beginning into any program that would like to be successful, as WOCE made. In a broader sense, data mining and qualified aggregation of pre-JGOFS and related-JGOFS cruises should be enterprise to extend range of observation towards decadal variability.

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Appendix B: Abstracts

SEASONAL AND ENSO VARIABILITY IN GLOBAL OCEAN PHYTOPLANKTON CHLOROPHYLL (James A. Yoder and Maureen A. Kennelly)

Seasonal changes in phytoplankton biomass and productivity are very important components of the total variability associated with ocean biological and biogeochemical processes. Seasonal changes in phytoplankton biomass and productivity are generally related to incident solar irradiance, upper ocean mixing and stratification and other processes that affect the ocean's light and nutrient environment. SeaWiFS and other satellite ocean color sensors now provide data sets to assess seasonal and other sources of phytoplankton variability on global scales. We used empirical orthogonal function (EOF) analysis on a 4-year time series of global SeaWiFS chlorophyll a measurements to quantify the major seasonal (as well as the 1998 ENSO) signals in phytoplankton biomass between 50° S and 50° N, and then a second analysis to quantify summer patterns at higher latitudes. Among the important effects we resolved are a 6-month phase shift in maximum chlorophyll a concentrations between subtropical (winter peaks) and subpolar (spring-summer peaks) waters, greater seasonal range at high latitudes in the Atlantic compared to the Pacific, spring and fall biomass peaks at high latitudes in both hemispheres, and the effects of the 1998 ENSO cycle in the tropics. Our EOF results show that dominant seasonal and ENSO effects are captured in the first 6 of a possible 182 modes. These first six modes explain 67% of the total temporal variability associated with the global mean phytoplankton chlorophyll pattern in our smoothed data set. The results also show that the time (seasonal) /space (zonal) patterns between the ocean basins and between the hemispheres are similar, albeit with some key differences. Finally, the dominant global patterns are consistent with the results of ocean models of seasonal dynamics based on seasonal changes to the heating and cooling (stratification/de-stratification) cycles of the upper ocean.
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MARINE PRIMARY PRODUCTION ESTIMATES FROM OCEAN COLOR: A COMPARATIVE STUDY OF ALGORITHMS (Mary-Elena Carr and Marjorie Friedrichs)

The Primary Production Algorithm Round Robin 3 (PPARR3) aims to compare models or algorithms that estimate marine primary production from satellite measurements of ocean color (PP models). It is a continuation of previous PPARR exercises, which compared in situ carbon14 uptake rates with an estimate of primary production using satellite-accessible data. PPARR2 found that modeled primary production would be within a factor of two of the in situ rates if systematic offsets were corrected. PPARR3 aims to provide a forum to compare model output, improve parameterization, and help identify the source of biases. This community project presently counts with over twenty modeling groups who estimate primary production for input fields provided by the organizers. The PPARR3 exercise consists of 3 stages, the first stage is a comparison of monthly global primary production fields generated by the different algorithms. Stage 2 is a step-by-step sensitivity study of the different algorithms tracking the derivation of sub-products in a series of point value estimates. The third stage is similar to PPARR1 and PPARR2 and is a blind comparison to the quality-controlled database of carbon-14 measurements in the equatorial Pacific. We present here the results of the first stage, which compares the output of the models throughout an annual cycle, and preliminary results from the latter two.

A RECIPE FOR OCEAN PRODUCTIVITY, AND VARIATIONS (John Marra)

I discuss a formula for calculating ocean productivity based on the ingredients chlorophyll, irradiance, phytoplankton absorption, and quantum yield for photosynthesis. From satellite sensors, chlorophyll and irradiance can be estimated with known reliability. The geographic and temporal variability of phytoplankton absorption and quantum yield, however, are not well understood. The key for phytoplankton absorption is the variability in the pigment composition. Thus, understanding how communities change and adapt along environmental gradients will help in refining the formula. Progress has been made, too, in understanding the determinants for the quantum yield. I will consider sources of variation in quantum yields, exemplified by results from the U.S. JGOFS programs in the Southern Ocean and Arabian Sea. Finally, I consider the variations that can occur with mesoscale variability, using examples from eddies west of the island of Hawaii and in the Leeuwin Current off western Australia.

SEA-AIR CO_2 FLUX DETERMINED FROM IN SITU AND REMOTELY SENSED DATA: ITS VARIABILITY IN THE SOUTHERN OCEAN
(Y.Rangama, J.Boutin, J.Etcheto, L.Merlivat)

The Southern Ocean is expected to play an important role in the sea-air exchange of CO_2. But, this role is not known precisely. In this region, the sea-air CO_2 fluxes estimated using atmospheric inversions, ocean biogeochemical models or in situ measurements are still in large disagreement. In this presentation, we study the sea-air flux of CO_2 in the Sub-Antarctic zone (SAZ) and its spatial and time variability. We combine in situ measurements and remotely sensed parameters (ERS2 and QUICKSCAT wind speed, SEAWIFS chlorophyll (Chl) and AVHRR SST) to extrapolate the sea-air CO_2 fluxes in different regions. We estimate the local flux as the product of the CO_2 exchange coefficient (K) and of the sea-air CO_2 partial pressure gradient (ΔP) and then, integrate the flux over given regions. We use wind speed satellite data (U) to estimate K and its variability, according to the Wanninkhof (1992) K-U relationship. As for ΔP, in situ measurements conducted during JGOFS campaigns were extrapolated in the region south of Australia. We use relationships between sea surface partial pressure (pCO_2) and parameters measurable from satellite. North of SAZ, in situ pCO_2 and Chl are well correlated : pCO_2 rms with respect to pCO_2-Chl linear fit is between 5.5 µatm and 9.3 µatm. South of this chlorophyll rich region, pCO_2 is better correlated with SST. pCO_2 rms with respect to pCO_2-SST fits is between 4.2 µatm and 11.5 µatm. These fits were determined season by season from in situ measurements; then, space and time distribution of pCO_2 was deduced from satellite measurements for different seasons. Distribution of atmospheric CO_2 partial pressure (pCO_2a) was deduced from atmospheric CO_2 concentration given by Global View, from temperature to compute saturated water pressure and from atmospheric pressure inferred from ECMWF atmospheric model. Then, we analyse sea-air CO_2 fluxes south of Australia and their variability. We also use measurements made by CARIOCA drifters deployed in the central Indian ocean (one buoy in November 2001 and two buoys in January 2002 near 45°S-73°E). Buoys are drifting eastward in SAZ. They measure primarily pCO_2, SST, wind speed, fluorescence, atmospheric pressure and air temperature. In addition, one of the buoys deployed in January measures SSS. The buoys trajectories are influenced by ocean dynamics as can be observed from satellite SST images. We study the correlations between pCO_2, SST and SSS. At the beginning of the observing period, pCO_2 computed at 10°C to compensate for the thermodynamic effect correlates very well with SSS, indicating a mixing of different water masses with different mixing lines above and below 34.1 psu, 330 µatm. The possible phenomena causing the mixing (vertical and horizontal) will be discussed. Most of the thermodynamic effect is compensated by other effects, mainly mixing, so that pCO_2 - SST correlations are less clear.

HOW PRODUCTIVE IS THE SOUTHERN OCEAN? RESULTS FROM INVERSE MODELING COMPARED WITH SATELLITE BASED ESTIMATES
(Reiner Schlitzer)

The utilization of dissolved nutrients and carbon for photosynthesis in the euphotic zone and the subsequent downward transport of particulate and dissolved organic material strongly affect carbon concentrations in surface water and thus the air-sea exchange of CO_2. Efforts to quantify the downward carbon flux for the whole ocean or on basin-scales are hampered by the sparseness of direct productivity or flux measurements. Here, a global ocean circulation, biogeochemical model is used to determine rates of export production and vertical carbon fluxes in the Southern Ocean. The model exploits the existing large sets of hydrographic, oxygen, nutrient and carbon data that contain information on the underlying biogeochemical processes. The model is fitted to the data by systematically varying circulation, air-sea fluxes, production, and remineralization rates simultaneously. Use of the adjoint method yields model property simulations that are in very good agreement with measurements. In the model, the total integrated export flux of particulate organic matter (POC) necessary for the realistic simulation of nutrient data is significantly larger than export estimates derived from primary productivity maps. 10 GtC required globally, the Southern Ocean south of 30°S contributes about 3 GtC (33%), most of it occurring in a zonal belt along the Antarctic Circumpolar Current and in the Peru, Chile and Namibia coastal upwelling regions. The export flux of POC for the area south of 50°S amounts to 1±0.2 GtC, and the particle flux in 1000 m for the same area is 0.115±0.02 GtC. Unlike for the global ocean, the contribution of the downward flux of dissolved organic carbon (DOC) is significant in the Southern Ocean in the top 500 m of the water column. Comparison with satellite based productivity estimates (CZCS and SeaWiFS) shows a relatively good agreement over most of the ocean except for the Southern Ocean south of 50°S, where the model fluxes are systematically higher than the satellite-based values by factors between 2 and 5. This discrepancy is significant, and an attempt to reconcile the low satellite-derived productivity values with ocean-interior nutrient budgets failed. Too low productivity estimates from satellite chlorophyll observations in the polar and sub-polar Southern Ocean could arise because of the inability of the satellite sensors to detect frequently occurring subsurface chlorophyll patches, and to a poor calibration of the conversion algorithms in the Southern Ocean because of the very limited amount of direct measurements.

DYNAMIC ECOLOGICAL PROVINCES:A BIOGEOCHEMICAL AND PHYSIOLOGICAL TEMPLATE FOR THE GLOBAL OCEAN

(Mark D. Dowell, Janet W. Campbell, and Timothy S. Moore)

The concept of oceanic provinces or domains has existed for well over a century. Such systems, whether real or only conceptual, provide a useful framework for understanding the mechanisms controlling biological, physical and chemical processes and their interactions. Criteria have been established for defining provinces based on physical forcings, availability of light and nutrients, complexity of the marine food web, and other factors. In general, such classification systems reflect the heterogeneous nature of the ocean environment, and the effort of scientists to comprehend the whole system by understanding its various homogeneous components. If provinces are defined strictly on the basis of geospatial or temporal criteria (e.g., latitude zones, bathymetry, or season), the resulting maps exhibit discontinuities that are uncharacteristic of the ocean. While this may be useful for many purposes, it is unsatisfactory in that it does not capture the dynamic nature of fluid boundaries in the ocean. Boundaries fixed in time and space do not allow us to observe interannual or longer-term variability (e.g., regime shifts) that may result from climate change. A satellite-based methodology is presented using multiple satellite-derived variables and a novel mathematical procedure based on fuzzy logic to address temporal and spatial variability of primary productivity in the ocean. We have identified nine ecological provinces or "classes" based on a large primary productivity data set with accompanying in-situ measurements of surface chlorophyll (CHL), sea surface temperature (SST), and photosynthetically available radiation (PAR). Based on the CHL, SST, and PAR statistics derived from the in-situ data, we have mapped the global distribution of these classes using monthly composited satellite observations of these properties. Thus mapped globally, the classes represent spatially coherent and seasonally dynamic provinces within which the environmental controls on primary productivity are homogeneous. A multi-year time series synthesizing the geographic and seasonal variability of specific variables relevant to primary production modeling as well as the global distribution of net primary production has been produced based on the province distribution. Nutrient depletion temperature maps for the limiting nutrient (e.g. NO3, PO4, SiO2) have been determined and subsequently matched with coincident temperature maps for each month to identify nutrient-deplete and nutrient-replete areas at the global scale. This approach is relevant to existing algorithms for primary productivity (Behrenfeld - PhotoAcc) and pigment packaging (Carder - MODIS chlorophyll). The variability of photosynthetic parameters and light limitation has also been characterized in each province, thus providing input to existing models for estimating primary production. In short the proposed approach provides all of the oceanographic and ecological insight of traditional classification schemes whilst retaining the fluid boundaries and dynamic interaction of the different ocean biomes as perceived in global satellite imagery.

REMOTE SENSING OF PHYTOPLANKTON PHOTOSYNTHETIC RATES AND PRODUCTION FROM MEASUREMENTS OF OCEAN COLOUR

(Jim Aiken, Gerald Moore, James Fishwick, Tim Smyth, Claudia Omachi & Kathryn Woods)

The most widespread remote sensing algorithms for the interpretation of ocean colour data (Rrs, λ) have only one variable, Chlorophyll-*a* concentration (Chla) and use a band ratio at 2 wavelengths (Rrs, 490, 555 nm). Chla absorbs light in the blue (400 to 470 nm) and these algorithms work only because accessory pigments, mostly the photosynthetic carotenoids (PSC), co-exist and co-vary robustly with Chla over most ocean provinces (marine ecosystems). The inter-province variance of the Chla to PSC is the main source of error in global phytoplankton pigment, band-ratio algorithms. Algorithms for the determination of primary production from ocean colour data are relatively simple and most use Chla as the principal variable. Chla is a crucial component of the photosynthetic apparatus, though a variable fraction of only 1 in 200 to 1 in 600 of Chla-molecules are part of Photosystem (PS) I or II; the remainder 'antennae Chla' are part of the light-harvesting complex along with the photosynthetic carotenoids. Since all the photons absorbed by the photosynthetic pigments contribute to photosynthesis, the total absorption of light by phytoplankton $a_p(\lambda)$ is the most appropriate variable for the determination of primary production. Chla, as a measure of the 'steady-state biomass', at best might be related to net production. Because of these uncertainties, the use of Chla as a surrogate for productivity, compounds the errors in the determination of primary production from remotely sensed measurements of ocean colour (Rrs, λ). Conceptually, ocean colour (Rrs), an inverse function of the light absorbed, should be functionally related to primary production, a direct function of the light absorbed, and in theory phytoplankton production should be derivable directly from Rrs. We have analysed data on phytoplankton pigment composition from the equatorial Pacific Ocean (IronEx II), the Southern Ocean (SOIREE), the Atlantic Ocean

(Atlantic Meridional Transect; AMT) and European shelf seas and derived the relationships to photosynthetic quantum efficiency (PQE, Fv/Fm) determined by Fast Repetition Rate Fluorometer (FRRF). The Chlorophyll *a* to total pigment fraction (Chla/Tpig) has been shown to be significantly correlated to PQE, both generally and more significantly, within provinces or within seasons. The inference is that in the enrichment experiments (IronEx II and SOIREE) plants when stimulated to grow, synthesise Chla in preference to other accessory pigments and decrease Chla synthesis relative to other pigments when stimulation wanes. A similar mechanism probably underlies the relationship between PQE and Chla/Tpig in the natural ecosystems of the Atlantic Ocean and the shelf seas. Evidence from laboratory culture experiments is consistent with these observations. We conclude that Chla is maintained at the level needed to sustain the maximum growth rate in the environment. In other words, Chla concentration is self-regulating, in response to the limitations imposed by other growth substrates. We show that the Chla/Tpig ratio is a proxy for Chla/Carbon ratio and may also be a proxy for cell nutritional status, both of which have variances in natural ecosystems that are related to photosynthetic activity and productivity. PQE x PAR x σ_{PSII} is proportional to production (σ_{PSII} is the effective absorption cross-section for PSII). An inference is that Chla/Tpig as a proxy for PQE may be a significant parameter in models of gross primary production and for dynamical processes such as the drawdown of CO_2. Chla has a unique deep blue absorption spectrum (centred at 443 nm), differing markedly from the other accessory pigments (mainly carotenoids) which absorb blue-green light (centred at 490 nm). We show that the Chla/Tpig fraction has a distinct optical signature, detectable in remotely sensed observations of ocean colour, providing a bio-optical algorithm for PQE and the other proxies.

SEASONAL AND INTERANNUAL VARIABILITY OF CHLOROPHYLL *A* AND PRIMARY PRODUCTIVITY IN THE SUBARCTIC NORTH PACIFIC DURING 1997-2000 USING MULTI-SENSOR REMOTE SENSING

(Kosei Sasaoka, Sei-ichi Saitoh and Toshiro Saino)

The objectives of this study were to describe and understand the processes controlling the temporal and spatial variability of chlorophyll-a (chl-*a*) and primary productivity in the subarctic North Pacific Ocean during 1997-2000. Remotely sensed data from multi sensors, including ocean color (OCTS and SeaWiFS), sea surface temperature (SST, AVHRR), wind (SSM/I) and photosynthetically available radiation (PAR, SeaWiFS) datasets were utilized for the purpose of this study. Calculation was made for primary productivity using VGPM Model (Behrenfeld and Falkowski, 1997), and sea surface nitrate using SST and chl-a data (Goes et al,. 1999,2000). Ocean color imagery clearly showed seasonal and interannual variability in the spatial abundance and distribution of chl-*a* and primary productivity in the study area. Magnitude of chl-*a* seasonal variability at WSG (Western subarctic Gyre, near the 50N, 165E) is greater than that at AG (Alaska Gyre, near the 50N, 145W). Ranges of chl-a concentrations at WSG were about 0.2-1.1 mgm^{-3} throughout the year, and a few peaks (about 1.0 mg m^{-3}) were seen in spring and fall bloom periods. Chl-a concentrations at AG were generally low (0.2-0.7 mg m^{-3}), and no bloom was observed. Contrary to this, ranges of primary productivity were similar in the west (100-850 $mgCm^{-2}Day^{-1}$ at WSG) and the east (150-800 $mgCm^{-2}Day^{-1}$ at AG), and the seasonal variability of primary productivity was similar in both regions, where one single peak was seen in summer (July or August). A large interannual variability of chl-a and primary productivity coincided with the 1997/1998 El Nĩno and 1998/1999 La Nĩna events. In 1998 fall, Chl-*a* and primary productivity at WSG were remarkably high (about 0.9 mgm^{-3} and 850 $mgCm^{-2}Day^{-1}$) compared with those in the same season of the other years. Coincidentally, chl-*a* and primary productivity at AG in summer to fall 1998 (about 0.3 mg m^{-3} and 400-650 $mgCm^{-2}day^{-1}$) were lower than those in other years. It appeared that high chl-a at WSG corresponded to the warmer SST and low chl-a at AG corresponded to cooler SST. We suggest, based on the multi-sensor satellite data, that the high chl-a around the WSG from summer to fall in 1998 was resulted from combination of; 1) larger nutrients inputs in winter, 2) stronger wind in spring to summer causing light limitation of phytoplankton growth, 3) higher PAR in summer, and 4) warmer surface waters in fall compared with the normal years. Further discussion will be made on the east-west differences in distribution patterns of chl-*a* and primary productivity, and their controlling factor in the subarctic North Pacific in relation to ENSO events.

INCORPORATING RESPIRATION INTO THE OCEAN CARBON BUDGET: LIFTING THE LID OFF PANDORA’S BOX

(Peter J. le B. Williams)

One of JGOFS primary aims has been to quantify the oceanic carbon budget. The organic budget is a major component of this. The organic budget for the euphotic zone comprises some six terms, of which three dominate: planktonic photosynthesis, export to the mesopelagic zone and euphotic zone respiration. JGOFS studies have concentrated on former two. For reasons that are not entirely clear, the quantification of respiration was not seen as a priority matter. This is unfortunate as our consequential poor understanding of respiration prevents us closing the organic budget. We thus lost a valuable constraint. The last 5 years has seen a considerable growth is the assessment of respiration in relation to organic production – curiously by the scientifically community mainly outside the JGOFS community. These studies have brought to light major apparent problems when the respiration term is introduced into the budget. Put bluntly, we have difficulties balancing the books. This could reflect the rudimentary understanding of respiration in the oceans, however there are strong suggestions that some of aspects of our present budget may be need revision. The first area of concern is associated with the balance between P and R in the euphotic zone of the central parts of the oceans. Common sense and the physics and chemistry tell us that these areas must have a substantially isolated organic budget. As the euphotic zone exports organic material to the mesopelagic and bathypelagic zones, the euphotic zone organic budget must be slightly positive. Geochemical measurements of upper water column net production, based on calculation of air-sea gas (O_2 and CO_2) exchange are consistent with this. However, analysis of observations of P and R suggest otherwise – they imply deficits. I shall point to two possible solutions to this dilemma – both imply that we are currently underestimating organic production. The second problem is associated with the second measured major term – the export of organic production from the surface. This is an important and extensively studied feature of the oceans. The prevailing view is that the euphotic zone exports some 10 to perhaps as much as 25% of primary production, thus some 75 to 90% must respired in the euphotic zone. Thus, the implied ratio of respiration in the epipelagic (150m depth horizon) to that in the mesopelagic (150-1000m) zone must be 3:1 to 10:1 or more. Present assessments of the relative distribution of direct measurements of metabolism in these two zones imply much lower ratios – in some cases approaching unity. In this case it is less clear where the discrepancy may lie. Although there have been past concerns over the accuracy of sediment traps, especially for the upper parts of the ocean, complementary studies based on ^{234}Th-thorium and ^{13}C give support to the sediment trap values. Whatever the eventual explanation, the disparity reveals the importance in obtaining a more accurate assessment of the level of mesopelagic metabolism. In conclusion, respiration is a valuable and underused constraint of the oceanic carbon budget and, as it can in many instances be easily measured, it should feature more prominently in future programmes.

ROLE OF ZOOPLANKTON IN THE TRANSFORMATION, REMINERALIZATION, AND EXPORT OF PARTICULATE ORGANIC MATTER IN THE SEA
(Deborah K. Steinberg)

Developing predictive models of the relationship between primary production and carbon flux requires an understanding of food web processes. Zooplankton, through the processes of ingestion, metabolism, and egestion, play an integral role in the biological pump by feeding in surface waters and producing sinking fecal pellets. Vertically migrating zooplankton and nekton also play an important role in transport by consuming organic particles in the surface waters at night and metabolizing the ingested food below the mixed layer during the day. Changes in zooplankton biomass and species composition in surface waters can dramatically affect the sedimentation rate of fecal pellets and thus the export of organic material to the deep ocean. Results from JGOFS studies show differences in the importance of fecal pellet flux, relative to primary production or total carbon flux, from one ocean basin or season to another. Below the euphotic zone, zooplankton affect particle flux by grazing (and remineralizing or repackaging) particles, disaggregating particles by their feeding or swimming actions, vertical migration, and by producing dissolved organic matter through their metabolism and feeding the microbial loop (ultimately increasing flux). Studies to date indicate zooplankton metabolic activity can account for a significant proportion of the loss of particulate organic matter (POC) with depth (9 -100% of sinking POC respired, 6 - 38% of sinking POC consumed). Zooplankton vertical migration increases flux via production of feces at depth (but equals on average only 2-7 % of passive POC flux) and by actively transporting dissolved material (on average 4-40% of passive POC flux), fueling the microbial loop. Combining information on zooplankton biomass and species composition across the ocean basins with empirical models for determining zooplankton feeding, metabolic, and production rates will allow us to determine the global role of zooplankton in particle cycling. While we have dramatically increased our ability to make this determination during the JGOFS era, still much is unknown about zooplankton processing of organic matter, especially below the euphotic zone.

MAGNITUDE, VARIABILITY AND CONTROLS ON THE RATIO OF PARTICLE EXPORT TO PRIMARY PRODUCTION IN THE UPPER OCEAN
(Ken O. Buesseler)

The transport of biogenic particles from the surface to the deep ocean is the key driver of the ocean's biological pump. Globally, the magnitude and efficiency of the biological pump will in part modulate levels of atmospheric CO_2, and from the geological paleo-oceanographic record there is evidence of elevated rates of export of POC resulting from changes in the functioning of the pump. Thus there is a need to better understand what are the key determinants of this pump in the present day, and how they might be altered in response to climate change. This talk will examine the present day relationship between primary production and particulate export in the upper ocean. Recent advances in satellite derived algorithms for primary production lend well to improved global predictions of the rate of C uptake, however our ability to determine particle fluxes is much poorer. A pronounced mismatch between spatial patterns in primary production and the export of carbon to the deep ocean, points to the complex suite of transformations that occur in the upper 300 m of the ocean. The results thus far indicate that the relative rates of C uptake and losses via sinking particles vary as a function of the local food web dynamics. In particular, diatoms appear to play an important role in enhancing the ratio of export:production in the upper ocean. In spite of the recent development of promising modeling approaches to assess export production on global scales (Laws et al., 2000), our understanding of the key processes determining what controls the efficiency of particle transport between the surface and deep ocean remains weak.

A NITROGEN-, PHOSPHOROUS- AND SILICON- BASED MODEL OF PRIMARY PRODUCTION AND EXPORT APPLIED TO STATION ALOHA: CAN WE GET THE MODEL TO AGREE WITH THE DATA FOR PRIMARY PRODUCTION, DOM CONCENTRATIONS AND POM FLUX?
(S. Lan Smith, Yasuhiro Yamanaka and Michio J. Kishi)

We have developed a one dimensional coupled biological-physical model, consisting of a marine ecosystem model based on the NEMURO formulation developed by the PICES program coupled to a Mellor-Yamada level-2 mixed-layer model. We plan to incorporate this model into global three dimensional simulations in the near future. But first, using this one dimensional implementation we aim to address some of the challenges of simulating the production and export of organic matter at several time series sites. This study simulates the Hawaii Ocean Time-series (HOT) Station ALOHA. Because of the importance of N2 fixation for supplying nitrogenous nutrients at this location (and in much of the ocean) we have modified the NEMURO formulation to include this process. To simulate the dynamics of diazotrophs (N2 fixing organisms) and to account for the phosphorous limitation that is expected to result from the supply of nitrogen by N2 fixation, we have added phosphorous and phosphorous-limitation to the model. We have also added a formulation for the cycling of Dissolved Organic Matter (DOM) via the microbial food web, which is particularly important at this location and others where most production is recycled. To allow for the varying composition of organic matter, we simulate the concentrations of C, N, P, Si and CaCO3 separately in each compartment (e.g., DOM) except for plankton, for which we apply constant (but distinct) stoichiometries. Using high frequency data for wind speed and solar radiation collected by the HALE-ALOHA buoy (University of Hawaii at Manoa), and data from the Station ALOHA time series (Hawaii Ocean Time series, HOT), we drive this model for 1997 and 1998. We compare the simulations to time series data for nutrients and organic matter from the HOT program. In short simulations (a few years), the model is able to simulate the export of Particulate Organic Matter (POM) reasonably well (the annual average and some features of the seasonal cycle) and variations in its stoichiometry with depth (e.g., N:P ratio). Tuning the model to do this, however, produces primary production and DOM concentrations that are far too low (by roughly a factor of two). Furthermore, in longer simulations (10 to 100 years) nutrient trap-ping becomes a major problem and the simulated concentrations of nutrients below the euphotic zone are unrealistically high. Similar to what others have found in previous studies, tuning the model (especially the ratio of sinking rate to degradation rate of POM, termed the Remineralization Length Scale) to avoid the nutrient trapping problem results in erroneous simulations of export flux. We will discuss some of the challenges of consistently simulating primary production, DOM concentrations and POM export at Station ALOHA.

MAXIMUM RESILIENCY AS A FOOD WEB ORGANIZING CONSTRUCT: HETEROTROPHIC BACTERIA AND PHYTOPLANKTON BIOMASS ACROSS A TROPHIC GRADIENT
(Edward Laws)

Application of the principle of maximum resiliency to a pelagic food web model leads to the conclusion that the ratio of heterotrophic bacterial biomass to phytoplankton biomass will be greatest under oligotrophic conditions. This prediction is in accord with the results of several field studies. Under eutrophic conditions, model results indicate that the same ratio will be positively correlated with temperature, and that microbial biomass will be dominated by phytoplankton at low temperatures and high production rates. Heterotrophic bacterial biomasses predicted from information on temperature and phytoplankton biomass or production are in excellent agreement with field data collected among a wide variety of limnetic and marine systems. Export ratios are closely correlated with the ratio of heterotrophic bacterial biomass to phytoplankton biomass. Because of the short generation time of marine microbes, pelagic food web behavior that is determined primarily by the activity of these organisms may tend to display characteristics expected of the mature stages of ecological succession. Maximum resiliency, a characteristic expected of such mature stages, may therefore prove to be a useful construct in modeling the response of pelagic food webs to environmental change.

TRANSLATING NET PRODUCTION TO EXPORT: BIOLOGICAL IMPACTS ON EFFICIENCY (Raymond Sambrotto, and Sara Green)

The net production of organic material in the surface ocean can be measured with incubation experiments and remote sensing. However, neither approach directly measures the amount of biogenic material that is exported to depth, and this is the most important process redistributing material among major ocean and atmosphere reservoirs. In our comparison of net production and export, we found a significant lag between the two processes in systems that undergo significant seasonal changes in productivity. The export lag ranged from a short (or non-existent) period in the southern region of the Antarctic Circumpolar Current, to almost two months in the offshore regions of the northern Arabian Sea. The lag time also is related to the efficiency of export, in that the sedimenting flux of material relative to surface production decreased as the lag time increased. Some of the lag can be related to a faster response of microbial grazing at warmer temperatures, as suggested by previous export models that related lower f-ratios to temperature. However, to a large extent, the lag time is effected by the floristic composition of the phytoplankton, in that regions characterized by heavily silicified diatoms had significantly greater export efficiency than predicted by temperature alone. The dependence of export efficiency on the floristic composition of surface production adds significant uncertainty to global export predictions. Possible approaches for predicting the occurrence of heavily silicified diatoms include their dependence on iron and the advective supply of seed populations.

GLOBAL EXPORT FLUX AND REGIONAL FUNCTIONALITY OF BIOLOGICAL PUMP; A RESULT FROM JGOFS SEDIMENT TRAP PROGRAMS SINCE 1982 (Sus Honjo, Roger Francois, Rick Krishfield and Steve Manganini)

It has become clear that the export of atmospheric CO_2-carbon to the ocean interior by biological pump is a result of the interplay of all the oceanic particles. The removal of particulate organic and inorganic carbon from the productive ocean layers to the interior sink is the most critical process in the operation of the biological pump that contributing to the CO_2 cycles. However, the gross specific gravity of highly hydrated photosynthetic organic carbon particles is lighter or equivalent to that of the seawater. Particulate organic carbon (C_{org}) is only allowed to depart from the upper ocean layers in aggregates whose gross specific gravity is ballasted by substantially heavier particles. We found that $CaCO_3$ particle flux is taking the critical role to remove organic carbon from upper oceans to the deeper sink as ballast. In regard to the ballasting effect, export flux of biogenic silica in opal (Si_{bio}) is not as important as we suspect; the amount of transfer efficiency of settling particles (TEC_{org}) that contained >30 % of $CaCO_3$ is far greater than the amount of settling particles with >50 % of Si_{bio}. Lithogenic particles are efficient ballasts for bringing the TEC-org to similar a level as what $CaCO_3$ does, however, the area where large quantities of lithogenic particles are limited in the world ocean therefore its global effect is insignificant. Thus we reached to an algorithms to estimate organic carbon flux based on ballasting effects of other oceanic particulate matters (Francois et al., this meeting). The algorithms for C_{inorg} (C in biogenic $CaCO_3$) and Si_{bio} fluxes were modeled directly from the sea surface temperature and primary production. Si_{bio} in the moderate climatic zones where seasonality was recognized were calculated from the sea surface concentration of SiO_2 in winter. Si_{bio} in the Equatorial Oceans and Arabian Sea was estimated from primary production. Algorithms for C_{inorg} and Si_{bio} were optimized using the observational flux data as C_{org}. *Global distribution* of the three elements in 250 km-grid were composed and the *global fluxes* of these elements at 2,000 m were estimated by summing the fluxes representing all individual cells. Thus our estimate of annual global fluxes of C_{org}, C_{inorg} and Si_{bio} using the data since 1983 are 36.2, 33.8 and 34.6 Tera Moles, respectively. The range of annual global organic carbon is about 0.2 to 25 gC m^{-2}. Global distribution of annual C_{inorg} is less variable than the other two criteria and ranges from 0.2 to 10 gC m^{-2}. The range of annual Si_{bio} was as wide as 0.5 to >100 gSi m^{-2}. The global biogeochemical ratios, C_{org}/C_{inorg}, Si_{bio}/C_{org} and Si_{bio}/C_{inorg} are amazingly similar, approximately 1.1, 1.0 and 1.0 in our estimate. Global distribution of C_{org}/C_{inorg} is monotonous ranging from 0.5 to 6, except in a part of the Southern ocean where this value reaches >10. The range of Si_{bio}/C_{inorg} is 0.2 to 50 and by far the largest among the above mentioned biogeochemical ratios. The oceanic region where Si_{bio}/C_{inorg} is maintained consistently at >10 is clearly demarcated from low latitudinal, moderate ocean and forming clear zones what can be identified as *silica ocean* in the higher latitudinal regions in the North Pacific and in the Southern ocean. We thus propose to distinguish three functional oceanic provinces based upon the ternary mole ratio among Corg Cinorg and Sibio: the

Organic Carbon Ocean (the Polar Oceans) Carbonate Ocean and Silica Ocean. The removal of photosynthetically produced $CaCO_3$ also withdraws alkalinity from the surface ocean reducing that ocean's capacity to absorb the atmospheric CO_2. A silica ocean situation, defined as oceanic regions where the ratio of biogenic silicon flux (Sibio) to inorganic carbon flux (Cinorg) is larger than 1 (in mol-ratio), reduces the surface alkalinity in far less extend. However, TEC-org is smaller than in the case of the carbonate ocean where Sibio/Cinorg is <1. This indicates that fewer organic carbon particles penetrate the Mesopelagic layer under a silica ocean than under a carbonate ocean. Therefore, hypothetically, the settling organic carbon in the silica ocean would be more remineralized in the Mesopelagic layer thus an intermediate layer can be a significant CO_2 sink. However, more organic carbon particles can reach the deeper oceanic interior under a carbonate ocean condition.

FACTORS CONTROLLING THE FLUX OF ORGANIC CARBON TO THE BATHYPELAGIC ZONE OF THE OCEAN
(Roger Francois, Susumu Honjo, Richard Krishfield, and Steve Manganini)

Multiple linear regression between mean annual satellite-derived estimates of export production and settling fluxes measured with deep (>2000m) moored sediment traps at 68 diverse oceanic sites reveals that the fraction of the flux of organic carbon exported from the euphotic zone that reaches the bathypelagic zone of the ocean is directly related to the accompanying flux of calcium carbonate and inversely related to seasonality. Similar statistical relationships also show a strong inverse relationship with the mean annual f-ratio and a strong positive relationship with mean annual SST. In contrast, the transfer efficiency of organic carbon to the deep sea is essentially unaffected by the accompanying flux of biogenic opal, while the flux of lithogenic material is generally too low at open ocean sites to have a significant impact. These statistical correlations suggest that the ballasting effect of carbonate minerals, and possibly a "packaging" factor statistically related to carbonate production (e.g. hydrodynamic fecal pellets in carbonate-dominated regions versus loose aggregates in opal-dominated regions), may be important factors promoting the transfer of organic carbon to the deep sea. The negative correlation with seasonality and f-ratio and positive correlation with SST are tentatively interpreted as reflecting the effect of the biodegradability of the exported organic matter. Organic matter exported from cold, highly seasonal regions with high f-ratios, which are often dominated by diatoms, may be more labile and prone to degradation in the mesopelagic zone than organic matter exported from warm, carbonate-dominated regions with low f-ratios, where complex food webs and the microbial loop more effectively process organic matter before export. We thus postulate that higher mesopelagic respiration in cold regions results from the settling of more biodegradable organic matter in the form of loose aggregates. In warm, carbonate-dominated regions, higher transfer efficiency through the mesopelagic zone would reflect the export of more refractory organic matter packaged into more hydrodynamic fecal pellets. As a result, low latitude productive regions (e.g. Arabian Sea, equatorial upwelling regions) are the most efficient open ocean sites at transferring organic carbon from the base of the euphotic zone to bathypelagic depths. The resulting algorithm appears globally applicable and is able to explain > 80% of the variability in the transfer efficiency of organic carbon to the deep sea. Comparing the new algorithm to Martin's equation suggests that the exponent of the latter algorithm (b) must be adjusted systematically between oceanic regions proposed to accurately predict carbon fluxes at depth > 2000m. In high latitude productive oceanic regions, $b < -1$; in low latitude productive oceanic regions, $b > -0.7$; and in low latitude oligotrophic and mesotrophic regions, $-1.0 > b > -0.7$, close to Martin's original value of –0.86.

HOW POC EXPORT, CURVATURE IN THE MARTIN FUNCTION, BIOGENIC SI CONTENT AND PARTICLE SETTLING VELOCITY ARE RELATED
(W. M. Berelson)

I have examined the fit of the 'Martin Function' to US-JGOFS data from open ocean sites and find that there is a positive relationship between the absolute value of b, expressing the curvature in this power law, and export flux of particulate organic carbon (POC). This implies that sites with the largest export flux of POC are sites where much of this carbon is remineralized in the upper water column. I attribute this relationship to couplings between POC export, biogenic Si content, and particle settling velocity. This relationship is tested with analysis of POC flux vs. depth data from continental margin sites. These regions may be complicated by advective transport, nonetheless, there are data from several margin settings that also indicate a positive correlation between POC export and the b-value. Martin's data from margins support this observation as well. The relationship between POC export, curvature in the Martin function and bSi content is developed when one looks at the bSi/POC ratio in sediment traps from around the globe. At any given site, this ratio increases with depth, suggesting a greater loss of POC relative to the loss of bSi with depth in the ocean. However, there is a systematic increase in this trend; bSi/POC ratios increase more (with depth) when sites are rich in bSi. This pattern could be caused by several processes and mechanisms, but I propose that settling velocity is a major contributor, i.e. sites with more bSi are sites where particles are falling with a lower net velocity. The more time it takes for particles to settle, the more time for differential remineralization rates to modify the bSi/POC ratio. The velocity—biogenic composition relationship was tested by examining sediment trap fluxes from the Equatorial Pacific. I found that particle settling velocities increase with depth between 1000-4500 m. I also found that during times of greater bSi production, particle settling rates were slower than during times of less bSi production.

GLOBAL DISTRIBUTION OF DOWNWARD PARTICLE FLUX FROM MODELS AND MEASUREMENTS: DO WE BELIEVE ANY OF THEM?
(R.S. Lampitt, E.E. Popova, and I.J. Totterdell)

Three approaches have been made to examine the strength of ecosystem models in the description of downward particle flux in the deeper parts of the water column. The first has been to use a simple one dimensional upper ocean model at a location near to the NABE site in the Northeast Atlantic. This model is driven by meteorology to predict export flux and from that to provide a measure of downward flux at 3000m over a ten-year period. The results have been found to compare very favorably with measured flux at this depth using sediment traps in terms of both the general magnitude and the characteristics of seasonal variation. The observed of interanual variability in flux is not however well described by the model. The other two approaches have taken the global perspective. Ecosystem models have been embedded into two general circulation models of the oceans (HADOM3L and OCCAM). Both are Bryan-Cox based level models the most important difference between them being the level of spatial resolution. The ecosystem models are of similar complexity. They have been used to derive global patterns of downward flux of organic carbon and we compare the model outputs with each other and, at 41 specific locations in the oceans where long term sediment trap data are available, we compare the model output with measured data. Conclusions are drawn about the conditions under which sediment traps provide reliable data and the potential of simple ecosystem models embedded in GCM's to provide satisfactory descriptions of carbon sequestration.

COCCOLITHOPHORIDS FROM THE EASTERN MEDITERRANEAN: LINKING SURFACE AND EXPORT PRODUCTION. PRELIMINARY RESULTS
(E. Malinverno, C. Corselli, P. Ziveri and G. J. De Lange)

In the pelagic eastern Mediterranean, coccolithophorids represent the most important phytoplankton group for most of the year and contribute significantly to the carbonate flux to the bottom sediments. For time periods that are close to the present, coccolith species variability throughout the sediment layers is commonly used to derive paleoceanographic reconstructions, based on information from extant species ecology. Nevertheless, the actual correspondence between surface production and the sediment record is still not completely understood. In fact export production that part of primary production that is exported from the upper photic zone and which determines the downward particle flux to the sediments, is highly variable on a seasonal scale, and is subject to variations with depth. This research presents an attempt of integration of coccolithophorid surface production data (surface water samples) with their flux at different depths in the water column (sediment trap samples collected throughout the year) and in the underlying bottom sediments. A comparison with satellite-derived chlorophyll data related to the sampling period will provide a further step in the understanding of such relation.

QUANTIFYING PHYTOPLANKTON CONTRIBUTIONS TO EXPORT USING ^{13}C
(Tom Trull)

Many recent models for the ecosystem control of surface ocean carbon export have emphasized the role of direct export of large phytoplankton, which grow rapidly and thus "escape" grazing by their relatively long-lived predators [*Boyd and Newton*, 1999; *Laws et al.*, 2000; *Michaels and Silver*, 1988]. This view has been promoted as a JGOFS paradigm [*Ducklow et al.*, 2001, but the detailed mechanisms of this export pathway and its quantitative significance have yet to be fully explored. If grazing is not involved, then presumably physical aggregation is involved, because individual large algae appear to sink too slowly [*Riebesell and Wolf-Gladrow*, 1992; *Waite and Nodder*, 2001]. There have been few quantitative observations to document this pathway for export, either in the water column, or in sinking particles collected by sediment traps. Does this aggregation selectively remove only the large phytoplankton, or are all particles aggregated and removed? How can we quantitatively assess the relative contributions of small and large phytoplankton to carbon export over the full annual cycle of production and export? Stable carbon isotope mass balances offer some promise to address these questions. Recent observations of the organic-^{13}C of Southern Ocean phytoplankton found that large phytoplankton (70-200 micron size class dominated by the pennate diatom, *Fragillariopsis kerguelensis*) were enriched in ^{13}C in comparison to small phytoplankton (1-5 micron size class, comprised of a mix of small diatoms and other algae) by ~ 8 per mil [*Trull and Armand*, 2001]. This range is consistent with predictions from models and laboratory experiments on the moderation of isotopic fractionation by the limitation of CO_2 supply to larger algae as a function of the cellular surface to volume ratio [*Popp et al.*, 1998], and thus is likely to be a general characteristic of phytoplankton communities. In the Southern Ocean study, comparison of phytoplankton organic-^{13}C compositions with the seasonal mixed layer increase in ^{13}C of dissolved inorganic carbon (^{13}C-DIC) suggests that large phytoplankton must have been responsible for the majority of seasonal export, and that this export appears to have occurred without co-export of small phytoplankton. In principle, the ^{13}C mass balance approach can be applied to quantitatively assess export contributions from small and large phytoplankton at any site where seasonal surface water ^{13}C-DIC enrichments have been measured. This does require consideration of calcite export and air-sea gas exchange using other constraints such as seasonal alkalinity and pCO_2 estimates, although these terms are often small.

SPATIAL PATTERNS OF OPAL AND CACO3 FLUXES IN SEDIMENT TRAPS: APPLICATION TO THE LGM CARBON CYCLE
(C. Klaas, and D. E. Archer)

Model studies by *Archer et al.* [2000, 2001] have shown that possibly the most important factor driving interglacial glacial variations in atmospheric pCO2 is a change in the Particulate Organic Carbon/CaCo3 (POC/PIC) rain ratio to the sediments caused by shifts in the plankton community in surface water. In a recent study of vertical flux composition from deep-sea sediment traps we have shown that deep-sea fluxes of organic carbon are linearly related to mineral fluxes opal, CaCO3 and lithogenic material) with most of the POC export being associated to the flux of CaCO3 to the deep ocean *[Klaas and Arche*r, In press]. Here, we analyze spatial variability of opal / CaCO3 flux ratios from deep-sea sediment trap experiments in an attempt at parametrising export flux of opal and calcium carbonate. Our results indicates that variability of opal / CaCO3 export fluxes shows different trends depending on region. Comparison between CaCO3 and opal fluxes with environmental parameters points toward the importance of temperature in determining the relation between CaCO3 and opal fluxes. In high latitude regions (mean sea surface temperatures below 7°C-10°C) the Si / Ca flux ratios increase linearly with opal fluxes In warmer regions (mean sea surface temperature above 7°C-10°C) CaCO3 and opal fluxes are correlated; a comparison with environmental conditions indicates that CaCO3 fluxes respond to increases in nutrient availability (including iron deposition) as do opal fluxes. We use the results of the sediment trap analysis to constrain variations in the export production of opal/CaCO3 in simulations with the coupled circulation carbon cycle model LSG-HAMOCC2 and the effect of plankton community changes on glacial/interglacial pCO2 variability.

THE EFFECTIVE CARBON FLUX IN THE ATLANTIC OCEAN
(Wolfgang Koeve)

The mean depth distribution of the POC:PIC ratio of sinking particles, measured with particle interceptor traps deployed in the Atlantic ocean, is fitted by an exponential function (POC:PIC = 64.3 * $Z^{-0.56}$; r^2=0.69). The function is successfully evaluated by comparison with (a) estimates of the POC:PIC ratio of export production, computed from seasonal changes of nitrate and alkalinity and (b) estimates of the POC:PIC ratio of remineralisation on shallow isopycnals. The basin mean POC:PIC ratio of export production is 4.2 to 4.37. The POC:PIC-depth function is combined with empirical relationships between the flux of particulate organic matter, primary production and depth, satellite derived primary production data sets and the regional distribution of ψ (the ratio of released CO_2: precipitated carbonate during $CaCO_3$ formation) in order to estimate the effective carbon flux (J_{eff}) in the Atlantic ocean. Remineralisation of organic carbon above the winter mixed layer (11-17%) and $CaCO_3$ sequestration from the winter mixed layer (13-16%), which is the balance between $CaCO_3$ production and shallow dissolution, are the two main processes which control the difference between export production (0.9 and 2.9 GT C yr^{-1}) and J_{eff} (0.64 and 2.2 GT C yr^{-1}) on the basin scale (65°N to 65°S). $CaCO_3$ sequestration is the dominant process modulating effective carbon export in the tropics, while shallow POC remineralisation dominates in temperate and polar waters. Observed regional patterns like polarward increases of the POC:PIC export ratio and of ψ counteract each other largely when J_{eff} is computed.

GLOBAL DISTRIBUTION AND MAGNITUDE OF DEEP PARTICULATE ORGANIC CARBON FLUXES ESTIMATED BY BENTHIC FLUX MEASUREMENTS
(Richard A. Jahnke)

The deep sea floor is the ultimate sediment trap. Once deposited, the majority of the particulate organic matter (POM) reaching the sea floor is remineralized on time-scales of weeks to decades. Because this is rapid relative to rates of deep sea lateral transport, patterns and magnitudes of seafloor remineralization reasonably represent modern-day deep water column POM fluxes. Benthic fluxes are also linked to pore water gradients in the underlying sediments which can only change on time-scales controlled by molecular diffusion rates. Measurements are, therefore, not subject to short-term fluctuations, greatly facilitating the evaluation of mean fluxes. Additionally, since remineralization is a destructive process, resuspension and other transport processes can not affect the evaluation of total flux rates. Because of these attributes, the measurement of benthic fluxes represents an important strategy for accurately assessing the magnitude and distribution of deep particulate fluxes of organic matter. Over the last three decades, instrumentation has been developed to accurately assess sea floor fluxes and benthic fluxes have been determined at hundreds of deep sea locations. Additionally, correlations have been developed with other sedimentary characteristics to assist in extrapolating measured fluxes throughout the deep ocean basins. The deep POM flux distribution derived from benthic flux estimates is generally consistent with the distribution derived from inverse model calculations but differs significantly from that derived from remotely-sensed surface chlorophyll, chlorophyll-productivity, and productivity-flux-depth relationships. Sea floor-derived flux distributions exhibit greater fluxes along continental margins and smaller fluxes in the high latitudes, especially in the North Atlantic Ocean relative to those based on surface productivity-flux-depth relationships. Globally, sea floor measurements indicate that continental margins supply approximately 1/2 of the total POM flux to the deep ocean and that approximately 2/3 of the total flux is transferred to the deep ocean between 30ºN and 30ºS. For models to accurately represent the present-day biological pump and to predict how the biological pump will operate in the future, it is critical that they incorporate parameterizations for those ecosystems that control the main flux pathways to the deep ocean. Future studies must, therefore, reconcile the differences that currently exist between flux distributions derived from surface productivity-depth relationships and sea floor measurements.

CROSS-BOUNDARY EXCHANGES OF CARBON AND NITROGEN IN THE MARGINAL SEAS
(Chen-Tung Arthur Chen)

Continental marginal zones are characterized as those areas where rivers, lands, oceans, the atmosphere and sediments meet and interact. Despite their moderately-sized surface areas, marginal zones play a significant role in the biogeochemical cycles of both carbon and nitrogen in that they receive huge upwelled and riverine inputs of both. Although the riverine flux of nutrients has been on the rise in the past few decades, this study confirms the results of a recent synthesis (Chen *et al.*, 2002) according to which eutrophication-derived carbon deposits in the continental margins do not yet account for all the reportedly missing anthropogenic CO_2. Nevertheless, marginal zones absorb 30×10^{12} mol C y^{-1} (0.36 Gt C y^{-1}) from the atmosphere, therefore representing important, albeit often neglected, links in the global carbon cycle. On the other hand, most shelves and estuaries do show that the production of other such greenhouse or reactive gases as CH_4, dimethyl sulfide (DMS) and N_2O are an on-going feature, making up a net total flux of 0.1 ´ 10^{12} mol y^{-1} CH_4, 0.07 ´ 10^{12} mol y^{-1} DMS and 2.5 ´ 10^{12} mol N y^{-1} N_2O to the atmosphere. The shelves also transport 50 ´ 10^{12} mol y^{-1} DOC, 45 ´ 10^{12} mol y^{-1} POC, 21 ´ 10^{12} mol y^{-1} PIC, 5 ´ 10^{12} mol y^{-1} DON and 5 ´ 10^{12} mol y^{-1} PON to the open oceans.

DECOUPLING SURFACE PRODUCTION FROM DEEP REMINERALIZATION AND BENTHIC DEPOSITION: EMPIRICAL EVIDENCE AND MODELING CHALLENGES
(Robert A. Armstrong)

Global models of the oceanic carbon cycle have two moving parts: a production part, which calculates primary (organic matter) production in the ocean's mixed layer, and an export-and-remineralization part, which is used to partition primary production into that which is remineralized within the mixed layer and that which is exported to the deep ocean. Recent evidence suggests that the connection between surface production and deep remineralization and deposition is far from linear, and that the transfer may be mediated by mineral "ballasts" -- carbonate and silicate minerals that are heavier than seawater, allowing efficient sinking of organic matter, and that may also protect organic carbon from degradation on its way to the seafloor. The fact that mineral ballasts may be produced by a diverse group of phytoplankton and zooplankton species raises significant challenges for the modeling community. Specifically, we must be able to model mechanistically the competition between phytoplankton species that do and do not produce mineral ballasts, and we must be able to accommodate mineral-secreting zooplankton. Suggestions on how we might meet these challenges are offered.

CONSIDERING THE COASTAL OCEAN IN GLOBAL OCEAN BIOGEOCHEMICAL MODELS
(Giraud X, Le Quéré C.)

The coastal ocean covers about 10% of the total area of the world ocean. Yet in these regions take place one quarter of the oceanic primary production, half of the carbonate burial and most of the burial of organic carbon. Moreover, constant input by human activities occurs in these fragile areas. State-of-the-art Global Ocean Biogeochemical Models have coarse resolution of at the best 100 km, which is too coarse to reproduce processes occurring in the coastal regions. Here we present a simplified approach to represent vertical processes occurring in the coastal ocean in the global biogeochemical models. We focused on sediment resuspension, upwelling, vertical mixing, river inputs, and atmospheric depositions. We evaluate the importance of these different processes using both data and model simulations. Each process is evaluated in term of carbon or nutrient source (input or recycling) in the coastal area.

RESPONSES OF MARINE ORGANISMS AND ECOSYSTEMS TO HYDRO-METEOROLOGICAL FORCING
(Grégory Beaugrand)

Interpretation of the temporal variability of biological processes and identification of the main variables that drive the dynamic regime of marine ecosystems is complex. Indeed, many external forcing ranging from the micro- to the mega-scale can influence the long-term variability of the marine biological environment. In this context, understanding and predicting responses of marine ecosystems to current climatic warming represent a key challenge. This talk reviews the diversity of hydro-meteorological influences on biological processes, marine organisms and ecosystems and their variety of responses to physical forcing. Possible consequences of hydro-meteorological variability on the biogeochemical processes are also highlighted.

AN ECOSYSTEM MODELS RESPONSE TO NORTH ATLANTIC OSCILLATION LIKE FORCING
(Martin Visbeck, Marina Levy, Naomi Naik, and Jessie Cherry)

A coupled ecosystem - general circulation ocean model has been used to estimate changes in the biological productivity and resulting export of carbon in response to different phases of the North Atlantic Oscillation. We find that the response of the ecosystems depends not only on the physical forcing anomalies, such as changes in the mixed layer depth, but also on the mean ecosystem environment. In the subtropical gyre productivity is limited by nutrient supply and enhanced deep winter mixing during a negative index NAO season results in a slightly increased export of carbon. In the subpolar gyre the response is more complex. During the positive index phase increased and longer lasting deep winter mixing delays the spring bloom by about 2 weeks. Since the system is not nutrient limited the total export of carbon is quite insensitive with a slight reduction. However, in a belt between 40 and 50 N productivity and export are enhanced by 10% following a positive NAO index winter. We can understand this by a the slow response of the ocean circulation where we found an enhanced transport and poleward displacement of the subtropical gyre which persists a few seasons and causes anomalous advection of nutrient rich waters into the eastern subtropical gyre.

INCREASED STRATIFICATION AND DECREASED PRIMARY PRODUCTIVITY IN THE WESTERN SUBARCTIC NORTH PACIFIC - A 30 YEARS RETROSPECTIVE STUDY
(Sanae Chiba, Kazuaki Tadokoro, Tsuneo Ono, and Toshiro Saino)

The Oyashio Water locating along the western edge of the North Pacific subarctic circulation is one of the most productive regions of the world oceans. Analyzing the time series data sets collected from 1970s to 1990s in the Oyashio Water, we observed a sign of alteration of physical, chemical and biological environments of the water column in the western subarctic North Pacific. Salinity, phosphate concentration and apparent oxygen utilization (AOU) in winter subsurface layer (on isopycnals between 26.7 and 27.2 σ_0) linearly increased for the 30 years, by averages of 0.0008 psu/y, 0.9 µmol/l/y and 0.005 µmol/kg/y, respectively. At the same time, salinity and phosphate of winter surface mixed layer decreased. Increase of density gradient between the surface and subsurface suggested that upper water column stratification be intensified to retard vertical water exchange during the period. Net community production, which was estimated from the phosphate consumption from February through August, also declined by an average of 0.51 gC/m 2 /y for the decades. Average springtime diatom abundance (cell number) decreased one order of magnitude while that of wintertime more than doubled during the 30 years, consistent with the multi-decadal decreasing trend of net community production. Nevertheless, no negative influence was observed in secondary production. As for dominant herbivorous zooplankton, *Neocalanus plumchru*s, the abundance increased, maturity timing was shifted earlier by ca. 30 days and the prosoma length increased by ca..3% for 20 years after 1980. In the Oyashio Water, extensive phytoplankton spring bloom is reported to occur when the surface water becomes stratified to form a stable, shallow mixed layer with sufficient nutrients supplied during winter. Our results suggested that attenuation of winter vertical water mixing limited nutrient supply to the level decreasing winter-summer net community production for these 3 decades. With the fact of doubled wintertime diatom abundance, it is speculated that earlier stabilization of the mixed layer might have gradually expedited the timing of phytoplankton bloom. This condition might have allowed zooplankton to effectively utilize phytoplankton from earlier timing, resulting in its apparent abundance increase, although further investigation should be made to clarify the link between primary and secondary productions.

SEASONAL VARIATION OF EXPORT RATIO IN THE ARABIAN SEA PREDICTED BY AN ECOSYSTEM-CIRCULATION MODEL WITH PARTICLE AGGREGATION
(Michio Kawamiya and Iris Kriest)

Seasonal variation of export ratio (e-ratio) in the Arabian Sea is investigated using a three-dimensional, ecosystem-circulation coupled model with an eddy-permitting resolution, in which particle sinking velocity is computed as a dependent variable by a particle aggregation sub-model. The model shows the sudden increase of e-ratio in late southwestern monsoon season that has been indicated in the 234Th data compiled by Buesseler (1998). The cause of the time lag in the model between the onsets of monsoon and the e-ratio increase is that a certain time is required before the nitracline is lifted up to supply enough nitrate to the surface. The pattern of e-ratio is totally changed in an experiment with a constant sinking velocity. An unrealistic process turns out to be critical for e-ratio in this experiment, illustrating advantage of a model with aggregation process over those with the traditional prescription of particle sinking.

POTENTIAL RESPONSES OF LOWER TROPHIC LEVELS TO CLIMATE VARIABILITY AND CLIMATE CHANGE OVER THE INDUSTRIAL ERA
(P. Monfray, L.Bopp, O.Aumont, C.Le Quéré, and J.Orr)

A suite of simulations using up-to-date global biogeochemical models is employed to investigate the impact of climate variability and climate change on marine production and ecosystems. Two biological models are used: the first one is a NPZD-type model including one generic phytoplankton limited by phosphate only (Aumont et al., 2002a); the second one is based on two phytoplanktonic groups(diatoms and nano/picoplankton) limited by the availability of phosphate, silicate and iron (Aumont et al., 2002b). Intra-decadal to inter-decadal variabilities as well as potential impact of future global warming are presented. Reconstructions are made above the 1979-1999 period using meteorological archive or satellite observations (Le Quéré et al., 2001) and over the industrial period (1860-2100) using a coupled climate-carbon model forced by anthropogenic CO2 emissions (Bopp et al., 2001). Preliminary analysis on variabilities, trends and shifts of both biological properties (chlorophyll, phytoplanctonic groups) and geochemical properties (oxygen, CO2, DMS) will be presented.

SIMULATED TEMPORAL VARIABILITY OF BIOGEOCHEMICAL PROCESSES AT THE SUBARCTIC NORTH PACIFIC TIME-SERIES STATIONS
(Masahiko Fujii, Yasuhiro Yamanaka, Yukihiro Nojiri and Michio J. Kishi)

Recent studies have been revealed that oceanic biogeochemical processes, such as distributions of nutrients, total carbonate and marine ecosystem dynamics are primarily controlled by physical environments. However, it is little known how the biogeochemical processes are affected the by the variations of the physical environments with longer time scale than the marine ecosystem itself has. To tackle this issue, not only observations but the marine ecosystem modeling can be a powerful method. In this study, a vertically one-dimensional ecosystem model is applied to Stations KNOT (44°N, 155°E) and PAPA (50°N, 145°W), both located in the Subarctic North Pacific. This model has fifteen compartments including two categories of phytoplankton (diatoms and non-diatom small phytoplankton) and three categories of zooplankton (small, large and predatory zooplankton). The model is driven by *in situ* solar radiation, wind speed, and water temperature and salinity at the sea surface. Observed seasonal features of the physical environments and biogeochemical processes at each site, *i.e.,* larger seasonal variation in each compartment, deeper mixed layer depth in winter, higher surface nutrient concentrations and greater dominance of diatoms at KNOT than at PAPA, are successfully reproduced by the model. The ENSO Events and Pacific Decadal Oscillation, which have longer time scales, might be apt to affect the biogeochemical processes at PAPA compared with at KNOT. However, further information about the biogeochemical processes, such as zooplankton stock sizes and iron concentration is necessary for verification of the differences in the interannual variations of the biogeochemical processes between the two sites.

THE IMPACT OF CLIMATE CHANGE ON THE MARINE BIOGEOCHEMICAL CYCLING:DETECTING CHANGE WITH BIOGEOCHEMICAL TRACERS
(Richard J. Matear)

Model simulations project significant alterations in the ocean circulation with climate change, like reduced thermohaline circulation and increased density stratification in the upper ocean. Recent observations suggest that these changes may already be occurring. How will these circulation changes impact marine biogeochemical cycling? In this talk, I first review the simulated impact of climate change on marine biogeochemical cycling. Second, I discuss the present limitations in the marine biogeochemical formulations used in these model simulations. Third, I explore the potential of using biogeochemical tracers to detect climate change and validate climate change simulations.

IMPLICATIONS OF VARIOUS DEPTH LEVELS USED TO COMPUTE EXPORT PRODUCTION
(Andreas Oschlies)

In a steady state, the export of organic matter must be compensated by a supply of nutrients to the light-lit upper ocean. This nutrient supply can be simulated with considerable accuracy by a high-resolution ecosystem-circulation model of the North Atlantic. The model results are used to examine physical processes that govern the transport of nutrients into the euphotic zone and the export of organic matter leaving it. Illustrated is the requirement for a rigid definition of the surface across which export production or nutrient supply are computed. Possible choices for this surface include a fixed depth level, the varying depth of the euphotic zone, and the depth of the winter mixed layer. Implications of the different choices are discussed with respect to the associated re-emergence timescales of an exported biogeochemical tracer flux. The basin-scale model is then used to investigate the climate sensitivity of organic matter export across the various depth surfaces.

CONTROLS ON GLOBAL PARTICLE EXPORT AND REMINERALIZATION: MODEL DEVELOPMENT AND CALIBRATION
(John P. Dunne, Robert A. Armstrong, Curtis A. Deutsch, Anand Gnanadesikan, Jorge L. Sarmiento, Panangady S. Swathi and Nicolas Gruber)

We have developed a model to simulate ecosystem dynamics relating to regenerated production, sinking particle export and transport of dissolved organic matter in the global ocean. A key feature of this model is a representation of grazing that reproduces observed allometric relationships between large and small phytoplankton. We present an extensive compilation of data on primary production and particle export, and use this data to calibrate this relatively simple, highly parameterized model of particle export and remineralization. Production is determined by forcing nutrients toward observations. Regeneration is described as a function of temperature and community structure, competing with the sinking of detrital material through the water column. Detrital sinking is described as a function of mineral ballast. Dissolved organic matter production is described as a function of phytoplankton production and nutrient limitation. This model has been calibrated through the generation of a synthesis of euphotic zone data on temperature, chlorophyll biomass, primary production and new production and/or particle export from over 100 sites. Where available, we have also utilized data on size-fractionated phytoplankton biomass and the carbon:chlorophyll ratio of phytoplankton. The resulting model has been incorporated into the Princeton Ocean Biogeochemical Model to diagnose total production, phytoplankton biomass, particle export and dissolved organic matter transport through restoring of surface nitrate, phosphate, silicate and alkalinity in the MOM3 general circulation model. Model results are compared with a synthesis of dissolved organic carbon survey data and satellite-based phytoplankton biomass from ocean color.

PRELIMINARY RESULTS WITH CFC-11 IN A HIGH RESOLUTION GENERAL CIRCULATION MODEL
(Akio Ishida, Yoshikazu Sasai and Yasuhiro Yamanaka)

Chlorofluorocarbons (CFCs) are known as an ideal tracer for evaluating the ability of ocean general circulation models (OGCMs) to simulate the uptake and redistribution of anthropogenic CO2 in the oceans. CFCs are of purely anthropogenic origin and are therefore qualitatively similar to anthropogenic CO2. Though many model studies of CFCs have been done with OGCMs, there are few such experiments that use a high resolution OGCM permitting or resolving mesoscale eddies and boundary currents. We are conducting a numerical experiment to simulate CFC-11 using the high resolution OGCM developed at JAMSTEC based on the Modular Ocean Model version 2 (MOM2) of GFDL. The model has 1/4 degree resolution in both latitude and longitude and 55 vertical levels. Hellerman and Rosenstein's [1982] monthly mean wind stress is used to force the model ocean. We apply heat and salt fluxes by restoring the model surface temperature and salinity to Levitus [1982] monthly data. After a time integration for 30 years, the CFC-11 simulation starts with atmospheric CFC-11 in 1950. Air-Sea exchange of CFC-11 is implemented by the same formulation used in the Ocean Carbon Model Intercomparison Project (OCMIP) phase 2. As the experiment is now going, the preliminary results for the 1970s are compared with those from a coarse resolution model. The results represent a realistic detailed distribution of CFC-11 corresponding to sharp density fronts associated with boundary currents, meanders and local upwelling. The results also show the importance of mixing by mesoscale eddies.

PRELIMINARY RESULTS OF A MARINE ECOSYSTEM MODEL COUPLED WITH OCEAN GENERAL CIRCULATION MODEL
(Yasuhiro Yamanaka, Maki N. Aita, S. Lan Smith and Michio J. Kishi)

To predict the effects of global warming on ecosystem dynamics and the effects of those changes in ecosystem dynamics on biogeochemical cycles and oceanic CO2 uptake, we need to develop (Biogeochemical General Circulation Models (BGCMs) which represent explicitly the dynamics of oceanic ecosystems and settling particles. During the last few years, we have been developing a one dimensional ecosystem model with Nitrogen-Silicon-Carbon cycles, which is an extension of the NEMURO model developed by PICES. We have applied this model to several Times Series Stations: HOT, Papa, KNOT, and A7 (the last two stations are in the western North Pacific and are maintained by Japanese groups). We divide phytoplankton and zooplankton into two and three categories, respectively: large phy-toplankton, small phytoplankton, large zooplankton, small zooplankton and predatory zooplankton. Large phytoplankton represents diatoms that make siliceous shells. A fraction of the small phytoplankton and zooplankton are regarded as calcarous-shelled cocolithophorids and foraminifera, respectively. The model includes three nutrients and three kinds of settling particles: nitrate, ammonium, and silicate, particulate organic matter, opal, and calcium carbonate. Dissolved organic matter is also included in the model. We also calculate total alkalinity, total carbon dioxide and partial pressure of carbon dioxide. Now we are incorporating this ecosystem model into a three-dimensional ocean general circulation model, which has one degree resolution in both latitude and longitude and 40 vertical levels. After a time integration of ten years, the global distributions of chlorophyll-a and sea surface nutrients agree roughly with observations, although we still need to tune the biological parameters.

ONE MORE 3D GLOBAL BIOGEOCHEMICAL MODEL: ARE WE DOING A BETTER JOB?
(E.E. Popova, A.C. Coward)

A nitrogen-based, five compartment biological model has been coupled to a 1^{o} OCCAM (Ocean Circulation and Climate Advanced Modelling Project) model with a KPP ('K profile parameterisation') of the vertical mixing. The biological model state variables are Phytoplankton, Zooplankton, Detritus, Nitrate, and Ammonium. A comparison of the solution with global satellite ocean colour shows that the model is capable of a realistic description of the main seasonal and regional patterns of the surface chlorophyll. Agreement is also good for satellite derived estimates of primary production. In situ data available from local study sites (such as BATS (32 ^{o} N, 65 ^{o} W), NABE (47 ^{o} N, 20 ^{o} W), India (59 ^{o} N, 19 ^{o} W), Papa (50 ^{o} N, 145 ^{o} W)) are used for the detailed comparison of the model output with the observed ecosystem dynamics in different biological provinces. We will discuss model derived estimates of the primary and new production and compare them with other estimates obtained from global and basin-scale coupled models.

ANALYSIS OF MARINE PRODUCTIVITY AND CHLOROPHYLL A WITH INVERSE TECHNIQUES (Arne Winguth, Matt Dobbel, Ben Kirby)

Distribution of carbon, nutrients,and oxygen in the ocean is strongly affected by the production of biomass near the ocean surface. Seasonal chlorophyll a concentrations simulated by carbon cycle models differ from the observed values. These differences are of complex nature, related to an inadequate parameterization of the coupling of the physical and biogeochemical system, and to uncertainties in the observations. In contrast to the bias between observed and model chlorophyll a, the models generally reproduce the large scale structure of the nutrient concentration. In this study we explore and discuss potential causes of the model-data differences by sensitivity studies with a marine ecosytem model (HAMOCC4) using optimized flow fields from data assimilation experiments. These sensitivity experiments are designed to be a first step towards an inverse ecosystem model to quantify large scale interannual-to-decadal fluctuations of the marine carbon cycle. In addition we discuss future plans to provide a synthesis of geochemical tracer distribution, such as dissolved carbon, nutrients, and alkalinity, to define the current biogeochemical state of the ocean and predict its future evolution in response to climate change.

DUST IMPACT ON MARINE BIOTA AND ATMOSPHERIC CO2 DURING GLACIAL PERIODS (Laurent Bopp, Karen E. Kohfeld, Corinne Le Quéré and Olivier Aumont)

We assess the impact of high dust deposition rate on marine biota and atmospheric CO2 using a state-of-the-art ocean biogeochemistry model and observations. Our model includes an explicit representation of two groups of phytoplankton and co-limitation by iron, silicate and phosphate. When high dust deposition rate from the Last Glacial Maximum (LGM) is used as input, our model shows an increase in the relative abundance of diatoms in today's iron-limited regions, causing a global increase in export production by 6% and an atmospheric CO2 drawdown of 15 ppm. When the combined effects of changes in dust, temperature, ice cover and circulation are included, the model reproduces roughly the regional changes in export production during the LGM based on several paleoceanographic indicators. In particular, the model reproduces the observed increase north of 50S in the Southern Ocean and in the western North Pacific bassin, and the decrease south of 50S and in the east part of the North Pacific bassin. We derive a residual CO2 signal corresponding to the fraction of CO2 at Vostok, which can be associated to high dust deposition rates. This residual signal suggests that the impact of dust on atmospheric CO2 during glacial periods is <30 ppm, consistent with our model results.

WHAT'S MISSING IN THE OCEAN THAT THE LAND ALREADY HAS? (Corinne Le Quéré, I. Colin Prentice, Erik T. Buitenhuis)

In recent years, a variety of climate models have been used to assess the impact of climate change on the oceanic CO2 sink. These models systematically suggest that the oceanic CO2 sink will be reduced by 5-25% in 2050, mostly due to the thermodynamic effect of warming and to ocean stratification. Similar models of the land biosphere show a much less predictable behaviour, mostly due to the poorly understood response of the soils. While the ocean and the land CO2 reservoirs are fundamentally different, some processes included in land models are also important in the ocean, but are nearly absent from ocean models. These processes are 1)the consideration of plant functional types, 2) variable stoichiometry, 3)variable nutrient content and 4) remineralization of refractory organic carbon. In addition, 5) the alkalinity cycle and 6) fluxes in the coastal ocean are only simply represented. On time scales from 50 y to thousands of years, these processes have the potential to lead to variations in atmospheric CO2 concentrations of some tens of ppm. The fact that no global model can reproduce the observed glacial-interglacial variations in atmospheric CO2 is a strong incentive to explore these avenues. Here we present recent advances and ideas in relation to each of these processes, and discuss if and how they can be included in ocean biogeochemical models.

ECOLOGICAL RULES FOR MANAGING COMPLEXITY
(John H Steele)

Two assumptions have simplified earlier JGOFS and GLOBEC models. (1) Physical processes determine population responses, (2) slow and fast time scales are separable. These assumptions encouraged the development of independent research programs. Attention now focuses on decadal regime shifts involving (3) longer time scales (eg. twilight zone) for BGC processes, and (4) lower trophic level constraints on fisheries yield. The increased trophic linkages and expanded range of time and space scales would add significantly to model structure and complexity. I will suggest that the traditional mathematical simplification into either, (5) many variables/small perturbations; or (6) few variables/large amplitude changes; can reflect corresponding temporal separation in the underlying ecological processes – a form of punctuated equilibrium.

MODELLING THE RESPONSE OF THE OCEAN CARBON CYCLE TO CLIMATE CHANGE: IS DOM NECESSARY?
(Ian J. Totterdell)

Two simple marine ecosystem models are compared; both are versions of the Hadley Centre Ocean Carbon Cycle (HadOCC) model. The first is a Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) model while the second also features Dissolved Organic Matter (DOM). Both models are based on nitrogen, and have related flows of carbon (and alkalinity) coupled by means of C:N ratios. The models have been spun-up to (separate) near-equilibrium states, and the flows of nitrogen and carbon through the ecosystems have been calculated. The NPZD+DOM model shows slightly higher global primary production than the NPZD model, and the different pathways by which the nutrient is recycled are shown. In the NPZD+DOM model, some of the export of fixed carbon from the euphotic zone is in the form of DOM, while in the NPZD model that mechanism is not available, and the consequences for the magnitude of the sinking flux at various depth levels is examined. Transient simulations have also been run using the two models, corresponding to the years 1855 to 2095. The atmospheric pCO2 and the climatological forcings were varied according to observations and model projections as appropriate. The response of the two models to the atmospheric carbon and climate perturbations is found to be very similar. This implies that, for the purposes of modelling the response of the ocean carbon cycle to climate change, it is not necessary to represent dissolved organic matter explicitly.

THE ROLE OF ATMOSPHERIC DUST DEPOSITION IN SUPPLYING FE TO OCEANIC SURFACE WATERS AND THE LIMITATIONS OF CURRENT MODELING APPROACHES.
(Chris Measures)

An important factor moderating the biological productivity of the surface ocean is the availability of the micronutrient Fe. A required component of many crucial biochemical pathways, dissolved Fe is in limited supply in the surface oceans as a result of the extreme insolubility of its oxidised form. During the remineralisation of organic matter exported from surface waters there is fractionation between the solubility-limited Fe and the soluble macro-nutrients N and P. Upwelled waters therefore are always deficient in the amount of dissolved Fe required to enable the biological removal of the accompanying macro nutrients. Thus, there must always be an external source of Fe to oceanic waters when nutrients are brought into the photic zone by upwelling, deep mixing or simple diffusion. While this Fe may be supplied by sedimentary sources in shallow coastal regions, in the open ocean only eolian deposition can supply the required Fe. Thus the deposition of Fe-containing mineral dust to the surface ocean is a vital part of the biogeochemical cycle that couples carbon and nutrient cycling. In the contemporary ocean we have already identified several regions where, apparently, the deposition of eolian Fe is insufficient to support macronutrient removal. These High Nutrient Low Chlorophyll (HNLC) regions appear to generally coincide with oceanic regions that receive minimal dust loads. Specific dust deposition rates range from > 10 g m-2 yr-1 in the Atlantic Ocean downwind of the Sahara to < 0.01 g m-2 yr-1 in the waters around Antarctica. These estimates are based on converting measured suspended dust loads collected at various land-based sampling stations (e.g., islands) into deposition rates using settling velocities and scavenging ratios. The derived values, therefore, are subject to significant uncertainty for a variety of reasons. For example, scavenging ratios used to estimate wet deposition in the North Pacific and the North Atlantic differ by a factor of 5. Estimation of suspended loads is also complicated by the high frequency temporal and spatial nature of dust deposition events and the sparsity of oceanic island sampling sites. Thus, despite the best efforts of large numbers of people, even the finest data-based dust deposition maps, such as that produced by Duce et al. (1991), are based on extrapolation of spatially limited data sets. In addition, these deposition estimates cannot be validated in the remote ocean by direct aerosol sampling programs from short duration oceanographic cruises. This means that there are no ground-truthed dust deposition data over the open ocean, only estimates extrapolated from adjacent land-masses. Thus, a crucial component of biogeochemical models, namely the adequacy of atmospheric Fe supply to contemporary oceanic surface waters, is completely unvalidated. We cannot expect to develop realistic models that provide meaningful insights into climate change and yield accurate prognostications of future climate variations until the temporal and spatial pattern of dust deposition to the surface of the contemporary ocean are delineated and its geochemical effects are understood. On going approaches using dissolved Al and Fe in oceanic surface waters to delineate the magnitude and geochemical effects of dust deposition and the opportunity to extend this validation process to large oceanic regions in collaboration with repeat global hydrography projects will be discussed.

A STUDY OF OCEAN CIRCULATION USING A TRACER IN A HIGH RESOLUTION MODEL
(Yoshikazu Sasai, Akio Ishida and Yasuhiro Yamanka)

Oceanic uptake of anthropogenic carbon dioxide (CO2) is important because CO2 is considered the major greenhouse gas. Physical processes such as advection and diffusion in the ocean are key to determining the magnitude of this uptake. Because past studies used coarse resolution models to estimate this uptake, the role of western boundary currents and eddies in the oceanic carbon cycle has not been elucidated. In this tracer study, we use a high-resolution ocean general circulation model (OGCM) to investigate the role of middle-scale phenomena, especially eddy processes, on the distribution of tracers. The ocean circulation model is the JAMSTEC high-resolution OGCM with a fine grid of 1/4 degree in the horizontal and 55 levels in the vertical. We apply atmospheric forcing from the monthly mean Hellerman and Rosenstein [1982] wind stress and relaxation of surface temperature and salinity to Levitus [1982]. The quasi-equilibrium state of the model ocean circulation after 30 years time integration is used as an initial state for this tracer study. The tracer is initialized as an idealized tracer uniformly stratified from one at the sea surface to zero at the bottom (6000m). We apply this simple distribution to investigate tracer movement, especially vertical displacement by general circulation and eddies. The tracer's concentration is damped to its initial value at the sea surface with a timescale of 30 days. We have completed the tracer study for 20 years. The computed distribution of the tracer reflects the large-scale ocean circulation from the model. It clearly shows the upwelling in the subpolar and equatorial regions and in the Southern Ocean as well as the downwelling in subtropical regions. It also suggests that the tracer is strongly influenced by the western boundary currents (the Kuroshio and the Gulf stream) and by the eddies south of Africa.

OCEAN CARBON MODELLING: WORLD PERSPECTIVE
(R. S. Sundarvel)

The world's oceans contain about 60 times more carbon than either the atmosphere or the world's terrestrial vegetation. Thus, at equilibrium, the oceans might be expected to absorb about 60 times more of the released carbon than the atmosphere, or 98 percent of total emissions. Sea water is strongly buffered with respect to carbon-dioxide, however, the percentage change in the concentration of total dissolved carbon-dioxide is about ten times less than the percentage change in the partial pressure of carbon dioxide alone. Because the practical pressure of carbon-dioxide in the oceans is what determines the equilibrium with atmospheric carbon-dioxide, the oceans are expected to hold about 86 percent of the total emissions when the equilibrium is reached. As of 1980, the oceans are thought to have absorbed only about 20 to 47 of the total emissions. There are clearly two mechanisms which slows down the oceanic absorption of carbon-dioxide: 1.The transfer of carbon-dioxide across the air-sea interface, and 2. The mixing of water masses within the sea. The rate of transfer of carbon-dioxide across the air-sea interface is believed to have reduced the oceanic absorption of carbon-dioxide by about 10 percent. From the knowledge of the concentrations of carbon-dioxide, oxygen, and alkalinity throughout the oceans, it is theoretically possible to calculate the increased abundance of carbon in the oceans as a result of the increased concentration in the atmosphere. The approach is based on the assumption that the surface waters were in equilibrium with the atmosphere when they sank, or at least, that the extent of des-equilibrium is known. For convenience, the ocean models have assumed the carbon cycle to be in steady state prior to the start of Industrial revolution. Evidence from the concentrations of carbon-dioxide in ice cores, however, shows that no such steady state existed. Oceans are currently absorbing less carbon than estimated by models. If the analysis is correct, terrestrial ecosystems and not the oceans must have accumulated much of carbon released over the decades. Some other studies show that the alkalinity of tropical waters may have increased in recent years. Then the uptake of carbon-dioxide by the oceans has been larger than estimated by models.

HOW MAY PRIMARY PRODUCTION BE INFLUENCED BY OCEAN DMS EMISSIONS: A CLIMATE MODELLING STUDY OF THE CLAW HYPOTHESIS
(S. A. Spall, A. Jones, D. L. Roberts, M. J. Woodage, T. R. Anderson, and S. Woodward)

Charlson *et al.* (Nature 1987; 326:655-661) proposed a feedback mechanism on the earth's climate involving the release of dimethylsulphide (DMS) by ocean plankton. The so called CLAW hypothesis suggests DMS emitted from the ocean, via atmospheric chemistry producing sulphate aerosol, can alter the properties of clouds. Changes in cloud lead to changes in solar radiation and temperature at the ocean surface, producing a change in the conditions under which the plankton live and potentially feeding back to ocean production of DMS. The Hadley Centre's coupled atmosphere/ocean climate model, HadCM3, is used to simulate the DMS feedback on climate. Schemes for representing ocean DMS concentration and the atmosphere sulphur cycle are included to make these simulations possible. Ocean DMS concentrations are predicted from an empirical fit to data. In sensitivity simulations, increased DMS emissions increase cloud albedo and cloud cover though the production of sulphate aerosol from DMS. A consequence is less solar radiation penetrating beneath the cloud and the earth is cooled. There is a reaction of the ocean ecosystem to the induced changes in climate and this is the emphasis of the presentation. Phytoplankton growth in the simulations is temperature and light dependent, hence primary production is decreased in high latitudes under the cooler, 'darker' conditions experienced with increased ocean DMS emissions. Also changes to climate induced by changes in oceanic DMS emissions will impact on atmospheric dust, i.e. dust production over land, dust transport in the atmosphere and dust deposition in the ocean. A consequence is a potential further feedback mechanism, with changes in atmospheric dust deposition impacting on primary production in iron limited ecosystems. Through modelling the production, transport and deposition of atmospheric dust, dust deposition in the Southern Ocean is found to vary regionally under the different climates induced by changes in oceanic DMS emissions. Some regions experience increases in dust deposition and others decreases. This suggests any feedback to primary production through iron supply to the Southern Ocean will be complex and not have the same sign everywhere.

THE DYNAMIC GREEN OCEAN MODEL: PLANKTON FUNCTIONAL GROUPS IN AN OCEAN GLOBAL CIRCULATION MODEL.

(Erik T. Buitenhuis, Corinne Le Quéré, Olivier Aumont)

In the Dynamic Green Ocean Project our goal is to improve the representation of biogeochemical fluxes in an Ocean General Circulation Model. The components of the project are impoving model parameterisation, including a coastal model, improving the representation of the marine food web and extending model validation datasets. Here we focus on the inclusion of six major phytoplankton groups in the model food web. This project is analogous to the inclusion of plant functional types in models of land biology. The Dynamic Green Ocean Model (DGOM) is developed in collaboration with a group of scientists worldwide (http://www.bgc-jena.mpg.de/bgc_prentice/projects/green_ocean/start.html). The basis for this project is the PISCES ocean biogeochemistry model (Aumont et al. in preparation), which includes the potentially limiting nutrients NO_3^-, Fe and SiO_3^- in colimitation with light. The PISCES model already includes diatoms, nanophytoplankton, micro- and mesozooplankton. The Green Ocean Model will further represent coccolithophorids, N_2 fixers, phaeocystis and picophytoplankton. We will discuss the selected plankton functional types and their parameterisation. We will show preliminary model results of the mean, seasonal and interannual variability of the different groups, and compare our results to observations.

ROBOTIC OBSERVATIONS OF CARBON CYCLE PROCESSES IN REMOTE AND VERY STORMY OCEANS
(Jim K. B. Bishop)

Approximately 1 Pg (10^{15}g) of marine plant carbon biomass photosynthetically fixes ~50 Pg of carbon per year. The very fast turnover times for ocean carbon biomass coupled with slow traditional observing systems means that a major `space-time' gap exists for ocean carbon cycle observations in all but a few locations. The international project ARGO is now beginning to seed the ocean with several thousand autonomous profiling floats over the next few years to measure mid-depth ocean circulation, temperature, and salinity to provide an improved view of the climate state of the ocean. The recent 20-times plus improvement of rates of ocean to satellite data telemetry permits augmentation of the long-lived ARGO - style floats with low-power sensors for carbon system components and fluxes. We have developed a robotic autonomous Carbon Explorer capable of performing real-time high frequency(diurnal) observations of carbon biomass variability of the upper kilometer for seasons to years. Our first two Carbon Explorers were deployed in the subarctic North Pacific Ocean on April 10 2001 near ocean station PAPA (50N 145W) to explore biological/physical coupling of high nutrient low-chlorophyll (HNLC) waters. Several days later, an intense cloud of Gobi desert dust passed overhead. The Explorers both recorded a two times biomass enhancement - likely due to iron fertilization from the dust - in the weeks following the passage of the dust. Both Explorers continued observations until late December 2001. Another four profiling Carbon Explorers were deployed during the NSF/DOE funded SOFEX experiment in January 2002 and are still operating in the southern ocean in the howling 50's and seasonal ice zone 60's. The ability of these low cost observers to survive 25+ m/sec winds and 12+ m seas (we don't know yet about ice cover) in the southern ocean while at the same time transmitting nearly unbroken data streams opens up a real possibility for an international 'C-ARGO' program aimed at carbon biogeochemistry of the seas.

LARGE-SCALE ESTIMATES OF PRIMARY PRODUCTION AND EXPORT PRODUCTION: THE JGOFS LEGACY
(Shubha Sathyendranath and Trevor Platt)

It was during the JGOFS years that the satellite-derived methods for estimating primary production and export production became an established tool in biological oceanography. It is now essential to consolidate continuity of data, analyses and interpretation, to address questions related to long-term trends and variations in these processes. Such analyses would only be possible well after the sunset years of JGOFS, when many years of data become available. But the foundation for such studies has to be established now. If successful, it will become an invaluable legacy of JGOFS. Some of these efforts will be carried out as part of new research programmes that emerge in the wake of JGOFS. However, some complementary efforts can be made under initiatives that would have a longer life span than individual research programmes. In this presentation, the efforts of two organisations, the Partnership for Observation of the Global Oceans (POGO) and the International Ocean-Colour Co-ordination Group (IOCCG) are discussed. The IOCCG strives to ensure continuity of satellite ocean-colour data, the quality of the data, and the availability of the data to the research community. POGO has recently turned its attention to enhancing biological observations in general, and observations related to phytoplankton dynamics in particular. These efforts by organisations have to be matched by complementary efforts from the research community to improve the models and the quality of the products that are derived from the observations, especially as the technology advances.

CURRENT JGOFS DMTT ACTIVITIES, AND DATA MANAGEMENT REQUIREMENTS FOR FUTURE MARINE BIOGEOCHEMICAL PROJECTS - INSIGHTS FOR MODELERS
(Margarita Conkright)

The JGOFS Data Management Task Team (DMTT) is currently focusing on compiling all JGOFS data and associated metadata into a comprehensive, uniform database that will ensure its rapid, worldwide dissemination and long-term stewardship within the World Data Center (WDC) system, thanks to a PANGAEA/WDC-MARE initiative. The user interface for this International JGOFS Master Dataset is still under discussion, especially regarding the core parameters archived, the retrieval/searching tools and the datasets viewing/exporting tools. The views and feedback from the JGOFS modeling community regarding the present DMTT plans are welcome. Present efforts of the DMTT are on data acquisition from national JGOFS contributions and individual scientists from participating countries without national DMTT representatives, quality control and conversion into a common format. We will present a description of data currently available for scientists involved in modeling and data synthesis. In addition, the DMTT has elaborated several recommendations for international program managers and funding agencies, regarding the management of data from future international projects, which should result in the rapid availability of data, concurrent with synthesis and modeling activities. An international framework with adequate financing and a coherent framework for data management is essential for future marine biogeochemistry programs.

INTERANNUAL VARIABILITY OF OCEAN MIXING AND BIOGEOCHEMISTRY IN THE NORTH ATLANTIC OCEAN.
(M.J. Follows, J.C. Marshall, G.A. McKinley and S. Dutkiewicz, R.G. Williams and A.J. McLaren)

Using illustrations from numerical models and remotely observed data, we examine how interannual variability of upper ocean mixing modulates productivity and air-sea gas fluxes in the North Atlantic. We comment on the contribution of North Atlantic variability on the global scale. New production in the North Atlantic is modulated on the gyre scale by interannual and decadal changes in convective mixing. Observations have shown that winter mixing is enhanced in the subpolar North Atlantic, and diminished in the western subtropics, during periods of positive North Atlantic Oscillation (NAO) index, and vice versa. Our models suggest that new and export production behave consistently with the strongest correlation between the NAO index and new production in the subpolar gyre. Primary production is modulated by variations of both nutrient and light availability (and other factors). Remote observations and numerical models suggest that the North Atlantic ``spring bloom'' is enhanced in the nutrient limited, subtropical gyre by increased storminess and upper ocean mixing in the bloom period (winter), associated with a low NAO index. Conversely, the bloom is retarded by increased bloom-period mixing in the light limited subpolar gyre. However, the subpolar bloom occurs in late spring and summer and this season has no systematic, large scale patterns of variability related to the NAO index. Hence interannual variability of the bloom in the subtropical gyre shows a clear relationship with year-to-year changes in meteorological forcing but the subpolar bloom does not. In contrast to the expectation for new production, we suggest that there will be a signature of the NAO in the subtropical bloom, but not the subpolar. This can be tested as the time-series of remote ocean colour observations is extended. Air-sea fluxes of CO_2 and O_2 in the North Atlantic are also modulated by the variability of convective mixing. The dominant effect is the year-to-year change in the exposure of carbon rich, oxygen depleted waters of the thermocline. Local changes in new production have less impact, partly due to light limitation in the subpolar gyre. The response of the air-sea flux of CO_2 to changes in winter mixing is damped due to its long air-sea equilibration timescale, but there is a significant, basin-scale, interannual variability of air-sea O_2 flux. In a global biogeochemical model the interannual variability of the global, annual flux of O_2 across the sea surface feels contributions of comparable magnitude from the Tropical Pacific and North Atlantic. Variability of the annual CO_2 flux is dominated only by the Tropical Pacific. The global O_2 flux, and its North Atlantic contribution, are significant for interpretations of trends in atmospheric O_2/N_2 which are used to infer the oceanic and terrestrial sinks of fossil fuel CO_2. These methods presently assume that there is no net annual flux of O_2 across the sea surface.

GLOBAL TRANSMISSOMETER DATABASE AS A TOOL FOR BASIN-WIDE POC ASSESSMENT (W.D. Gardner, A.V. Mishonov, M.J. Richardson)

A global data base on beam attenuation coefficient due to particles has been compiled from field data collected during WOCE, JGOFS, SAVE, and other field programs. Transmissometer data from 50 cruises were loaded into an intermediate data base and sections of Beam Attenuation Coefficient (Beam c) were constructed for all WOCE, SAVE, and others lines in the Atlantic, Pacific, Indian, and Southern Oceans. The relationship between Beam cp (attenuation due to particles) and Particulate Organic Carbon (POC) was evaluated based on simultaneously acquired data sets localized in fixed area in the Atlantic, Indian, Pacific and Southern Oceans. Data sets for the Atlantic were obtained during the JGOFS NABE expedition and limited data from the Bermuda Atlantic Time Series. These two data sets contain about 800 data pairs and yield a high correlation ($r>0.9$) between these two variables. This correlation allows us to calculate the POC values based on transmissometer data and build the sections and maps of the POC distribution for the Atlantic Ocean. Data for the Pacific Ocean are still being processed. Correlation between Beam cp and POC in the Pacific will be assessed based on data sets from the Ross Sea, Antarctic Polar Front Zone and Hawaii Oceanographic Time (HOT) Series. Using the relationship between Beam cp vs POC has been shown to be a reliable and cost-effective technique for basin-wide assessment of the standing stock of carbon. This approach would be even more successful on future hydrography cruises if POC measurements were collected simultaneously during each cruise. Moreover, concurrent ocean color observations would allow the further development of algorithms to predict POC from ocean color products. The web-site of our SMP grant, "Global Synthesis of POC Using Satellite Data calibrated with Transmissometer and POC Data from JGOFS/WOCE" (http://www-ocean.tamu.edu/~pdgroup/TAMU-SMP.html) provides access to all sections and maps created from our existing data. The transmissometer data together with calculated POC concentration will be posted on this web site as well as submitted to the appropriate archives during the coming year.

RECENT JGOFS DMTT ACTIVITIES: WHAT DO WE HAVE ACHIEVED SO FAR? WHAT ARE OUR PLANS? (Bernard Avril, Margarita Conkright)

To really optimise the scientific value of an international research project, such as JGOFS and its successors, proper data management practices are essential. They should aim to ensure the elaboration of quality-controlled, homogeneously formatted and extensively documented datasets and their rapid, worldwide dissemination and long-term stewardship within the World Data Centre (WDC) system. The JGOFS data management is the responsibility of each national participant, without a centralized clearinghouse for the data. As a result, many data are still not fully available for the modelling and synthesis phase. The DMTT, a consortium of national data managers (DMO), is working hard to put together a single database (so-called, the International JGOFS Master Dataset), in a single location (in the WDC system, thanks to an initiative of PANGAEA / WDC-MARE), in a single format. This should be achieved by adapting previously developed tools, especially from the US-JGOFS DMO (for the user query interface) and from ODV/PANGAEA (for the datasets visualization and metadata handling). In this framework, the major past and current DMTT activities include: production of nationally approved JGOFS cruise inventories;

- preparation of a list of core parameters, associated units, methodology, and quality control criteria;
- preparation of metadata standards to describe the datasets;
- production of CD-ROMs and/or on-line databases (JGOFS and JGOFS-related);
- adaptation of existing data management tools, such as user interface (e.g., J-LAS) and visualization package (e.g., ODV-derived), to be incorporated into the International CD-ROM dataset;
- collection of relevant references associated with the datasets;
- interactions within the DMTT and with other competent bodies (e.g., NODCs, WDCs, ICES, IODE, national data managers not involved in the DMTT);
- interactions with other JGOFS WGs and TTs;
- preparation of recommendations for proper data management to the JGOFS SSC, the GOFS parent bodies (IGBP and SCOR) and (inter)national funding agencies; in preparation of the future marine biogeochemistry programme(s).

We hope that DMTT representatives and modellers can work together (nationally and internationally) during the remaining period of the JGOFS project. Your inputs regarding the needs of the modelling community (e.g., parameters collected, quality, resolution, accessibility) will be very welcome.

PANGAEA AND THE WORLD DATA CENTER FOR MARINE ENVIRONMENTAL SCIENCES – FACILITIES FOR THE FINAL GLOBAL DATA SYNTHESIS OF JGOFS DATA
(Michael Diepenbroek, Hannes Grobe, Rainer Sieger)

The World Data Center for Marine Environmental Sciences (WDC-MARE, http://www.pangaea.de) is aimed at collecting, scrutinizing, and disseminating data related to global change in the fields of environmental oceanography, marine geology, paleoceanography, and marine biology. WDC-MARE uses the scientific information system PANGAEA (Network for Geosciences and Environmental Data) as its operating platform. PANGAEA in addition serves significant amounts of terrestrial, lacustrine, and glacial data. Essential services supplied by WDC-MARE / PANGAEA are project data management, data publication, and the distribution of visualization and analysis software (freeware products). Among the recent data management projects are the final global data synthesis for the Joint Global Ocean Flux Study (JGOFS) and the International Marine Global Change Study (IMAGES). Together with the WDC for Paleoclimatology, Boulder, WDC-MARE forms the essential backbone within the IGBP/PAGES Data System (Eakin, 2002). Organization of data management includes quality control and publication of data and the dissemination of metadata according to international standards. Data managers are responsible for acquisition and maintenance of data. The data model used reflects the information processing steps in the earth science fields and can handle any related analytical data. A relational database management system (RDBMS) is used for information storage. Users access data from the database via web-based clients, including a simple search engine (PangaVista) and a data-mining tool (ART). With its comprehensive graphical user interfaces and the built in functionality for import, export, and maintenance of information PANGAEA is a highly efficient system for scientific data management and data publication. WDC-MARE / PANGAEA is operated as a permanent facility by the Centre for Marine Environmental Sciences at the Bremen University (MARUM) and the Alfred Wegener Institute for Polar and Marine Research (AWI) in Bremerhaven, Germany.

MODELLING THE OCEAN WITH THE AID OF COMPILED DATA.
(Jan R. Andersen, and Helge Sagen)

How can data archives aid the modeller? Field data / measured data complement models. To the modeller, a set of measured data is the “correct answer” which his model should be able to reproduce. Measured data is therefore important for evaluating the model at hand. For a working model, measured data may serve as initial/boundary conditions. Thus, field data can provide two milestones, a starting point and a checkpoint. Oceanographic datacenters compile and store enourmous amounts of data. Easy access to these data is required if the modeller is supposed to make use of them. This poster will show some of the works at the Institute for Marine Research in Norway, with special emphasis on the JGOFS project data. The Norwegian JGOFS datasets includes physical, biological and chemical data. These are stored in a database that is accessible through web technology. SQL databases and the scripting language PHP is used to retrieve the data selected by the user. The data is displayed on a web page accessible with web browsers like MS Explorer or Netscape. This technology makes it simple to create interfaces between the researcher and the database, and the interface is easily accessed via internet/intranet. NMD (Norwegian Marine Datacenter) is using this technology on the NGOFS (Norwegian JGOFS) datasets and other tasks.

STRUCTURE AND FUNCTIONING OF THE SYMPAGIC COMMUNITY AT TERRA NOVA BAY (ANTARCTICA)

(Guglielmo L., Carrada G.C., Catalano G., Cozzi S., Dell'Anno A., Fabiano M., Mangoni O., Misic C., Modigh M. , Pusceddu A., Saggiomo V.)

During the fifteenth Italian Antarctic expedition, in the framework of the PIED (**P**ack **I**ce **E**cosystem **D**ynamics) program, we investigated structure and functioning of sympagic communities in the annual pack ice at Terra Nova Bay (74°41.72’ S, 164°11.63’ E). To do this, we collected at 3 interval days (from November 1 to November 30, 1999) both intact sea ice and platelet ice samples which were analysed for inorganic nutrients, autotrophic biomass and productivity, pigment spectra, extracellular enzymatic activities and bacterial carbon production, micro-algal and metazoan community structure. In addition, mesocosm experiments were carried out in order to investigate photosynthetic and photo-acclimation processes of sympagic flora associated with intact sea ice and platelet ice. Autotrophic biomass in the bottom ice increased up to two order of magnitude from November 1 to November 30 (from 4 to 400 mg chlorophyll-a m^{-3}, respectively). Similar pattern was observed for inorganic nutrient concentrations, which significantly increased (from 5 to 111 µM NO_3 and from 0.05 to 14.0 µM PO_4). The observed increase of autotrophic biomass in the bottom sea ice cannot be only explained by *in situ* growth as we estimated, from the photosynthetic parameters, a doubling time of ca. 3 days. Pigment spectra and microscopic analyses revealed that bottom ice communities were different from those of the platelet ice. Bottom sympagic flora was mainly represented by cryobenthic species, whereas the cryopelagic population was confined to the pack-platelet ice interface. Zooplankton community in the bottom sea ice was largely dominated by copepods. In particular, the calanoiod *Stephos longipes* and the harpacticoid *Harpacticus furcifer* accounted for more than 90% of the sympagic fauna. These two species displayed different stages of their life cycle, as *S. longipes* was largely represented by nauplii, whereas for *H. furcifer* mainly exuviae were observed. Aminopeptidase activities were very high and double in platelet ice (29.8 ± 3.1 µM h^{-1}) than in bottom sea ice (13.0 ± 6.1 µM h^{-1}). Platelet ice displayed also high bacterial carbon production values (from 0.80 to 4.18 µgC l^{-1} h^{-1}), whereas in bottom sea ice were very low (0.01-0.08 µgC l^{-1} h^{-1}). This was even more evident, when autotrophic biomass in the bottom ice reached very high values, suggesting that autotrophic biomass accumulation in the bottom sea ice determines inhibiting conditions for bacterial growth, possibly due to extracellular substances released by micro-algae. Mesocosm experiments revealed that platelet ice algal community became adapted to 60% and 10% incident irradiance within a few days and, in both conditions, a bloom was observed until total disappearance of nutrients (N and P). In contrast, the bottom ice community was photo-damaged at irradiance levels commonly occurring in ice-free water column, suggesting that sympagic flora of the bottom ice might play a minor role in pelagic phytoplankton bloom.

C:N STOICHIOMETRY OF NEW PRODUCTION IN THE NORTH ATLANTIC

(Wolfgang Koeve)

New production (synonyms: export production, net community production, NCP) is one important measure of the intensity of the biological pump in the oceans. Traditionally, new production has been estimated on the base of ^{15}N-NO_3 incorporation, NO_3disappearance or seasonal nitrate budgets. Conversion to carbon units was usually done by multiplying with the canonical ‚Redfield‘ C/N ratio (6.6). Over the JGOFS decade, however, evidence has accumulated that the C/N ratio of NCP may at times exceed the Redfield value significantly. Little, however is known about the regional distribution of the seasonally integrated C/N ratio of NCP and also about sources and sinks of the excess carbon uptake. This study takes the example of the temperate and subarctic Northatlantic and estimates seasonally integrated C/N ratios of NCP. Additionally, data from process studies and hydrographical transects are used to discuss the seasonal evolution of the C/N ratio. Nitrate and carbon based NCP is estimated for the Northatlantic from historical data and empirical models. In the temperate and subarctic North Atlantic the major uncertainty in both estimates is due to the scarcity of winter time data and the need to estimate these data fields from either interpolations in space and time (climatologies), from summer to winter extrapolation methods and from empirical relationships between observed (SST, NO_3 or pCO_2) and modelled properties (alkalinity). The initial uncertainty for winter time NC_t north of 45°N, for example, is about 50 µmol kg^{-1}, which is about the magnitude of the observed seasonal NC_t change at the surface. This uncertainty, however, can be reduced considerably by a combination of different approaches; for NC_t it reduces to < 10 µmol kg^{-1}. Much more nitrate data are available from summer, which permit to construct a late summer dataset. From a close inspection of historical data (WOA98) and the eWOCE Atlas, it is concluded that the availability and distribution of data prevents a higher temporal resolution. Uncertainties in the winter data sets clearly propagate when NCP is computed. For the estimate from this study, which is based on the most likely winter data sets, the contribution of air-sea CO_2 exchange (ASE) and $CaCO_3$ production to the seasonal carbon budget of the upper 100m are about 30% and 15%, respectively. The C:N ratio of NCP along 20°W varies between 10 and 13 north of 40°N and increases strongly towards the subtropical gyre. The integral C:N ratio in the North Atlantic between 40°N and 65°N (260°E to 380°E) is 11.2. The ratio of organic carbon : inorganic carbon (OC:IC) net production is estimated using the same datasets from the seasonal changes in nitrate and alkalinity and the C:N ratio estimate; the basin scale integral is 7.8. The basin scale integral value of 7.8 is significantly larger than the POC:PIC export ratio which was recently estimated from sediment trap data (3.4 to 4.3; see also the second poster by Koeve: The effective carbon flux in the Atlantic Ocean, ISPRA.JGOFS/GAIM meeting, 2002). This difference underlines that the organic carbon associated with high C:N ratio is not exported into the deep ocean. Conflicting evidence exists, whether already the spring bloom is characterized by high C:N ratios or whether carbon overproduction is due to net carbon uptake under nitrate depleted summer conditions. Evidence from process studies, hydrographical sections and models is used to suggest that most of the excess carbon production observed in the temperate and subarctic North Atlantic is associated with the summer system and not the phytoplankton spring bloom.