

Integrating biogeochemistry and ecology into ocean data assimilation systems

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Abstract

Although the first generation of operational oceanography systems has been designed to routinely estimate the state of the oceans' physical environment, there is considerable opportunity to expand the GODAE systems in order to include new models and assimilation components relevant to marine biogeochemistry and higher trophic levels. This expansion is a key challenge in an era of climate change requiring well-planned strategies supported by appropriate data to safeguard marine ecosystems. In this presentation, we will discuss some of the applications and limitations of operational oceanography systems to deliver ecological and biogeochemical products, as examined by the joint IMBER-GODAE working group.

A number of GODAE systems have already demonstrated potential to deliver products for (i) representing primary production using more realistic ocean dynamics at eddy scales to constrain the biological activity in the open ocean and upwelling systems; (ii) monitoring the oceanic component of the carbon cycle; (iii) modelling the mid-trophic component of the pelagic system using horizontal transport and primary production; (iv) physical and biogeochemical fields and/or time series needed for functional groups and higher trophic level species habitat prediction models; (v) studies of longer term variability and shifts in ecosystems based on decadal reanalyses of the ocean circulation and primary production, and (vi) regional modelling of ecosystems and water quality management in coastal areas by providing boundary conditions to estimate fluxes and cross-slope exchanges.

A number of applications, however, indicate that the GODAE systems need to improve the representation of physical state variables that currently are not yet considered as essential, such as vertical velocity, mixed layer depth, stratification and vertical mixing. These variables are important as they have direct impacts on biology. Additional issues to be addressed relate to the representation of physical processes in the GODAE products, on-line vs. off-line strategies and requirements for long-term re-analyses of coupled models. With regard to living resources, coupling between open ocean and shelf seas also raises issues concerning the modelling of critical physical processes at their interface, particularly as exchanges are in both directions.

In the future, an extension of the "integrated" approach developed during GODAE for the physics to coupled physical-ecological-biogeochemical models will require further developments of the observing systems, both in terms of *in situ* platforms (with intensified deployments of sensors for O₂ and chlorophyll, and inclusion of new sensors for nutrients, zooplankton and micronekton biomass etc.), ocean colour satellite missions (possibly on geostationary orbits), and improved methods to assimilate these new measurements. The extension of the GODAE metrics concept to biogeochemical variables will also be needed to measure progress and coordinate efforts of the international community in the longer term.

Key words: ecosystems, biogeochemistry, fisheries, modelling, data assimilation, prediction

1. Introduction

In its original design, GODAE was conceived as a practical demonstration of real-time ocean data assimilation in order to provide a regular and complete depiction of the global ocean circulation at eddy resolution and consistent with observations of physical parameters and dynamical constraints [Le Traon *et al.*, 1999]. In spite of a strong focus on the physics, this type of oceanic information was identified in the early stage of GODAE as potentially very valuable to different applications related to the “living ocean”, such as the fishing industry and fisheries management [Griffin *et al.*, 2002]. Major research and development projects like MERSEA¹ (Marine Environment and Security for the European Area) were undertaken in Europe during the GODAE timeframe, motivated in part by the objective to enable the sustainable exploitation and management of ocean resources like fish, and to more efficiently mitigate the effects of environmental hazards and pollution crisis (e.g. harmful algal blooms). The success of the MERSEA demonstration which was completed in 2008 enables a transition to operational services which is on the way with the MyOcean project [Bahrel *et al.*, this symposium] under the GMES (Global Monitoring for Environment and Security) umbrella. The long-term ambition is to provide services to a variety of users from public and private sectors including fisheries, aquaculture and tourism industries, marine environmental protection agencies, navies and the research community.

The GODAE systems are already producing valuable information about key environmental variables in real-time, hindcast and forecast modes. Temperature distributions, for instance, can be used by fisheries managers to monitor in real-time the location of fish species undergoing seasonal migrations and determine appropriate management boundaries [Hobday and Hartmann, 2006], or to drive simulations of mid-trophic and top predator levels of pelagic ecosystems [Lehodey *et al.*, 2008]. At climate variability time scales, temperature time series obtained from pluriannual reanalyses are potentially useful to analyse, detect and make projections about regime shifts of fish populations [Brander 2005]. Considering the dynamics, currents from circulation model nowcasts can be used to predict the transport and spread of fish larvae or species such as jellyfish, in situations dominated by advective regimes [e.g., Johnson *et al.*, 2005]. Other diagnostic quantities can be derived from estimates of the thermo-dynamic state, such as mixing coefficients, vertical fluxes or upwelling indexes associated to biological activity or fish abundance [Crosnier *et al.*, 2008].

Regarding marine biogeochemistry, there are pressing demands from institutions and scientists to develop monitoring systems of the global carbon cycle including its oceanic component. Empirical methods have been developed recently to estimate pCO₂ distributions based on Sea-Surface Temperature (SST) and mixed-layer depth as provided by GODAE systems, in addition to ocean colour observations [Jamet *et al.*, 2007]. This last example however shows that, in addition to physical parameters already produced by operational systems, other core variables such as chlorophyll, nutrient and oxygen concentration (which cannot be derived from hydrological parameters only) should be made available on a regular and sustained basis to stimulate new applications.

During GODAE, it has become apparent that the full benefit of operational oceanography would be realized if modelling of the physics was coupled to modelling of relevant marine biological properties in a consistent manner. Following the Beijing GODAE symposium, a consensus emerged noting that it was timely to start coupling models of simplified ecosystems [e.g. Johannessen *et al.*, 2006] into GODAE-type monitoring and forecasting systems. Although this issue clearly goes beyond the initial GODAE vision, the expansion of operational data assimilation to fully coupled physical/biogeochemical models is motivated by both scientific and strategic reasons. From a scientific point of view, the optimal estimation of biological fields will need to understand how errors in the physics cascade into the ecosystem models because of the multivariate nature of the assimilation methods underpinning the operational systems. On the other hand, observations of some biological properties such as obtained from satellite-derived chlorophyll maps may contain reliable and relevant information about the location of fronts, eddies and filaments. Thus feedback in the assimilation process should be in both directions in order to avoid misalignments between physical and

¹ EU project funded under FP6 and coordinated by Ifremer. The MERSEA consortium involves partners from: Canada, Cyprus, Denmark, France, Germany, Greece, Italy, Norway, Spain, The Netherlands, Turkey, United Kingdom.

biological fronts. The existence of other feedbacks from biology to physics should also be considered [Marzeion *et al.*, 2005]. Further, the sea-surface reflectance data measured from the “ocean colour” satellite missions are linked to other biological variables (such as chlorophyll or phytoplankton) through non-linear relationships involving hydrodynamic, radiative and biological features of the upper ocean. Ultimately, coupled models including optical modules could be required to properly process and assimilate Sea-Spectral Reflectance (SSR) data from satellites [Nerger *et al.*, 2007]. From the strategic viewpoint, the expansion of the GODAE systems to incorporate new ecosystem and biogeochemistry components will be relevant because it will benefit from previous expertise and efforts during the GODAE era, broaden the range of applications and improve the understanding of end-users requirements. This whole process is likely to provide forceful arguments for sustained observing systems of the physical and biological components of the ocean, and initiate convergence toward earth-system modelling and prediction initiatives.

This new perspective raises two pragmatic questions that need to be addressed in the short-term, in light of what has been achieved by, and learned during GODAE: (i) how should the physics of the GODAE products available today be improved in such a way as to increase their relevance, accuracy and availability to a variety of users interested by environmental applications, and (ii) which new modelling components should be incorporated in the existing systems in order to routinely deliver a few essential biogeochemical and ecosystem variables consistently with the physical variables ?

The research community has a key role in addressing these questions. Common scientific interests have been identified across the GODAE and IMBER communities concerning data synthesis and modelling activities [IMBER 2005], and a joint workshop was held in 2007 to initiate collaborations between the two groups [Wilmer-Becker and Monfray, 2007]. Some of the points discussed herein are based on the outcome of this workshop. This paper will present a number of on-going and planned applications linked to biogeochemistry and marine ecosystems, the main lessons learned from these experiments and the new developments required in the future.

2. Applications of GODAE to biogeochemistry and marine ecosystems

A main strength of the nowcast, forecast and reanalysis products delivered by the GODAE systems is their high horizontal and vertical resolution of the upper ocean, and their capacity to describe the variability synchronized to observed events. The potential merit of data assimilation systems expanded to ocean biogeochemistry and marine ecosystems are discussed herein for several areas of benefit, based on examples of ongoing demonstrations and new developments.

2.1 Phytoplankton biomass monitoring in the open ocean

Substantial progress has been accomplished during the past years to model the primary production in the ocean, which is the basic link between inorganic matter and higher trophic levels of the marine food web. In spite of still large uncertainties about the actual distribution and variability of primary producers in the ocean, real-time estimates of the phytoplankton biomass is a key product needed to develop downstream applications such as monitoring the global carbon cycle or living resources.

During the MERSEA project, the prototype of a coupled physical/biological assimilative system has been developed by the Mercator-Vert consortium [Moulin *et al.*, 2008] with the objective to routinely estimate and forecast biogeochemical variables over the globe using the Mercator operational setup. The biogeochemical model component is PISCES, which simulates 24 biological variables representing four plankton functional types (nano-phytoplankton, diatoms, meso- and micro-zooplankton) and co-limitations by N, P, Si, Fe and light [Aumont *et al.*, 2004]. The evolution of the biological tracers can be driven using physical hindcasts produced by the NEMO global $\frac{1}{4}^\circ$ circulation model which assimilates SST, altimetric data and *in situ* temperature and salinity profiles.

Several experiments have been performed to represent the seasonal evolution of the biogeochemical state during recent years and to compare the surface phytoplankton distributions computed by the model with ocean colour data from SeaWiFS. These experiments essentially show the positive impact of models with high-resolution physics compared to lower resolution models typically used in climate simulations, and the

benefit gained from using co-limitations (e.g. based on iron) near continental margins (Figure 1). A real-time demonstration was performed in 2008, delivering weekly a set of secondary products such as distributions of nutrients, primary production, depth of the euphotic layer, dissolved organic matter, dissolved oxygen and surface pCO₂ [El Moussaoui *et al.*, 2008]. While demonstrating the technological and scientific feasibility of the approach, comparisons with direct observations suggest that the phytoplankton biomass estimated by the Mercator-Vert prototypes could be improved further by using satellite ocean colour data as additional constraints.

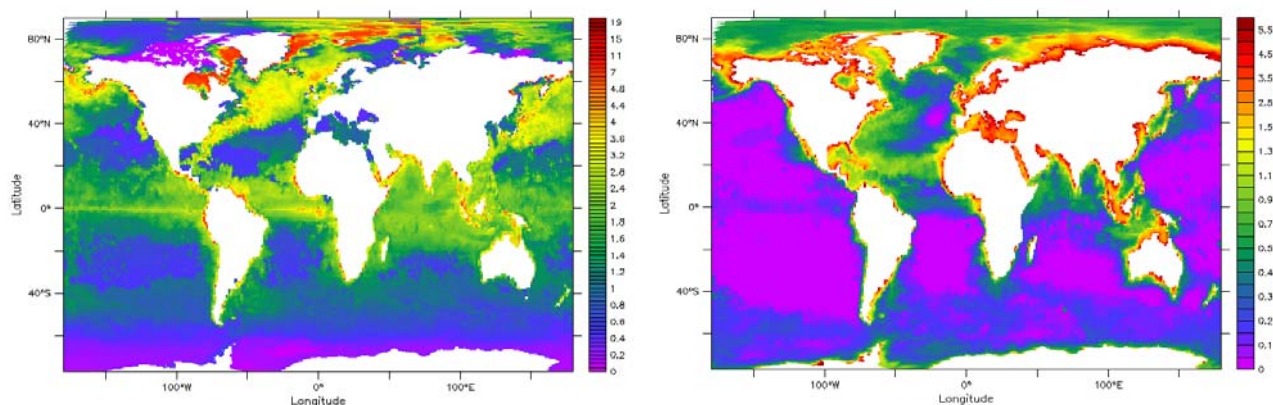


Figure 1. Phytoplankton biomass (left) and iron concentration (right) in June 2001, estimated by the PISCES model coupled to the Mercator global $\frac{1}{4}^\circ$ model. From El Moussaoui *et al.*, 2008.

The explicit assimilation of ocean colour data into coupled models is quite challenging, mainly because of the fairly poor accuracy of the observed signal (estimated as $\pm 50\%$), the complex relationship between the remotely-sensed property (SSR) and the model equivalent (most often phytoplankton concentrations), the non-linearities of coupled physical-biological processes and the still insufficient performances of the modelling tools available today.

In the system developed at NASA for instance, chlorophyll data from SeaWiFS are assimilated into a three-dimensional global Ocean Biogeochemical Model (NOBM) for the period 1998–2004 [Nerger and Gregg, 2007]. This system provides daily global surface chlorophyll fields and improves the chlorophyll estimates relative to a model simulation without assimilation.

Similar developments are being undertaken by the U.K. Met Office in a pre-operational coupled physical/biogeochemistry model that has been used to run experiments with FOAM (Forecasting Ocean Assimilation Model) coupled to HadOCC (Hadley Centre Ocean Carbon Cycle Model) for year 2003. The system is effective at simulating the onset of the spring bloom in good qualitative agreement with SeaWiFS and AMT data, but chlorophyll levels subsequently appear to be over-estimated. Higher resolution provides improved representation of advective processes, in particular. A nitrogen balancing scheme for ocean color data assimilation has been developed, jointly by NOCS and Met Office, and implemented within FOAM-HadOCC. Given increments for phytoplankton obtained from a univariate surface chlorophyll analysis, the scheme determines mixed layer concentration increments for the other nitrogen pools: zooplankton, detritus and dissolved inorganic nitrogen (DIN). The fraction of phytoplankton increment to be balanced by changing DIN varies dynamically with the likely contributions of phytoplankton growth and loss errors in the background state. Further increments are also applied below the mixed layer [Hemmings *et al.*, 2008]. Twin experiments as well as real-world experiments show that the scheme is able to improve the chlorophyll distribution (Figure 2).

A key question for the future will be to better understand and quantify the impact of climate changes on the phytoplankton. There is currently no clear consensus about the first-order response of primary producers to

the climate variability observed during the last two decades. Recent analyses based on CZCS and SeaWiFS ocean colour records indicate an overall increase of the world ocean average chlorophyll concentration by about 22% [Antoine *et al.*, 2005], while a reduction of the biological activity might take place in oligotrophic regions [Gregg *et al.*, 2005; Polovina *et al.*, 2008]. Recent simulations of the primary production of the North Sea covering the past 25 years indicate a maximum of about 20% variation from year to year in the annual and spatially averaged total production; however significantly larger variability is seen in different areas [Skogen *et al.*, 2007]. Accurate reanalyses of the physical ocean environment during the past 60 years will offer new insight into this important question as these decades offer the best reconstructed climate forcings and include trends, regime shifts, year-to-year and decadal variability.

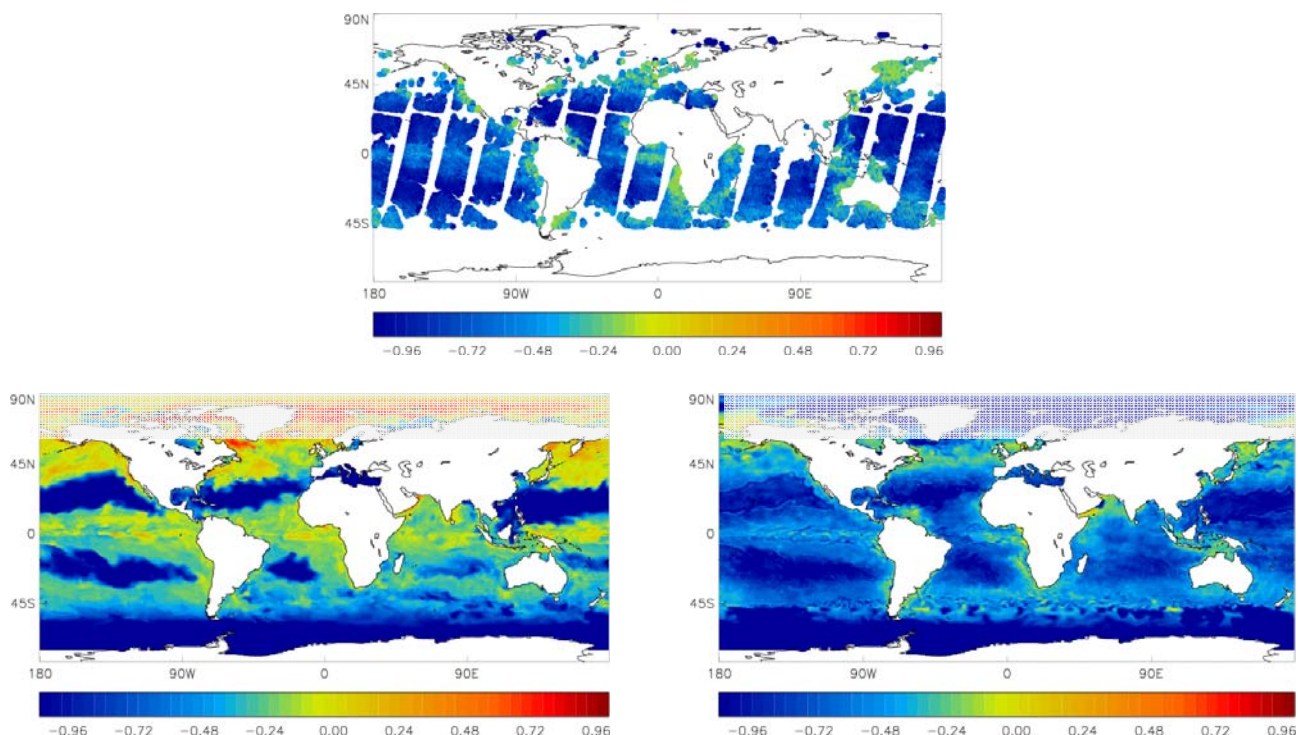


Figure 2. Chlorophyll concentration (log scale) on 1st July 2003, as derived from: SeaWiFS measurements (upper panel), the coupled model without assimilation (bottom left), and the coupled model with assimilation (bottom right). (Barciela *et al.*, personal communication).

2.2 Ocean carbon uptake monitoring

The operational systems available by the end of GODAE will not be able to accurately provide real-time monitoring of global or basin-scale air-sea carbon fluxes as, e.g., required for attempts to achieve reliable regional carbon budgets. Developing this capacity represents a research activity of strategic importance in the context of international conventions. Earlier attempts to obtain maps of pCO₂ and associated air-sea fluxes of CO₂ have focused on interpolation of *in situ* measurements with some help of ocean-colour and surface-temperature satellite data. As coverage of *in situ* data is sparse and synoptic satellite images are often dominated by clouds, numerical models can help to combine and interpolate the observational information contained in various data sets (Figure 3).

As part of the E.U. MyOcean project, further development of ecosystem and biogeochemical models will be performed such that they can (i) reliably convert from ocean colour measurements of chlorophyll to carbon within the phytoplankton (conversion factors vary by one to two orders of magnitude, depending on light, nutrients, temperature and history); (ii) account for sub-annual variations in upper-ocean dissolved organic carbon which can, in carbon units, be one order of magnitude larger than variations in particulate biomass, and (iii) link phytoplankton biomass to carbon export associated with sinking. This R&D work will rely on new modelling tools based on a recently proposed size-spectral formulation [Kriest and Oschlies, 2007].

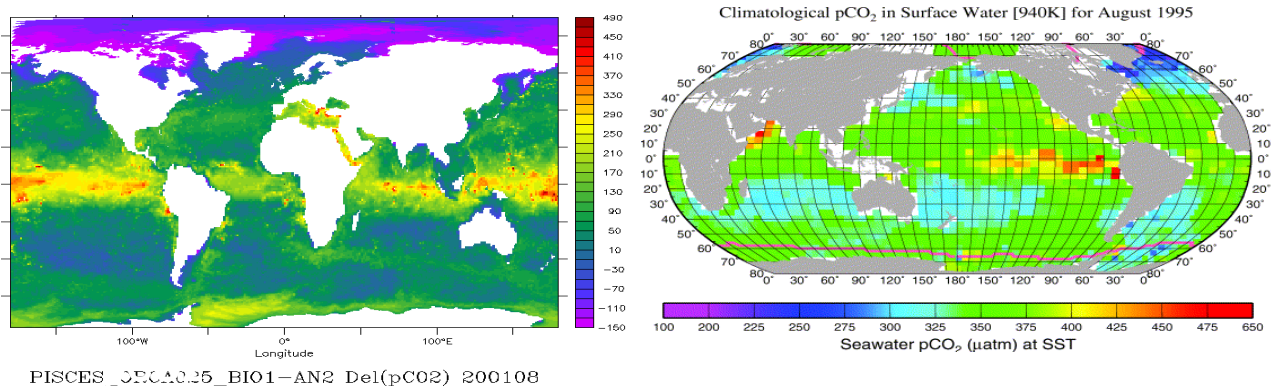


Figure 3. Distribution of pCO₂ estimated from a hindcast experiment in August 2001 using PISCES coupled to the global 1/4° Mercator model (left), compared to climatological estimates (right) from Takahashi *et al.* [2002].

2.3 Marine ecosystem management

Marine exploitation issues need to be addressed from an ecosystem perspective, i.e. using an ecosystem-based management approach [e.g., Svendsen *et al.*, 2007]. The long-term vision is to develop the systems required for the study and management of exploited marine resources, in particular for large pelagic species (e.g. bluefin tuna, billfishes, sharks, ...) and e.g. demersal white fish like cod species of the north Atlantic for which there are increasing concerns on the sustainability of their exploitation or even in some cases a risk of extinction (e.g. marine turtles). Management advice is about predicting the future either as the most probable future or as the answer to “what if” scenarii from human interference (e.g. fishing pressure, fertilization, pollution, introduced species, bottom habitat disturbance) interacting with the varying physics (climate variability and change). For most predictions it is important to have the best possible knowledge of the most recent status of the ecosystem.

One key explanatory variable that is usually missing to understand individual behaviour of these large oceanic predators is the dynamic of their prey species. The Spatial Ecosystem And Population Dynamic Model (SEAPODYM) is one approach that is proposed to model the spatial dynamics of tuna population [Lehodey *et al.*, 2008a] in interaction with the modelling of their prey described by several mid-trophic functional groups of the pelagic system in three vertical (epi-, meso-, and bathy-pelagic) layers. In this model, the dynamics of forage and predators are driven by environmental forcings (temperature, currents, oxygen, and primary production), which can be predicted from coupled physical-biogeochemical model outputs. Parametrization of the dynamics of mid-trophic components is based on an allometric relationship [Lehodey 2004]. Then, a simple energy transfer from primary production is used, justified by the existence of constant slopes in log-log biomass size spectrum relationships. Impacts of vertical behaviour of the organisms and horizontal currents are considered through a system of advection-diffusion equations. The top-predators themselves are coupled to the forage groups via habitat indices for spawning and feeding. This approach provides a pathway from physics to fish where NPZD-models coupled to an OGCM or a coupled ocean-atmosphere model provide the energy at the bottom of the pelagic mid-trophics (epi-, meso-, and bathy-pelagic).

A key issue for the coming years will be to gather available information allowing to calibrate this type of mid-trophic models based on functional groups or other approaches, e.g., a continuous size spectrum [Maury *et al.*, 2007]. But new tools are also needed, based on existing acoustic technology for large scale monitoring of these mid-trophic level organisms. Ultimately, collected data should be used for parameter optimization and data assimilation. For top predators, a large dataset of observation exists already, including catch data, size-frequency of catch, conventional and electronic tagging data. These data have been used for optimizing the parameter estimation of the SEAPODYM model for tuna species [Senina *et al.*, 2008]. With the achieved parameterization scheme, the model can help investigating the impact of fishing under various management

scenarios, and also conduct forecasts of a given species stock and spatial dynamics in a context of environmental and climate changes [Lehodey *et al.*, 2008b]. A special effort is also devoted to produce high resolution simulations to investigate individual behaviour of large predators as inferred from archival and satellite tags (Figure 4). Assimilation of these types of data to estimate the model parameters will be the next key effort in this modelling development.

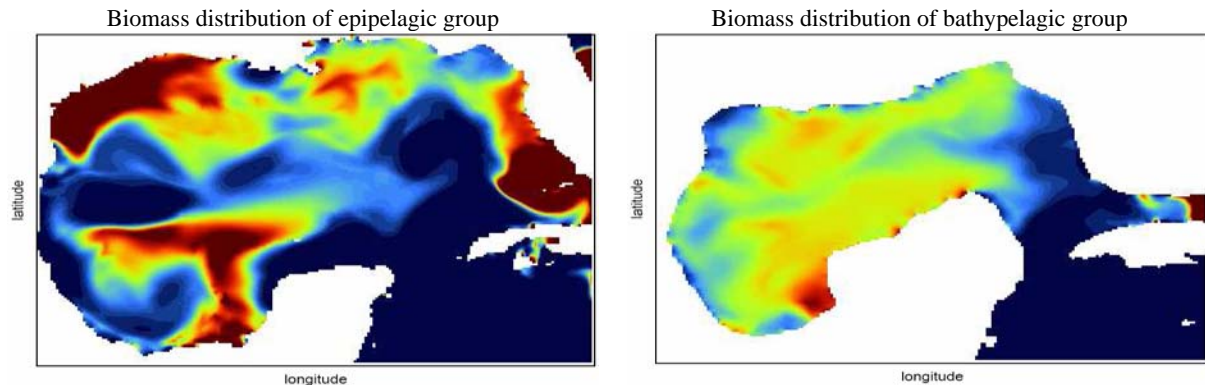


Figure 4: High resolution simulation (1/12 deg) of two mid-trophic functional groups (left: epipelagic, and right: bathypelagic) in the Gulf of Mexico, with ocean physics provided by the Mercator system and satellite-derived primary production (Behrenfeld and Falkowski 1997)

From the users' perspective, oceanographic information is used in fisheries management in two basic ways. First, traditional fisheries oceanography has involved a search for explanation of historical catch-related pattern. Environmental variables such as SST, mixed-layer depth and chlorophyll are used as covariates along with fishing-related variables to explain observed variation in catch rate [e.g. Heron *et al.*, 1998; Cole 1999; Zagaglia and Stech 2004; Bigelow and Maunder 2007]. Stock assessment scientists then use this information to correct observed catch rates, and derive historical population estimates [e.g. Bigelow *et al.*, 2002]. This leads to an understanding of how fishing mortality leads to a change in population size, and this mortality is what management seeks to adjust via gear restrictions, quotas, and spatial management.

The relationships with the environment are often quite weak, and this may be due to the selected environmental variables, which may be correlated with fish distribution and abundance, but are not strong drivers [Myers 1998]. Derived variables such as mixed layer depth, productivity, prey biomass, may be more relevant to the distribution and abundance of fish. Thus, improved "physical" and "biological" variables from coupled models may improve understanding of historical pattern, and offer improved management for ocean resources. In Svendsen *et al.* [2007] this is demonstrated through a 2-3 year prediction of 3 year old arctic cod recruitment based on nowcasting physics and primary production affecting the survival of larvae. To better understand the mechanisms, more focus is given to the modelled continuous food availability (primary production and zooplankton) and surrounding temperature for the larvae and the final settlement area of the juveniles.

The second, and growing way, in which fisheries management can use oceanographic information is in realtime or forecast modes. This offers the potential for strategic rather than reactionary management of marine resources. For example, oceanographic variables with a known relationship with the species of interest may be used to forecast distribution of suitable habitat. The access to this habitat can then be regulated by the fisheries agency. Such an approach is used in a longline fishery in eastern Australia, where southern bluefin tuna habitat is predicted every two weeks by combining physical fields derived from the Bluelink ocean model with tag-based environmental preferences [Hobday and Hartmann, 2006]. Figure 5 illustrates how real-time oceanographic information can be converted into fishing management maps. Fishery managers then restrict fisher access to the locations with predicted high concentration of tuna.

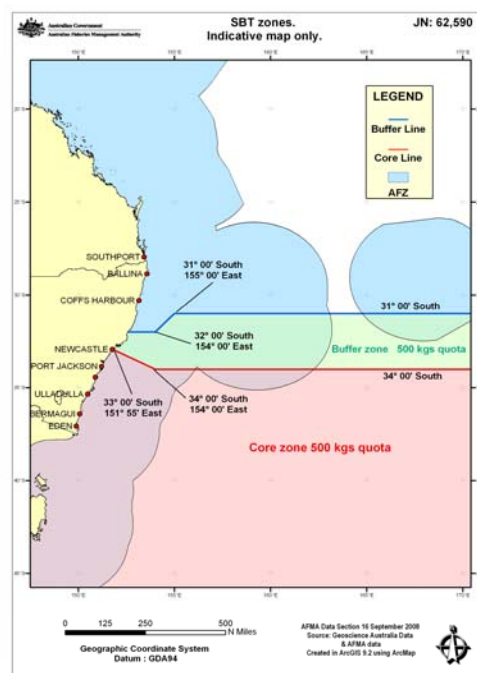
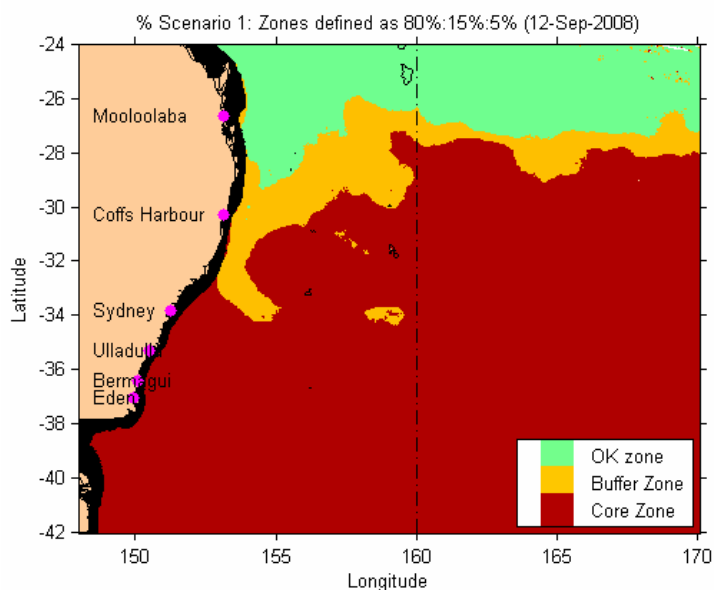


Figure 5: Example of real-time prediction of Southern Bluefin Tuna (SBT) habitats based on BlueLINK ocean model data and fish tags (left panel), and resulting management map distributed to stakeholders on September 16, 2008 (right panel). Three fishing zones are defined: the core SBT habitat (south of 34°S), the poor SBT habitat (north of 31°S) and the marginal SBT habitat (buffer zone).

Another example where oceanographic information support the fishing industry is the routine half a year prediction of the fishing of horse mackerel in the North Sea [Iversen *et al.*, 2002]. This is based on a simple relation between the inflow of warm nutrient rich Atlantic water into the northern North Sea during the winter and the fishing during fall. The assumed mechanism is that the migrating stock follows the “pleasant warm productive road” into the North Sea when the inflow has been strong.

2.4 Decadal shifts in ecosystems and longer-term planning issues

This section aims to show how GODAE products can be relevant for long term planning and in the investigation of decadal changes in ecosystems. It outlines some ideas about the kinds of products that are likely to be required.

Changes in marine ecosystems at time scales from one to several decades probably occur in all parts of the world oceans and have been detected and investigated extensively. In the North Atlantic a warm period from the 1920s to the 1960s caused very extensive changes in distribution and abundance of fish, plankton, benthos, and other biota. In the North Pacific decadal changes are often described in terms of “regime shifts”, when a fairly abrupt, persistent change in the ecosystem occurs simultaneously over a very large area due to alteration in atmospheric pressure patterns, upper ocean mixing, horizontal transport and upper ocean temperature. An important point with regard to fisheries is that harvest levels in one regime, may not be appropriate for another regime. Regime shifts in the North Pacific occurred in 1925, 1947, 1977 and 1989, with substantial changes in both physical and biological systems, including all taxa and trophic levels [King 2005]. Regime shifts have now also been described in other sea areas, but the linkage with physical processes and the duration of the subsequent regimes is less clear, therefore all decadal changes will be dealt with together here, whether they are gradual or abrupt.

Since decadal changes affect species composition, distribution and production they are of great significance to fisheries and marine ecosystem management. GODAE can provide three kinds of valuable information:

(i) reanalyses which provide an integrated reconstruction of past physical, chemical and biological changes and which help in interpreting the processes responsible for decadal changes, (ii) real-time indications of system changes, particularly if these show an increased likelihood of a regime shift in progress, and (iii) predictions of extreme events which may cause increased mortality in certain species or areas or give rise to prolonged system changes.

▪ **Reanalyses** – It is currently not possible to predict decadal changes because the underlying physical and ecological processes are unknown. A first step to gaining such understanding will be to interpret past decadal changes. This understanding is critical in order to recognise climate signals which may cause changes in the distribution, composition and productivity of marine populations [King 2005].

▪ **Real-time indications of system changes** – Some management systems already include physical factors where empirical studies show good evidence of underlying relationships, even if full details of the processes are not yet established. For example, the harvest control rule for Californian sardine uses a running average of SST to adjust the catch and harvest rate [Jacobson *et al.*, 2005]. In other cases it has become clear with the benefit of hindsight that production was affected by changes in ocean climate (e.g. the influence of the Labrador current on cod stocks on the Canadian shelf [Brander, 2007]). Although real-time information may give no indication of how long such a change may last, it nevertheless provides the basis for a cumulative estimate of the likelihood that a long term change is occurring. In addition, nowcasting the physics together with the “known” impact on the juveniles, opens the possibility of prediction (particularly of long lived species) based on the biological links between adults and juveniles and multi-species interactions as the physical environment often has the strongest impact on the early life stages of fish.

▪ **Extreme events** – Some decadal scale ecosystem changes, such as the bleaching of coral reefs may be precipitated by short term extremes in temperature and salinity conditions [Marshall and Schuttenberg, 2006]. Storms may also break up corals or bury seagrass beds in shallow water. Forecasts of extreme events can sometimes provide sufficient warning for protective action – for example pearl farms in the Cook Islands in the Pacific can move stock to deeper water when warned of extreme conditions. The salinity and oxygen conditions in the Baltic Sea are dependent on inflow of oxygenated, saline water from the North Sea and management of the marine ecosystems and fisheries in that area would benefit from information on both individual inflow events and also on likely changes in their frequency over periods of one to several years [MacKenzie *et al.*, 2007].

2.5 Regional downscaling and coastal applications

Broadening our interest from physics to the ecosystem level (biogeochemistry, marine resources) necessarily means increasing the focus of modelling systems to the coastal zone. Indeed, continental margin play a key role in the ocean carbon cycle with about 10 to 15% of global ocean productivity and more than 40% of the global burial of organic carbon occurring in these regions. The major part of fish and shellfish productivity, and thus fishing activity occurs on and along continental shelves. Hazardous environment events such as harmful algal blooms or eutrophication also take place in the coastal zone [Pettersen *et al.*, 2000], so this is a highly sensitive oceanic area to global change. Meanwhile, regional seas and coastal zones bring new challenges in terms of observing, modelling and assimilation systems.

During the late 1990's and early 2000's the first operational coupled physical/biological system MONCOZE (MONitoring the Coastal Zone Environment, <http://wms.met.no/moncoze/>) for parts of the North Sea was developed and implemented based on NORWECOM (the NORWegian Ecological Model system) with the biology from Aksnes *et al.* [1995] and the physics from the Princeton Ocean Model (POM). In addition to the functional algal groups of diatoms and flagellates the biology includes nitrogen, phosphorous, silicon, detritus, oxygen, suspended matter and light. More recently, a semi-operational system has been set up for transport and distribution of cod and herring larvae spawned during spring along the northern coast of Norway (Figure 6). This will be used for management advice during possible pollution from the petroleum industry or shipping accidents, directing research vessels for larval studies, and for studies of recruitment processes in general.

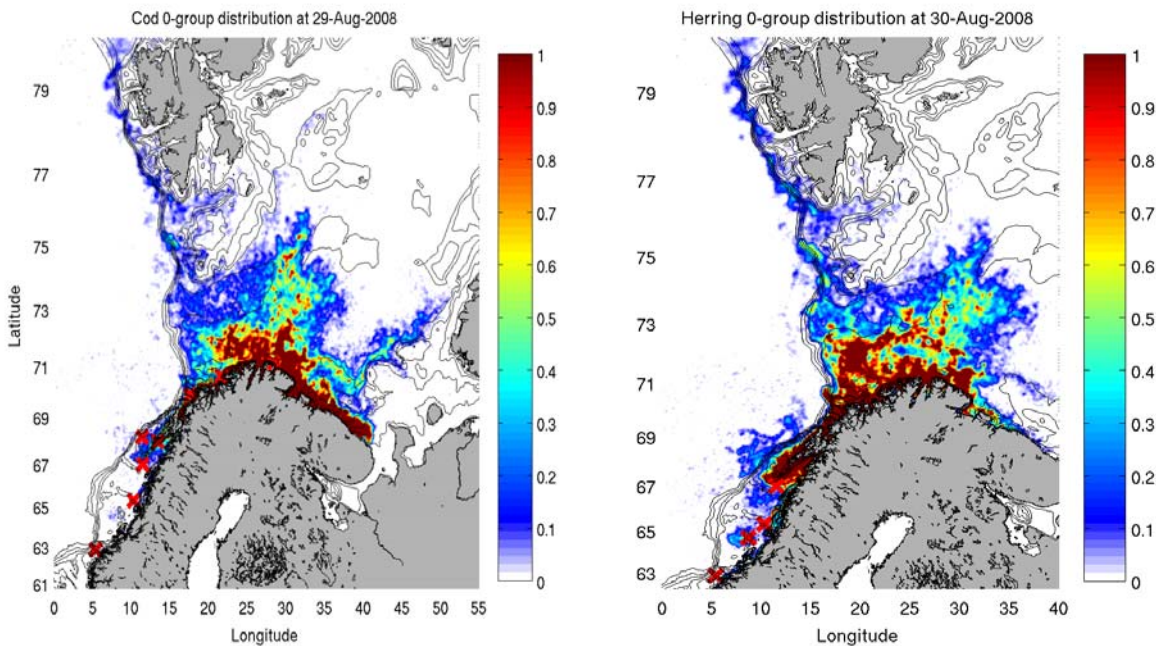


Figure 6. Operationally (daily updates) simulated distribution (end of August 2008) of cod (left) and herring spawning larvae along the Norwegian coast. The larvae have a vertical migration behaviour and are driven by operational current forecasts (using POM) supplied by the Norwegian Meteorological Institute. (Vikebø *et al.*, personal communication)

As demonstrated by these experiments, physical and biological processes of the coastal zone bring new challenges for modellers. Complex coastline and topography, high frequency of physical processes (external and internal tide) and their coupling to biology, high amplitude and rapidity of events (successive coastal blooms as compared to well defined oceanic spring blooms) are good examples of what modelling and assimilation tools have to deal with. Spatial scale of coastal processes often requires increasing resolution of global models, for which an increased resolution is limited by computing timeframe. Regional nesting or unstructured grid with higher resolution along the coast and over strong topography gradients may help solving this issue so that circulation patterns allow for biological material to be transported correctly [Huret *et al.* 2007]. Biological tracers or particles need to be transferred in a conservative way at the chosen boundary between the global and regional models. For that, the slope region, with its complex processes and high exchange of biological material, can not constitute a boundary for regional applications, but rather should be part of the regional high resolution model. This requirement has important implications for the design of the GODAE systems and their coupling with coastal models.

From the open ocean, boundary condition in real-time of the majority of these variables is necessary. Coastal ecosystem models by themselves bring new research domain because of the higher biodiversity and the more specific or full life-cycle problematic. Choice has to be made in the model complexity, often dependent on the question. A relatively few compartments model will be easier to constrain with data and allow carbon cycle studies, whereas a specific or more complex model (e.g. end-to-end models) will find difficulties to be data constrained but necessary to answer harmful algal bloom or trophodynamic questions. Experimentations along these lines will be undertaken for coastal applications within the framework of the MyOcean project that will start in 2009. A generic coupler will be designed which allow the transfer of information between the ERSEM/POLCOM hydrodynamic/plankton model [Allen *et al.*, 2001] and an IBM (Individual Bases Model) model, allowing bottom up control of the IBM model and top down control of the plankton model. The coupled model performance will be assessed in hindcast mode for the period 1999-2007 in European regional seas. This modelling approach will be generically applicable to sardine and anchovy in other regions.

3. Current limitations of GODAE products and coupling issues

The primary merit of the coupling experimentations performed with GODAE systems has been to provide qualitative indications about the main strengths and weaknesses of the assimilation products regarding their capacity to monitor and forecast the environmental conditions associated to biological activity. A first asset highlighted by the IMBER/GODAE working group is the high resolution in space and time of the GODAE products, a feature which is considered to be essential for realistic coupled hindcast/nowcast simulations. Another key asset is the capacity of the systems to produce ocean circulation reanalyses of homogeneous quality during pluri-annual periods. A number of applications have also shown that coupling biological models to physical hindcasts could reveal fundamental problems in the hydrodynamics solutions, and sometimes lead to degraded simulations of biogeochemical variables [Mc Kinley *et al.*, 2004]. The behaviour of simulated biological tracers can eventually be used as “bio-metrics” indicating how well sub-grid scale processes are described by the assimilation products.

A first common limitation of several GODAE products is the relatively poor representation of the vertical physics in the upper part of the water column, which is known to play a key role in the dynamics of biological tracers. This includes processes involving vertical advection, diffusion or mixed-layer dynamics. Such problems have been reported by Berline *et al.* [2006] in assimilation experiments conducted with a coupled physical-biogeochemical model of the North Atlantic basin at $1/3^\circ$ resolution. In these experiments, the SST and altimetric data assimilated in the model were only constraining the physical state of the coupled system. A detailed inspection of the simulations showed unrealistic increase of the vertical mixing of biogeochemical tracers in the surface layers triggered by hydrostatic instabilities in the analysed states. Due to the abundance of nutrients in deep layers below the euphotic depth, this spurious mixing is responsible for the unrealistic bioactivity observed within unstable water columns. This problem can often be attributed to the assimilation method used to propagate the observed information from the surface to the deeper layers of the model: because of the gaussian assumption made to represent the error statistics in methods like the Kalman filter, the conventional assimilation algorithms are unable to take into account non-linear physical constraints such as the positiveness of vertical density gradients.

Another possible source of difficulty lies in the intermittent nature of the sequential methods used in the GODAE systems to update the physical state, causing temporal discontinuities in the model trajectory. When the increments are physically unbalanced, the model states can experience strong convective adjustments that give rise to unrealistic vertical (advective and diffusive) fluxes of properties. This problem doesn't always manifest clearly in the physical state (e.g. in SST) in part because the effect of spurious vertical fluxes could be counteracted by the assimilation correction. However, the response of the biological tracers can be dramatic, for instance when strong vertical velocities are triggered by the adjustment process. Modifications of the assimilation protocol based on Incremental Analysis Updates [Ourmières *et al.*, 2006] have been implemented in the Mercator operational systems to alleviate this effect, but more rigorous approaches derived from optimal smoother algorithms will be needed in the future.

Regarding GODAE hindcasts, an issue of concern is the volume conservation which is not always rigorously satisfied since the correction of horizontal and vertical velocities by sequential methods may not properly take this physical constraint into account. This issue is expected to affect the conservation of ecosystem variables unfavorably and cause imbalance in the budget of ecosystem variables. A further limitation raised by several IMBER groups is the absence of the surface forcing fields consistent with the estimated physical states in most GODAE products. Up to now, only systems based on 4D-VAR provide forcings that are consistent with the oceanic state estimates. These surface forcings should be made available to biogeochemical modellers too.

Another open question regarding the use of GODAE products to drive IMBER-type models is the choice to be made between on-line vs. offline coupling strategies. Offline coupling is not novel; however, experience with online coupling suggests that the rapid and nonlinear responses inherent to the ecosystems and biogeochemistry of the oceans require detailed horizontal and vertical mixing information. The limitations for offline coupling are not simply related to the need for high-frequency flow-fields and mixing tensors, but careful thought must also be given to the cost-benefit involved in the numerical data sets required to drive

offline global IMBER models at eddy-permitting resolutions. The putative advantages of offline coupling may thus be lost if the costs of I/O more than compensate the computational costs of online coupling. In any case, detailed protocols for offline coupling need to be developed for the multi-GODAE drivers of IMBER models with separate sets of operational set up required for biogeochemical analyses/reanalyses in contrast to any hindcast/nowcast/forecast experiments.

4. The future: requirements and research priorities

In spite of the remarkable progress made in operational oceanography during the past 10 years, it must be recognized that the scientific basis required to develop the whole spectrum of applications linked to marine ecosystems and biogeochemistry needs to be consolidated. A strong involvement and coordination of the research community at international level will be required to further improve the existing systems and to develop new capabilities fitting the users needs. Active research and development activities around the topics mentioned here below will be essential to face this challenge [see also Schiller *et al.*, this symposium].

Observation systems

The lack of relevant observations is probably the most severe factor limiting the expansion of operational systems to biogeochemical and ecosystem applications. It will be necessary to undertake new instrumental developments, adaptations of the current observing systems (e.g. to achieve a better sampling of surface layers where most of the biological activity takes place) and design studies for optimal observation strategies.

As an example, ARGO is key component of the global ocean observing system which has been designed primarily to serve climate research. As a result, the technical specifications adopted for the profiling floats in terms of spatial and temporal sampling are not optimally fitting the requirements of biogeochemical and ecosystem monitoring. In the current mode of operation, the profiling floats are programmed to sample the upper layer of the ocean with a vertical resolution of about 10 m only, which is often insufficient to capture the strong biogeochemical gradients observed in the euphotic layer. A key question for the future will be to know if physical oceanographers are ready to revisit the design of their system in order to share interest with biogeochemical users, or alternatively if the duplication of the existing ARGO system will be more suitable.

In terms of technological innovations, new instruments will be required for in situ observations of geochemical parameters and ecosystem variables resolved by the most complex models. This will include new sensors on profiling floats that will automatically measure biogeochemical parameters such as O₂ and nitrate. The key role of nutrient data to constrain coupled physical-biogeochemical simulations has been evidenced recently by Ourmières *et al.* [2008] in the North Atlantic using the Mercator-Vert assimilative platform. Oxygen, fluorescence and turbidity sensors are being tested on Norwegian ARGO floats in the Nordic seas, giving previously unknown information of the seasonal development and vertical structure of the primary production in the open ocean (Figure 7). Further, the development of automatic acoustic sampling tools such as MAAS (Mid-trophic Automatic Acoustic Sampler) and their large scale deployments for sampling prey organisms will be an important issue for the future.

With regard to space observations, ocean colour missions are vital to ensure continuous and global measurements of sea-surface parameters related to chlorophyll, CDOM, suspended and particulate matter. New orbital concepts such as geostationary missions are being explored by space agencies, with great potential for research and operational monitoring. The advantages of a geostationary orbit for ocean-colour studies include better temporal coverage, the possibility of following episodic events at the scale of hours (e.g. red tides, dissemination of sediments), and improving the match between the temporal scale of satellite observations and those of models. Other potential applications include examining the daily cycle of ocean properties e.g. aerosols, eliminating the effect of clouds from ocean-colour measurements and better observation of planetary waves.

Processing of remote-sensing signal for the coastal zone has been a major research issue in the last decades, and improvements are still needed. For example, the so-called Case 2 waters of the coastal zone covered by

complex diffusive atmosphere make the processing of ocean colour data a difficult task. Specific algorithms are expected to deliver concentrations of inorganic Suspended Particulate Matter (SPM) and Colored Dissolved Organic Matter (CDOM) in addition to chlorophyll, all of these material being hardly distinguishable in the wavelength signals. This separation is necessary for a correct estimation of the phytoplankton compartment, but also because both SPM and DOM may ideally be part of coastal biogeochemical models [Gohin *et al.* 2005]. At the interface with continents, coastal models will require river or atmospheric supplied material. Thus real-time information from specific sensors on major river discharges, nutrients or SPM, should be part of a coastal observing system.

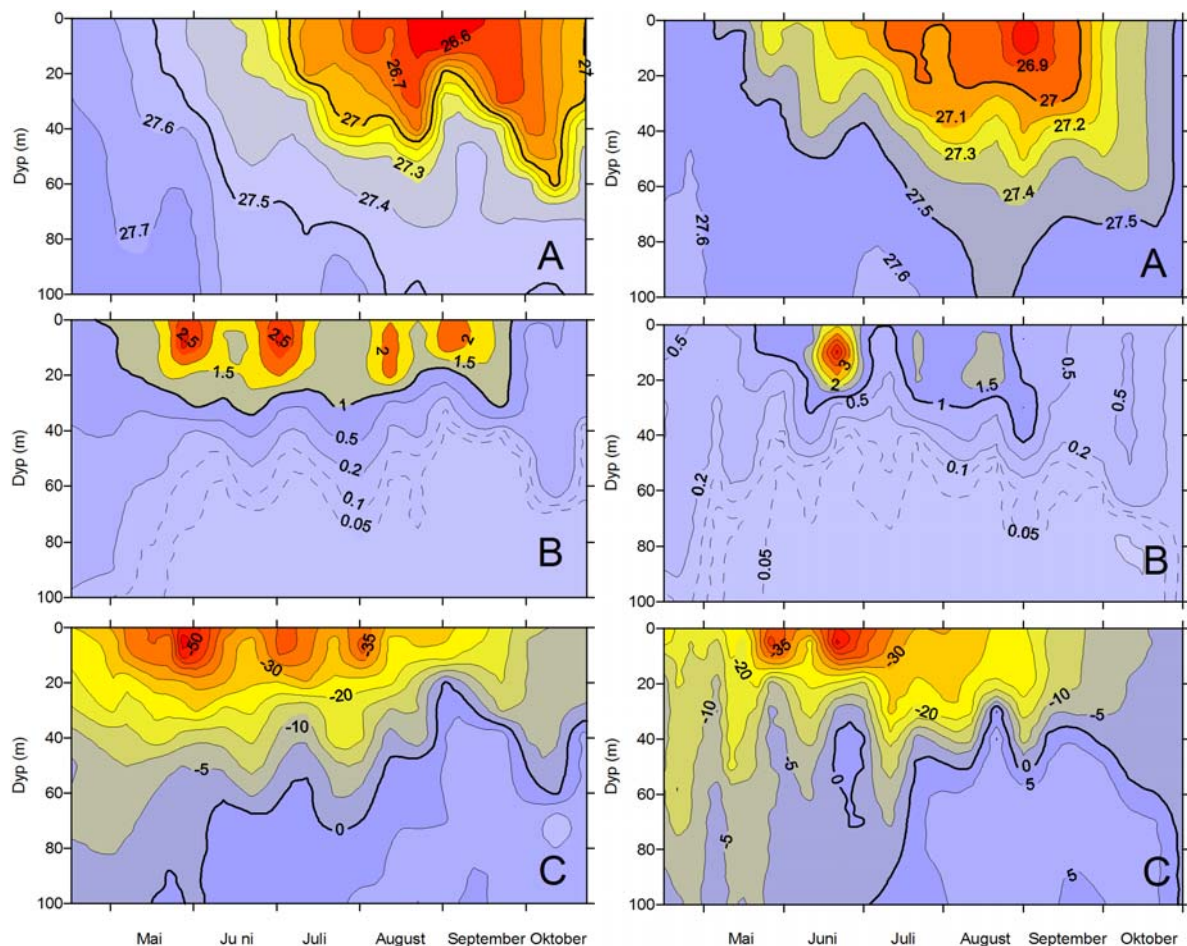


Figure 7. Development, April to October 2006, of the density (A), Chl_a (B) and AOU (a measure for oxygen production, C) from two ARGO floats in the Nordic Seas. (Mork and Svendsen, personal communication)

Integrated biogeochemical and ecosystem modelling, assimilation and assessment strategies

The real-time and systematic provision of core biogeochemical variables such as chlorophyll, nutrient, oxygen concentration, zooplankton biomass etc., in addition to physical parameters already delivered by the GODAE systems, will require not only new tools but also the scientific expertise required to develop and integrate relevant models.

The IMBER community has shown a strong interest and should be a key actor of this process. IMBER relies on the paradigm that the boundary between biogeochemical models of PP and ecosystem models involving different trophic levels is artificial. The goal is thus to evolve toward the concept of holistic “end-to-end” models which can be defined as feeding interactions, nutrient flows and feedbacks in an end-to-end food web of primary producers, consumers and decomposers. Quantifying the predictability of the ecosystems

and biogeochemistry will be another big challenge and important goal. Sensitivity to initial conditions and the role of initial conditions in generating ensembles and chaotic solutions as well as boundary-forced predictability will have to be explored.

The implementation of assimilation methods into the GODAE systems has been much inspired by operational meteorology practices, and guided by applications to ocean circulation models. However, the integration of observations into ocean models is still far from being optimal with regard to the dynamical nature of the estimated flow fields. In the perspective of coupling with IMBER-type models, progresses will be necessary into the following directions:

- with regard to physics, it will be necessary to reconsider the importance of the temporal dimension in the assimilation process; indeed, intermittent corrections in the current systems are a major source of sub-optimality which may have dramatic impact on biological tracers; therefore, the transition to fully 4D assimilation methods (by developing either 4DVAR or smoother algorithms) will be essential to improve not only the physics (e.g. estimates of the mixed layer depth) but also its impact on biology ;
- with regard to biology, the interactions between biological state variables are often subjected to non-linear behaviour and the resulting distributions of errors in biological systems are typically non-gaussian ; this will require major revisions of the assimilation framework used for the oceans' physics. The integration of inequality constraints (such as the positivity of tracers, vertical density gradients etc.) in the assimilation process should also yield more optimal estimates of biological state variables [Lauvernet *et al.*, 2008].

Finally, strategies for quantitative evaluation of hindcast, nowcast and forecast model skill (versus persistence) will be critical to determine the model's predictive power. The protocols developed for GODAE products have thus far not considered IMBER as one of their user groups. Much thought will be required in developing metrics for validation and inter-comparison and in quantifying uncertainties in the IMBER products made available to user communities. Novel approaches based on advanced statistical methods open new perspectives to explore the nature and spatio-temporal distribution of errors in complex ecosystem models [Allen *et al.*, 2008]. Validation of end-to-end models such as NEMURO [Fujii *et al.*, 2006] and pelagic ecosystem models such as SEAPODYM [Lehodey *et al.*, 2008] will be much more challenging than the lower-trophic ecosystem and biogeochemical models. Continued progress can only be accomplished by using existing models for generating end-user products and driving validation data gathering by observation system simulation experiments and by close interactions between IMBER and GODAE.

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