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QUARTERLY Newsletter

Mercator Ocean

Ocean Forecasters

Example of the NEMO ORCA mesh.
Credits: http://www.nemo-ocean.eu/

SPECIAL ISSUE

NEMO-MyOcean

Editorial – October 2012 – The NEMO European Ocean Modeling platform for research and operational applications

Greetings all,

This issue is dedicated to NEMO http://www.nemo-ocean.eu/ which is the European Modeling platform for ocean research and operational applications. NEMO (Nucleus for European Modeling of the Ocean) is a software for numerical simulation of the ocean. NEMO is available under free license and improves in order to stay as near as possible to technical needs and breakthroughs of research and operational projects. NEMO is in use in a wide variety of applications which main objectives are oceanographic research, operational forecasts of the ocean and seasonal weather forecasts or climate change studies. The NEMO ocean platform is for example widely used in the framework of the Myocean project. Its three main components are: the “blue ocean” NEMO-OPA which simulates the dynamics, the “white ocean” NEMO-LIM which simulates the sea-ice and the “green ocean” NEMO-TOP which simulates the biogeochemistry. Some other components allow data assimilation or grid nesting. NEMO also includes interfaces for ocean-atmosphere coupled configurations using the OASIS coupler. A number of “reference configurations” are also available to set up and validate implementations, so as pre- and post-processing tools. All of NEMO and its documentation are available on the NEMO website http://www.nemo-ocean.eu/.

The two first papers of the present newsletter are written by Levy et al. and are presenting the NEMO ocean code: What does NEMO produces? What are the applications? Its limitations as well as the NEMO Consortium and its organization.

Then, the next paper by Gehlen et al. is discussing the coupled physical-biogeochemical ocean modeling using NEMO components. Physical components of the NEMO system have been used with success in biogeochemical research coupled to four biogeochemical models of varying complexity: PISCES (provided with the passive tracer module TOP), MEDUSA, BFM/PELAGOS and HadOCC.

Next paper by Bouttier et al. is developing the progress toward a data assimilation system for NEMO and discusses the first achievement steps that have been carried out to set up a data assimilation system associated to NEMO. This data assimilation system is schematically made of three subcomponents: Interface Components, Built-in Components and External Components.

Next paper by Dombrowsky et al. is dealing with NEMO within the MyOcean Monitoring and Forecasting Centers (MFCs) context. During the MyOcean project, all the Monitoring and Forecasting Centers (MFCs) have implemented operational model configurations in order to cover the global ocean with a focus on the European waters. The NEMO ocean platform is used is most of the MFCs.

Ferry et al. are then dealing with the use of NEMO in the MyOcean eddy permitting Global Ocean reanalyses. They illustrate the use of NEMO ocean engine in three eddy permitting global ocean reanalyses and one reference simulation of the altimetric era (1993-2009) carried out in the framework of the MyOcean EC funded project. The ORCA025 model configuration (1/4° horizontal resolution) of the NEMO code is used both for the reanalyses and the non-assimilative reference simulation.

Beuvier et al. are then writing about MED12, i.e. the oceanic component for the modeling of the regional Mediterranean Sea earth system. It is the new regional configuration of the Mediterranean Sea of the ocean general circulation model NEMO. The development of MED12 is made in the continuity of the evolution of the French modeling of the Mediterranean Sea, following OPAMED16, OPAMED8 and NEMOMED8.

Guilyardi et al. are finally dealing with NEMO for climate modeling. Indeed, the ocean is a central component of the climate system, providing long term memory and contributing to the variability of heat and CO2 uptake on a number of time scales. NEMO global configurations are used in coupled mode by a large fraction of the climate modeling community.

We will meet again next year in January 2013. We wish you a pleasant reading,

Laurence Crosnier, Editor.

CONTENT

NEMO FOR DUMMIES

By C. Lévy[(1)] and R. Benshila[(1)]

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Abstract

As stated in the title, this paper briefly describes NEMO's basics, its scope and limitations.

Introduction

NEMO (Nucleus for European Modeling of the Ocean) is a software for numerical simulation of the ocean. Its three main components are: the "blue ocean" NEMO-OPA which simulates the dynamics, the "white ocean" NEMO-LIM which simulates the sea-ice and the "green ocean" NEMO-TOP which simulates the biogeochemistry. Some other components allow data assimilation or grid nesting. NEMO also includes interfaces for ocean-atmosphere coupled configurations using the OASIS coupler. A number of "reference configurations" are also available to set up and validate implementations, so as pre- and post-processing tools. All of NEMO and its documentation are available on the NEMO website http://www.nemo-ocean.eu/.

NEMO is available under free license and improves in order to stay as near as possible to technical needs and breakthroughs of research and operational projects.

What does NEMO produces? What are the applications?

Running NEMO generates some model outputs: three-dimensional fields on the configuration's grid such as temperature, salinity, velocities, ice cover or plankton concentration, and their evolution in time. These outputs can be used to compare with real data (in situ or satellite measurements) in order to check results, improve our knowledge of physical and biogeochemical processes in the ocean and quantify their importance. These outputs can also be used as forecasts for the ocean, or as contribution (in ocean-atmosphere coupled models) to seasonal forecasts or climate studies.

NEMO inside: appropriate use, limitations and borderlines

This paragraph gives details on the physical and numerical choices made in NEMO in order to highlight characteristics and limitations of the platform. For more details, see: http://www.nemo-ocean.eu/About-NEMO/Reference-manuals.

NEMO-OPA

Prognostic variables are the three-dimensional velocity field, a linear or non-linear sea surface height, the temperature and the salinity. In the horizontal direction, the model uses a curvilinear orthogonal grid and in the vertical direction, a full or partial step z-coordinate, or s-coordinate, or a mixture of the two.

The distribution of variables is a three-dimensional Arakawa C-type grid. Various physical choices are available to describe ocean physics, including Turbulent Kinetic Energy TKE, Generic Length Scale GLS and K-Profile Parameterization KPP schemes for vertical physics. Within NEMO, the ocean is interfaced with a sea-ice component (LIM v2 and v3), passive tracer and biogeochemical components (TOP) and, via the OASIS coupler interface, with several atmospheric general circulation models. It also allows two-way grid nesting via the AGRIF software.

The dynamical part of NEMO solves the primitive equations, i.e. the Navier-Stokes equations along with a nonlinear equation of state, which couples the two active tracers (temperature and salinity) to the fluid velocity, plus some additional assumptions made from scale considerations:

(1) Spherical earth approximation: the geopotential surfaces are assumed to be spheres so that gravity (local vertical) is parallel to the earth's radius.

(2) Thin-shell approximation: the ocean depth is neglected compared to the earth's radius.
(3) Turbulent closure hypothesis: the turbulent fluxes (which represent the effect of small-scale processes on the large-scale) are expressed in terms of large-scale features.
(4) Boussinesq hypothesis: density variations are neglected except in their contribution to the buoyancy force valid if not too small scales to depict.
(5) Hydrostatic hypothesis: the vertical momentum equation is reduced to a balance between the vertical pressure gradient and the buoyancy force.This removes convective processes from the initial Navier-Stokes equations and so convective processes must be parameterized instead. The hydrostatic hypothesis is not valid for very small scales. Non hydrostatic hypothesis is required for highly convective flows and may be important in getting the details right for flows associated with high frequency internal waves.
(6) Incompressibility hypothesis: the three dimensional divergence of the velocity vector is assumed to be zero.

With these basics and approximations, NEMO is able to deal with a wide panel of space and time scales, starting from 1km and a few hours to larger and global space and time scales. Because of Boussinesq, hydrostatic and incompressibility hypothesis, NEMO is obviously not appropriate for some smaller space and time scales.

Interfaces

Atmosphere - ocean interface: the exchanges are through the kinematic surface condition plus the mass flux of fresh water (the precipitation minus evaporation budget). The dynamic boundary condition, neglecting the surface tension (which removes capillary waves from the system) leads to the continuity of pressure across the interface $z = \eta$. The atmosphere and ocean also exchange horizontal momentum (wind stress), and heat.

Sea ice - ocean interface: the ocean and sea ice exchange heat, salt, fresh water and momentum.

Land-ocean interface: the major flux between continental margins and the ocean is a mass exchange of fresh water through river runoff.

Solid earth-ocean interface: heat and salt fluxes through the seafloor are small, except in special areas of little extent. They are usually neglected in the model. For momentum, the situation is different: there is no flow across solid boundaries. In addition, the ocean exchanges momentum with the earth through frictional processes. Such momentum transfer occurs at small scales in a boundary layer. It must be parameterized in terms of turbulent fluxes using bottom and/or lateral boundary conditions.

Coordinates systems

The equations are written in a curvilinear coordinate system, with a selection of possible vertical coordinates (z lateral boundary-following coordinate system or s terrain-following coordinate system, with the rescaled height coordinate formulation z*. The z* coordinate approach is a non-linear free surface implementation which allows one to deal with large amplitude free-surface variations relative to the vertical resolution, or s*)

For coastal modeling, these vertical coordinates still remain an important limitation towards a good evaluation of local and small scales phenomenon related to the coastal geometry. Using appropriate high resolutions and more studies on the representation of coastal dynamics are underway and will improve these aspects of the platform.

NEMO-LIM

To take the sea-ice into account, the mass balance of sea ice is the key diagnostic for climate simulations. The sea ice mass balance in a given region is determined, on the one hand, by ice growth and melt and by ice import in or export out of the region, on the other hand. The ice volume is the domain integral of ice concentration multiplied by ice thickness, while information on sea ice export requires the ice volume and velocity fields. Coverage, thickness and velocity are the main fields that NEMO-LIM aims at simulating.

The sea-ice component NEMO-LIM computes a series of thermodynamic state variables (thickness, concentration, temperature...) and a horizontal velocity vector. Model variables change with time due to atmospheric and oceanic influence via dynamic and thermodynamic processes.

Ice in NEMO-LIM has a snow cover which largely influences surface albedo and heat conduction. In addition, in order to resolve sub grid scale variations in ice thickness, the ice pack in NEMO-LIM is divided in sea ice categories with specific thickness, coverage and state variables, which move at the same velocity. Note that an interface to CICE model (Los Alamos) is also available even if CICE itself is not part of NEMO.

NEMO-TOP

The tracer transport model implemented in NEMO-TOP deals with passive tracers, which are carried by - but do not affect - ocean circulation. These contrast with active tracers such as temperature and salinity which feedbacks on ocean dynamics.

Passive tracers in the ocean are typically biogeochemical, biological or radioactive. The oceanic circulation carries them, but they may in nature also degrade or interact with one another. Typically, the associated "Source-Minus-Sink" (SMS) terms are also included in the transport equation and depend upon the application.

The NEMO-TOP component includes the tracer transport using the dynamics of NEMO-OPA and the "Source-Minus-Sink" terms (PISCES, etc…). Recently, a large amount of effort has been put on the development of a common interface between transport and various biogeochemistry models (BFM, MEUSA, ERSEM …). The main limitation of this component relates to the resolution of the transport grid, and the physical process taken in account, i.e. the NEMO-OPA capabilities.

NEMO in use: projects overview

Within these limitations, NEMO is in use in a wide variety of applications. Their objectives are oceanographic research, operational forecasts of the ocean and seasonal weather forecasts or climate change studies.

The configurations range from one-dimension vertical profile to global, i.e. covering the whole planet with a 1/12° (~10 km) mesh size, and a number of high-resolution regional configurations: Atlantic Margin Model AMM, near Atlantic IBI, Mediterranean, Peru coast…). Closed basin geometries as well as periodic domains and open boundary conditions are possible.

The configurations can be “forced” by external atmospheric data so as the operational forecasts at Mercator for example, or “coupled” to atmospheric models allowing reciprocal influence as time goes.

A major part of the ongoing work concerns high-resolution coastal configurations, partly a novelty for NEMO, since some of the physical processes in play, so as the vertical gridding choices must be revisited for these studies.

NEMO comparative

NEMO is a major contributor to ocean modeling at international level. Nevertheless, it is not the only partner in the game: numbers of other platforms or models are on the playground, see http://www.ocean-modeling.org/index.php?page=models&model=nom-ocom.

Some studies worked on model comparison to address this tempting question: which one is the best?

Among these studies one can highlight a 2008 report “Intercomparaison de modèles sur le Golfe de Gascogne pour l’année 2004” by G. Reffray et al. comparing results of three platforms (NEMO MARS and SYMPHONIE) used in a coastal configuration (deep ocean and continental shelf). One major contribution of this study has been to identify precisely the defect on each platform: none of them has been fully successful, although each of them includes its own capacity. NEMO is currently involved in the project COMODO gathering all ocean models in use in France, with a main target of improving the different models through intercomparaisons and new developments.

Another mid term project is devoted to this comparison: CORE (Co-ordinated Ocean-Ice Reference Experiments, http://www.clivar.org/organization/wgomd/core) to define the experiments and Ocean Model Intercomparison Project (OMIP) to explore the comparison. For a given topic (coastal, global, forced, coupled…), quality and defects depends on the history of the platform i.e. the acquired expertise, the number of projects exploring the topic, the scales in play, the process taken in account in the interfaces definitions, etc... The ongoing work mainly confirms that there is no absolute ranking between platforms.

NEMO has a long-term experience in global ocean modeling and a shorter one on coastal studies. The recent investment in development for coastal studies has already induced major improvements (tides, vertical grids and coastal processes…). Furthermore, since 2011 NEMO is one of the model involved in the French ANR COMODO (http://indi.imag.fr/wordpress/?page_id=11) which targets to improve numerics of ocean models through academic cases intercomparaisons.

Conclusion

NEMO is widely used in the world and for a large variety of applications. It is also an always-improving platform. The challenge for NEMO is to improve (i.e. stay alive), while remaining useful for research and operational projects. To know more on the NEMO project organisation, you can read the “NEMO organisation” paper, and to discover more on NEMO’s features, applications or results, you should scan through the other papers of this issue. Good readings!

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NEMO ORGANISATION

By C. Lévy[(1)] and R. Benshila[(1)]

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NEMO prerequisites

Building a robust and reliable ocean numerical platform is a long-term goal. For NEMO, it started during the 1980s, with an initiative in a French research laboratory (LOCEAN), with a focus on large scales studies and on climate modeling. First called A3D, and later on OPA, its use was disseminated in the research community through various projects (e.g. CLIPPER) before being adopted by Mercator as a base for all its operational prototypes. Doing so, it naturally gathered expertise and energy to improve, until the 2000s, where the need for a formal organization became obvious. At this stage, the platform was already in use in number of projects for oceanic research, operational ocean forecasts, seasonal prediction and climate change studies. It took some time to clarify the needs and expectations for each of those. This time has been very useful since it now gives its bedrock to the project. Essentially, NEMO is good enough to be useful for a wide diversity of projects, and our knowledge of the ocean is small enough to need progress and evolutions within NEMO in the future.

As a consequence, the NEMO Consortium was build with these objectives, pointing out the need for experts to support the platform (i.e. the NEMO system Team) and its evolutions, so as the need for coherency (a unique reference version, the readability of the code, its technical performances associated to the scientific improvements…) in order to ensure the sustainable development of the platform. As written in the Consortium Agreement preamble, "The purpose of this agreement is to set up appropriate arrangements for the successful and sustainable development of the NEMO System as a well-organised, state-of-the-art ocean model code system suitable for both research and operational work."

NEMO Consortium

At this point, the NEMO Consortium includes six institutions (in alphabetical order): CMCC (Italy), CNRS (France), INGV (Italy), Mercator Océan (France), Met-Office (GB), NERC-NOC (GB) sharing a common interest on the long term. They all need NEMO and its future improvements for their long-term projects. Indeed, choosing a numerical platform in this case induces long-term investment to gain the expertise to use and change the platform. On the other hand, a given project does not work on all components of the platform so that improvements from other projects are needed. Therefore, there is no short-term motivation to join the Consortium. For an institution, it is a long-term investment towards the progress and reliability of the platform in use. These are the basis on which the Consortium has been organised. Mainly:

- NEMO is under free licence (meaning that projects can use it freely, and also that all developments should come back into the platform);
- NEMO has a unique reference version, evolving in time, available through a unique portal (http://www.nemo-ocean.eu/);
- The System Team (composed of experts of the Consortium members) is in charge of the development and support of NEMO;
- Each institution of the Consortium is involved in ensuring the System Team's manpower (at least one man-year per institution).

The NEMO Consortium has set up several Committees and regular meetings.The Steering Committee is the consortium's decision-making and arbitration body. It includes one representative of each Consortium member, the Project Manager and Scientific Leader. It meets once a year.

The Developer's Committee's main role is to give advice on research developments plan. It includes the Executive Board (the NEMO Project Manager, NEMO Scientific Leader and a NEMO System Team Officer, from each consortium member); the External Experts chosen are scientists who, in particular, are able to give advice on research plans and who can co-ordinate developments of NEMO outside the NEMO System Team; and Consortium Experts chosen to cover the different fields of expertise required by NEMO, and with the appropriate level of responsibility to enable decisions to be made. The NEMO System Team members are also invited to the meeting, which takes place once a year.

The Users Meeting facilitates exchanges within the community, from the projects to the System Team and vice versa. It is open to all users and the presence of all the System Team is required. It includes presentations from users, projects and System Team and open discussions on problems, solutions and improvements. It is organised by the System Team and meets once a year.

NEMO System Team

The NEMO System Team is in charge of the NEMO reference, and its evolutions. The members of this team (about 20 people at this stage) are experts on the NEMO system: within their institution, they are involved in projects using and developing NEMO. One of its specificity is to be dis-

disseminated between the different institutions and locations, allowing covering a large range of applications and requiring close interactions (via regular teleconference, dedicated working groups …). Aside from the recurrent work, the developments are listed and scheduled in a yearly work plan discussed within the Developer's Committee and validated by the Steering Committee.

This work may include:

- Incorporation into NEMO of new developments (scientific or technical)
- Re-organisation of code to improve its readability, orthogonality or structure
- Optimisation of NEMO on the computers available in the consortium
- Maintenance of the paper and on-line documentation
- Configuration control of the available versions of NEMO
- Testing and release of new versions (typically once or twice a year)
- Making NEMO readily available to the scientific community and members of the consortium
- Providing assistance to users
- Support for user meetings
- Assistance in scientific development in an area of high priority

The NEMO reference (the platform, its environment and documentation) is available through a unique focal point, the NEMO website (http://www.nemo-ocean.eu/). The history and track of changes is available using a version control system. Each year the whole System Team meets during three days to merge all validated developments and produce the new release.

The members of the System Team are users and developers of NEMO. Thereby, they have the right information and experience to elaborate the right path toward a relevant and sustainable development of the platform.

NEMO as seen by projects and users

To gain access to NEMO, a user must register on the web site. He will then have access to the entire system: the code, its history, the documentation, the publications, the mailing lists, the FAQ pages, the forums, and the list of all projects. The user also needs to fill the bibliography with his own articles using NEMO, which is an efficient way to support the work of the System Team. Two emailing lists are available: (nemo_st@locean-ipsl.upmc.fr) in order to contact the System Team, and (nemo@locean-ipsl.upmc.fr) in order to contact all the users. A TRAC system is also available to open tickets if a bug is found.

Some training courses are also organised for new users or on specific topics. The Users meetings are also an opportunity for users to meet the System Team and exchange on their needs and difficulties. Whereas NEMO is the starting point of a project, the user's application is an intricate mix between NEMO and the chosen configuration (geographical domain, mesh size, boundary conditions…). Once facing a trouble, one has to separate those two to find its origin. Indeed, there is no way to check all possible configurations, and NEMO itself only supports its so-called "reference configurations" (http://www.nemo-ocean.eu/Using-NEMO/Configurations). These reference configurations are chosen to represent a wide variety (global, low and high resolution, regional with open boundaries, including sea-ice and biogeochemistry…). Since each release is validated on all the reference configurations set, it allows being quite confident for all the other user-build configurations.

Conclusion

Whereas the history of NEMO started quite a long time ago in the 1980s, the NEMO Consortium is more recent (signed in 2008). Since its birth, NEMO has grown up: it started with an ocean dynamical component only, and now includes the sea-ice, the biogeochemistry, the interface for ocean-atmosphere coupling, a data assimilation component and the ability for nested grids using AGRIF. The number and diversity of projects using NEMO allows a good confidence in its ability to perform properly at this stage. Nevertheless, dealing with such a large spectrum of scales (spatial and temporal) still remains a challenge, which can be faced by close interactions between the NEMO team and users.

Considering its organisation (the Consortium), the choice of a relatively light project structure, in which the major part of manpower is devoted to experts in numerical ocean modeling (i.e. the System Team) seems to be adequate for the present and near future.

Considering its evolution, the System Team will be the appropriate group, able to deal with the yet unknown ideas and discoveries of research, operational projects and High Performance Computing challenges.

COUPLED PHYSICAL-BIOGEOCHEMICAL OCEAN MODELING USING NEMO COMPONENTS

By M. Gehlen[(1)], A. Yool[(2)], M. Vichi[(3)], R. Barciela[(4)], C. Perruche[(5)], A. El Moussaoui[(5)] and C. Ethé[(1)]

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Abstract

The growing awareness for the potential of large scale changes in marine ecosystems in response to climate change, ocean acidification and deoxygenation has triggered the rapid development of marine biogeochemical models. These models allow quantifying the contribution of marine biogeochemistry to regulating Earth's climate, assessing anthropogenic impacts on marine ecosystems and projecting the future evolution of the 'green' ocean in the Anthropocene. Physical components of the NEMO system have been used with success in biogeochemical research coupled to four biogeochemical models of varying complexity: PISCES (provided with the passive tracer module TOP), MEDUSA, BFM/PELAGOS and HadOCC. The range of possible applications is large spanning from the assessment of ocean biogeochemical state and its natural variability to climate studies (past and future). It is illustrated here by selected examples of applications for biogeochemical and climate research, as well as operational oceanography. Biogeochemical models are briefly described and output is exemplified for global nutrient distributions (e.g. dissolved inorganic nitrogen), as well as for chlorophyll and integrated primary production. The qualitative comparison between model output and climatological data demonstrates the skill of models to reproduce large scale features of biogeochemical distributions and highlights the importance of the underlying physical model.

Introduction

Biogeochemistry refers to the study of exchange fluxes or pathways of chemical elements between Earth system reservoirs, as well as processes within these reservoirs mediated by biota. In other words, the discipline deals with pathways of cycling matter between the organic and inorganic compartments of the ocean in the case of marine biogeochemistry. Relative to large-scale physical modeling, marine biogeochemical modeling is a relatively young discipline within ocean research. It has witnessed a rapid development over the past 25 years leading from box models (e.g; Broecker and Peng, 1986; Shaffer and Sarmiento, 1995), over relatively simple mixed layer models (Fasham et al.1990) to increasingly complex 3D representations of lower trophic levels of marine ecosystems coupled to ocean general circulation models (e.g. Aumont et al., 2006; Maier-Reimer et al., 1996; Moore et al., 2004, Vichi et al., 2007a, b; Yool et al., 2011). The vitality of the discipline originates - at least in part - from the awareness of the contribution of oceanic biogeochemical processes to the mean state and variability of the wider climate system.

The combination of global warming and concomitant changes to the ocean physical environment, along with ocean acidification, eutrophication, deoxygenation, as well as the ongoing exploitation of living marine resources are driving major changes in marine biogeochemical cycles and put marine ecosystems at risk (e.g. Caldeira and Wickett, 2003; Bopp et al., 2005; Keeling et al., 2010; Lehodey et al., 2010; Steinacher et al., 2010; Gehlen et al., 2011; Stock et al., 2011). Biogeochemical modeling, along with observational programs and experimental studies is a central tool for (1) understanding marine biogeochemistry as a component of the Earth's climate system; (2) quantifying anthropogenic impacts on marine systems; and (3) projecting trends in ocean biogeochemistry against the backdrop of a changing global environment.

Here we present an overview of current global biogeochemical applications using NEMO components along with identifying scientific teams in charge. The NEMO system is presently structured around five principal components: the physical model OPA (Madec 2008); the sea-ice model LIM (Fichefet and Morales Maqueda, 1997), the passive tracer module TOP; the adaptive mesh refinement software AGRIF; and the data assimilation component NEMO_TAM (http://www.nemo-ocean.eu/). In turn, TOP consists of three independent components that account for transport (TRP, advection and diffusion routines), sources and sinks (SMS, biogeochemistry) and off-line configurations. In its standard set-up, TOP includes the biogeochemical code PISCES (Aumont and Bopp, 2006), along with modules for chlorofluorocarbons and bomb C14. Biogeochemical studies are, however, not restricted to simulations with PISCES, but include examples of applications based on MEDUSA (Yool et al., 2011), BFM/PELAGOS (Vichi et al., 2007 a, b) and HadOCC (Palmer and Totterdell, 2001). Similarly, not all groups use the sea-ice model LIM (Séférian et al., 2012) or data assimilation schemes. Biogeochemical models are either coupled on-line (i.e. run in parallel with) or off-line (i.e. run subsequently to) with the physical-components of the NEMO system. The off-line mode decreases computational burden. The variety of biogeochemical models used within NEMO corresponds to the diversity of research questions to address. The following sections illustrate applications from operational oceanography and from climate research. It provides a brief description of biogeochemical models, and overview of the configurations used in published studies, along with some standardized examples of model output.

Coupled physical-biogeochemical model configurations

Biogeochemical models suitable for large scale applications are by necessity simplifications of the complex network of biological interactions driving the cycling of matter between reservoirs of the Earth system. They are distinguished from ecological models by their focus on the processes that are most relevant to biogeochemical cycles rather than the organisms concerned. Examples of these processes include: primary production, export production, respiration, production and dissolution of biogenic silica and carbonates, denitrification, nitrogen fixation and many more. Rather than aiming at a detailed representation of the marine ecosystem, these models group organisms together according to their specific 'function' in the corresponding biogeochemical cycle. These so-called 'Plankton Functional Types' (PFTs) are central to modern state-of-the-art biogeochemical models (Le Quéré et al., 2005; Hood et al., 2006). In addition, these models frequently use organism size to differentiate between different PFTs. Size influences both bottom-up (e.g. nutrient acquisition) and top-down (e.g. control by predators) regulation in plankton ecosystems, with different sizes of organisms favored under different conditions. For instance, fast-growing small cells tend to dominate under oligotrophic conditions (low-nutrient; such as those in ocean gyres) because they can uptake nutrients more efficiently. Slower-growing large cells, in contrast, are favored under eutrophic conditions (nutrient-replete, such as those that prevail at the end of winter mixing or close to rivers); these groups can achieve large biomass values because they are controlled less tightly by slow-growing predators. An important simplification frequently used in biogeochemical models stems from the observation of near-constant elemental ratios (C:N:P=106:16:1) of fluxes within the marine food-web (Redfield, 1963) when averaged over space and time (e.g. seasonal cycle). This simplification allows models to use a single basic currency (e.g. carbon, nitrogen or phosphorus) and to derive the fluxes of the remaining elements from fixed stoichiometric relationship, without the need to include additional, computationally costly state variables. Models based on this principle are often called "Redfieldian". Other models are instead based on variable stoichiometry, which allows the ratios between the major elements to vary depending on environmental conditions and physiological requirements. While biogeochemical models are largely based on empirical parameterizations, rather than on first order principles comparable to those involved in physical models, they nevertheless mostly share a common conceptual framework. This holds for the models described below, but they do exhibit what might be seen as a progression in complexity from HadOCC and MEDUSA, to PISCES to BFM/PELAGOS. Besides the discrepancies in the number of PFTs, the major difference is that HadOCC and MEDUSA are more strictly "Redfieldian", while PISCES allows prognostic elemental ratios and the BFM/PELAGOS is fully stoichiometric. The following sections provide an overview of each of the models considered here, while Table 1 compares important common aspects.

	PISCES	MEDUSA-1.0	BFM/PELAGOS	HadOCC
biogeochemical cycles	N (NO_3, NH_4), Si, Fe, P, C [(1)], O_2	N, Si, Fe	N (NO_3, NH_4), Si, Fe, P, C [(1)], O_2	N (NO3, NH4), C[(1)]
autotrophic PFTs	nanophytoplankton, diatoms	small (picophytoplankton) large (diatoms)	picophytoplankton, nanophytoplankton, diatoms	phytoplankton
heterotrophic PFTs	micro-, mesozooplankton	micro- and mesozooplankton	nano-, micro-, mesozooplankton and bacterioplankton	zooplankton
BGC functions represented without explicit PFT	$CaCO_3$ production/ dissolution N-fixation/denitrification	$CaCO_3$ production	biogenic Si dissolution biogenic Fe dissolution	$CaCO_3$ production
external inputs	river carbon & nutrients aeolian Fe, Si, N sedimentary Fe source	aeolian Fe sedimentary Fe (optional)	aeolian Fe	
references	Aumont and Bopp (2006) Gehlen et al. (2007) Tagliabue et al. (2011) Séférian et al. (2012)	Popova et al. (2010) Yool et al. (2011) Popova et al. (2012)	Vichi et al. (2007ab) Vichi and Masina (2009) Vichi et al. (2011) Patara et al. (2012b)	Palmer and Totterdell (2001) Hemmings et al. (2008)

[(1)] dissolved and particulate, prognostic alkalinity, $CaCO_3$ production and dissolution, CO_2 chemistry fully resolved.
Table 1: Overview of biogeochemical models

PISCES

The PISCES (**P**elagic **I**nteraction **S**cheme for **C**arbon and **E**cosystem **S**tudies) model simulates biogeochemical cycles of oxygen, carbon and major nutrients controlling phytoplankton growth (nitrate, ammonium, phosphate, iron, silicic acid). The model has 24 state variables. The model distinguishes between two size classes of phytoplankton (diatoms and nanophytoplankton) and zooplankton (micro- and mesozooplankton). Phytoplankton growth depends on light, temperature and the external availability of nutrients. Prognostic variables of phytoplankton are total biomass in C, Fe, Si (for diatoms) and chlorophyll and hence the internal Fe/C, Chl/C, and Si/C ratios. For zooplankton, all these ratios are supposed constant and thus, the total biomass in carbon is the only prognostic variable (e.g. the model is "Redfieldian"). The bacterial pool is not modeled explicitly. The PISCES standard version distinguishes three non-living organic carbon compartments: semi-labile dissolved organic carbon (DOC) with timescales of several weeks to several years, two size classes of particulate organic carbon (small and big particles). While the C/N/P composition of dissolved and particulate matter is tied to Redfield stoichiometry, the iron, silicon and carbonate contents of the particles are computed prognostically. Next to the three organic detrital pools, carbonate and biogenic siliceous particles are modeled. In the standard model version, the parameterization of particle flux distinguishes two particle size classes: “small” with a constant prescribed sinking speed of 3m/d and “large” with a sinking speed increasing with depth. Ballasting of fluxes by biogenic Si and/or carbonate is not taken into account. PISCES simulates dissolved inorganic carbon and total alkalinity (carbonate alkalinity + borate + water). The CO_2 chemistry is computed following the OCMIP protocols (http://www.ipsl.jussieu.fr/OCMIP). Cycles of phosphorus and the nitrogen are decoupled by nitrogen fixation and denitrification. Boundary fluxes account for nutrient supply from three different sources: atmospheric dust deposition of Fe, Si and N (Aumont et al., 2008), rivers for macronutrients, dissolved carbon, and alkalinity (Ludwig et al., 1996) and inputs of Fe from marine sediments (Johnson et al. 1999; de Baar and de Jong 2001). The model is fully described in Aumont and Bopp (2006).

The PISCES model was developed as a flexible tool for global biogeochemical and carbon cycle studies (including ocean acidification) covering a range of time scales from glacial-interglacial cycles to future projections. Despite its relatively simple representation of first trophic levels of the marine ecosystem, it is successful in reproducing ocean productivity and biogeochemical cycles across major ocean provinces (Schneider et al., 2008; Steinacher et al., 2010). The model has been used for a variety of studies coupled both on-line and off-line to OPA from resolution ranging from 1/4° to 2°. It is part of the IPSL Earth system model and simulations contributed to the previous (e.g. Friedlingstein et al., 2006; Schneider et al., 2008; Roy et al., 2011; Steinacher et al., 2010), as well as to the current Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/) assessment report (Séférian et al., 2012). Moreover, PISCES has been integrated to the Mercator-Océan operational system (El Moussaoui et al., 2011). The model standard version is freely available through the NEMO website.

MEDUSA

MEDUSA-1.0 (**M**odel of **E**cosystem **D**ynamics, nutrient **U**tilisation, **S**equestration and **A**cidification) is a size-based, intermediate complexity model that divides the global plankton community into “small” and “large” portions, and resolves 11 state variables distributed between the nitrogen (6), silicon (2) and iron (1) cycles. Nutrients in MEDUSA are represented by three state variables: total dissolved inorganic nitrogen (the sum of all nitrogen nutrient species), dissolved silicic acid and total iron (all of the latter is bioavailable but a fraction is also available to be scavenged).The “small” portion of the ecosystem is intended to represent the microbial loop of picophytoplankton and microzooplankton, while the “large” portion covers microphytoplankton (specifically diatoms) and mesozooplankton. The intention of MEDUSA is to separately represent small, fast-growing phytoplankton that are kept in check by similarly fast-growing protistan zooplankton, and large, slower-growing phytoplankton that are able to temporarily escape the control of slow-growing metazoan zooplankton. Both modelled phytoplankton groups are limited by the availability of light and nitrogen and iron nutrients, with the diatoms additionally constrained by the occurrence of silicic acid. Diatoms and non-diatoms have separate, prognostic chlorophyll variables to permit shifts in the C:chl ratio, and the diatoms are described with an additional silicon variable to allow a dynamic Si:N ratio. MEDUSA is otherwise “Redfieldian” with other elements such as iron and carbon (implicit only) coupled to the nitrogen cycle via fixed stoichiometries. The non-living particulate detritus pool is similarly split between small, slow-sinking particles that are simulated explicitly, and large, fast-sinking particles that are represented only implicitly. Remineralization of the latter particles uses a ballast scheme that includes “protection” of sinking organic material by associated biogenic minerals, opal and calcite (Armstrong et al., 2002). Calcification in MEDUSA is represented via a function of latitude (higher at the equator, lower at the poles) and large detrital particle production. Since iron is scavenged from the water column, an important regulatory process in MEDUSA is the geographically-variable resupply of iron by aeolian dust, which acts to limit production in so-called high-nutrient-low-chlorophyll (HNLC) regions. See Yool et al. (2011) for a full description of MEDUSA-1.0.

Thus far, MEDUSA has only been simulated within on-line instances of the NEMO physical model at resolutions of 2°, 1° (Yool et al, 2011) and 1/4° (Popova et al., 2010; Popova et al., 2012). A revised version of the model, MEDUSA-2.0, is in development for ocean acidification studies and additionally includes the biogeochemical cycles of carbon, alkalinity and oxygen, and processes such as air-sea gas exchange and dynamic calcification. In the results shown here, MEDUSA-1.0 is used in NEMO v3.2 at 1° degree resolution (tripolar grid with equatorial focusing of resolution) with 64 vertical levels.

BFM

The **B**iogeochemical **F**lux **M**odel (BFM; Vichi et al., 2007 a, b, http://bfm.cmcc.it; http://bfm-community.eu) is a numerical tool designed to study stoichiometric relationships in the biogeochemistry of marine ecosystems. The major chemical and biological components that determine the dynamics of the planktonic ecosystem are described in terms of theoretical concepts of chemical functional families and living functional groups (Vichi et al., 2007 a, b). The model extends and advances the original philosophy of ERSEM (European Regional Seas Ecosystem Model; Baretta et al., 1995) in modern coding standards, taking into account both pelagic and benthic dynamics and the coupling between biogeochemical and physical processes in the marine environment. The model is freely available to the scientific community and it is maintained by a consortium of developers similar to the NEMO consortium. The global ocean configuration of the BFM is called PELAGOS (PELAgic biogeochemistry for the Global Ocean, Vichi et al., 2007b; Vichi and Masina, 2009) and uses a subset of the BFM state variables listed in Table 1. The living functional groups simulated by BFM are three unicellular planktonic autotrophs, three zooplankton groups and a separate group for aerobic and anaerobic bacterioplankton. The other biogeochemical tracers are nitrate, ammonium, phosphate, silicic acid, dissolved bio-available iron, oxygen, carbon dioxide, and dissolved and particulate (non-living) organic matter. Diatoms are the largest phytoplankton group and are characterized by high growth rates in cool and nutrient-rich conditions, whereas the nanophytoplankton group is adapted to more nutrient-depleted conditions. Nutrient uptake is parameterized following a modified Droop kinetics which allows for multi-nutrient limitation and variable internally-regulated nutrient ratios. Chlorophyll synthesis is also down-regulated when the rate of light absorption exceeds the utilization of photons for carbon fixation. Net primary production is parameterized as a function of light, temperature, chlorophyll, iron cell-content, and dissolved silicate concentration (Vichi et al., 2007 a). The cell availability of N and P does not directly control photosynthesis, but the subsequent transformation of carbohydrates into proteins and cell material. A portion of photosynthesized carbon is thereby released as Dissolved Organic Carbon (DOC) according to the internal nutrient quota (Baretta-Bekker et al., 1997; Vichi et al., 2007a). Nutrient remineralization by bacteria is controlled by the quality of dissolved and particulate organic matter (i.e. the stoichiometric content of nutrient respect to carbon), which in turn also regulates the competition of bacteria with phytoplankton for dissolved inorganic nutrients. This implies that the fluxes of carbon and limiting nutrients through the food web are not characterized by fixed values and ratios. Finally, the ocean carbonate chemistry is solved with a simplified solution proposed by Follows et al. (2006), and sea-air CO_2 fluxes are calculated using the Wanninkhof (1992) parameterization.

PELAGOS was originally coupled with the previous ocean engine of NEMO and it has now been ported to the current version by CMCC in the framework of the NEMO consortium. The next public release will allow all NEMO users to run the coupling with the BFM in a seamless way downloading the BFM code from its website. PELAGOS has shown skill at reproducing observed climatologies and interannual variability of biogeochemistry and plankton properties (Vichi and Masina, 2009; Patara et al. 2011) as well as responses to anthropogenic emission scenarios (Vichi et al., 2011; Patara et al. 2012b). Its flexibility in terms of material flows and elemental stoichiometry within the lower trophic levels of the ecosystem make is a flexible tool for the detection of ecological responses to climate changes.

HadOCC

The **Had**ley Centre **O**cean **C**arbon **C**ycle Model (HadOCC) is a simple NPZD (nutrient, phytoplankton, zooplankton and detritus), which also includes dissolved inorganic carbon (DIC) and alkalinity in order to complete the carbon cycle (Palmer and Totterdell, 2001). The main nutrient component in HadOCC is nitrate (ammonium is also calculated), and the NPZD variables are modeled in terms of their nitrogen content. Conversion between carbon and nitrogen is performed using fixed Redfield ratios and the model uses a variable carbon to chlorophyll ratio based on Geider *et al.* (1997). HadOCC also has the option to allow phytoplankton growth rates to increase with temperature through use of a Q_{10} parameter (Eppley, 1972; Palmer and Totterdell, 2001), and can use the multi-spectral light penetration model of Anderson (1993). The full HadOCC model equations are given in Hemmings et al. (2008).

HadOCC has been widely used for carbon cycle studies at the Met Office Hadley Centre, and was the ocean biogeochemical component of the first coupled climate-carbon model (Cox et al., 2000), which examined future climate-carbon feedbacks. A development of the model, Diat-HadOCC (Collins et al., 2011), which has a more complex ecosystem, is currently being used in CMIP5 simulations that will contribute to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report. HadOCC has also been coupled to the operational, global configuration of the Met Office's Forecasting Ocean Assimilation Model (FOAM; Storkey et al., 2010), which is based on version 3.2 of the Nucleus for European Modeling of the Ocean (NEMO) hydrodynamic model (Madec, 2008), and the second version of the Louvain-le-Neuve sea ice model (LIM2; Timmermann et al., 2005). At the surface the model is forced by six-hourly mean fluxes from the Met Office global Numerical Weather Prediction model. A key feature of FOAM is the ability to assimilate remotely sensed and in situ observations of temperature, salinity, sea-level anomaly (SLA), sea ice concentration. The data assimilation scheme is of optimal interpolation (OI)-type, and is described in detail in Martin et al. (2007) and Storkey et al. (2010). This capability has been extended to also assimilate biogeochemical observations, such as derived chlorophyll from satellite ocean colour (Hemmings et al, 2008; Ford et al., 2012) and in situ pCO2 (While et al., submitted). The coupled model assimilates chlorophyll derived from the level three merged ocean color data provided by GlobColour. The chlorophyll observations used are global, daily averaged fields (with associated error estimates and confidence flags) and they are assimilated using the nitrogen balancing scheme described in Hemmings *et al.* (2008), which directly updates all (observed and unobserved) biogeochemical model state variables. The observation operator performs a comparison between observations and model values at the observation time by using the FGAT (First-Guess at the Appropriate Time) technique, and this information is very useful for verifying the biological model, in addition to being used in the assimilation. For the merged level three GlobColour products, where no time information is supplied, the chlorophyll observations are taken to be valid at 12:00 UTC. HadOCC is coupled on-line to NEMO, and is called at every model time step (30 minutes). The coupling is effectively one-way, which means that the physical fields drive the biogeochemical variables, but there is no feedback from the biogeochemical to the physical variables. The state variables are all treated as oceanic tracers, and are advected using the Monotonic Upstream Scheme for Conservation Laws (MUSCL) scheme, which forms part of the NEMO code (Lévy et al., 2001). Though chlorophyll is assimilated in this study it is not a state variable within the model, but is derived from phytoplankton biomass using nitrogen to carbon and carbon to chlorophyll ratios. DIC and alkalinity are controlled by the physical and NPZD variables, but have no influence on them. Their inclusion allows the calculation of sea surface pCO_2 and air-sea CO_2 flux, which are in turn affected by atmospheric pCO_2.

The FOAM system is run operationally at the Met Office on a daily basis, producing analyses and six-day forecasts. It is run globally at 1/4° resolution, and in three 1/12° regional configurations, covering the North Atlantic Ocean, Indian Ocean and Mediterranean Sea. However due to the additional computational cost of the HadOCC biogeochemical model, for the purposes of this study a non-operational version of the FOAM system is being run globally, using a 1° tripolar grid with 42 vertical levels.

Physical-biogeochemical model applications

Marine biogeochemical cycles contribute to shaping the mean state and the variability of the climate system. The world ocean exchanges major greenhouse gases, such as CO_2, CH_4, N_2O with the atmosphere. Integrating up to 2008, the ocean has absorbed approximately 1/3 of total anthropogenic emissions of CO_2 (due to activities such as fossil fuel combustion, land-use change and cement production) since the start of industrialization (Khatiwala et al., 2009), making the ocean an important sink for anthropogenic CO_2. This continuous uptake, while decreasing the climatic impact of CO_2, is also the origin of important changes in seawater chemistry referred to as ocean acidification (Gattuso and Hansson, 2011). Chemical changes, along with modifications in ocean circulation in response to global climate change are anticipated to drive major changes in ocean biogeochemistry. It is expected that the reorganization of the ocean carbon cycle in response to warming and ocean acidification will lead to a decline in the efficiency of processes that lead to ocean storage of CO_2, and will result in a positive feedback to atmospheric CO_2 and hence further increased radiative forcing (e.g. Friedlingstein et al., 2006; Gehlen et al., 2011). However, anthropogenic forcing is not the only driver of changes in the marine carbon cycle, as the latter shows variability on interannual to decadal time scales in response to natural climate variability as well. The forecasting of ocean biogeochemistry and carbon cycle over the coming centuries, along with the detection of impacts of global change against the background of natural variability, are key issues in current biogeochemical research.

To capture the interannual and climatic variations, the models described above are used in typically one of two ways. Firstly, in traditional, forced-ocean mode, whereby the model ocean is forced at its surface by fixed external fields of atmospheric properties (temperature, humidity, winds, heat and freshwater fluxes) derived from reanalysis of observations or from atmospheric models. Secondly, as part of a fully-coupled ocean-atmosphere system, or Earth system model (ESM), in which both geophysical fluids are explicitly simulated and are fully interactive. All of the models described above are used in both modes, with the exception of MEDUSA which is currently only used in forced-ocean mode. In the case of forced-ocean simulations, an additional method involves running the biogeochemical model in so-called “off-line mode”, whereby ocean physics is provided by output from a pre-existing simulation rather from one running concurrently with the biogeochemistry. This mode is useful since it has lower computational costs.

The following section presents selected examples of model applications for climate and carbon cycle research. This is followed by a discussion of applications of biogeochemical models for operational oceanography. This is an emerging field of research made possible by the increase in computing power and the development of global close-to-real-time observing systems (e.g. ocean color, Eulerian time-series stations, bioargo). These latter developments aim to provide ocean biogeochemical state estimates (reanalysis) and short-term forecasts mainly for marine resource management.

Biogeochemical cycles

One key use of biogeochemical models is to simulate the magnitude and distribution of major processes in order to better understand the factors that regulate them. To illustrate model performance in this context, Figure 1 compares a standard suite of output from 5 model configurations of the four models discussed here. The plot shows: (1) two ESM configurations (BFM/PELAGOS in CMCC-ESM and PISCES in IPSL-CM5-LR); (2) two coupled physical-biogeochemical configurations (MEDUSA and BFM/PELAGOS); and (3) a coupled physical-biogeochemical configuration constrained by the assimilation of chlorophyll data (HadOCC). Model output is shown for three key variables simulated by all of the biogeochemical modes: Figure 1a, surface dissolved inorganic nitrogen (DIN); Figure 1b, surface chlorophyll; and Figure 1c, vertically-integrated net primary production (NPP). The output shown in each case is the 5-year mean for the period 2001-2005 (inclusive). Modeled DIN is compared to the World Ocean Atlas 2009 climatology (Garcia et al., 2010), while chlorophyll and NPP are compared to satellite-derived observations and estimates for the same period of time.

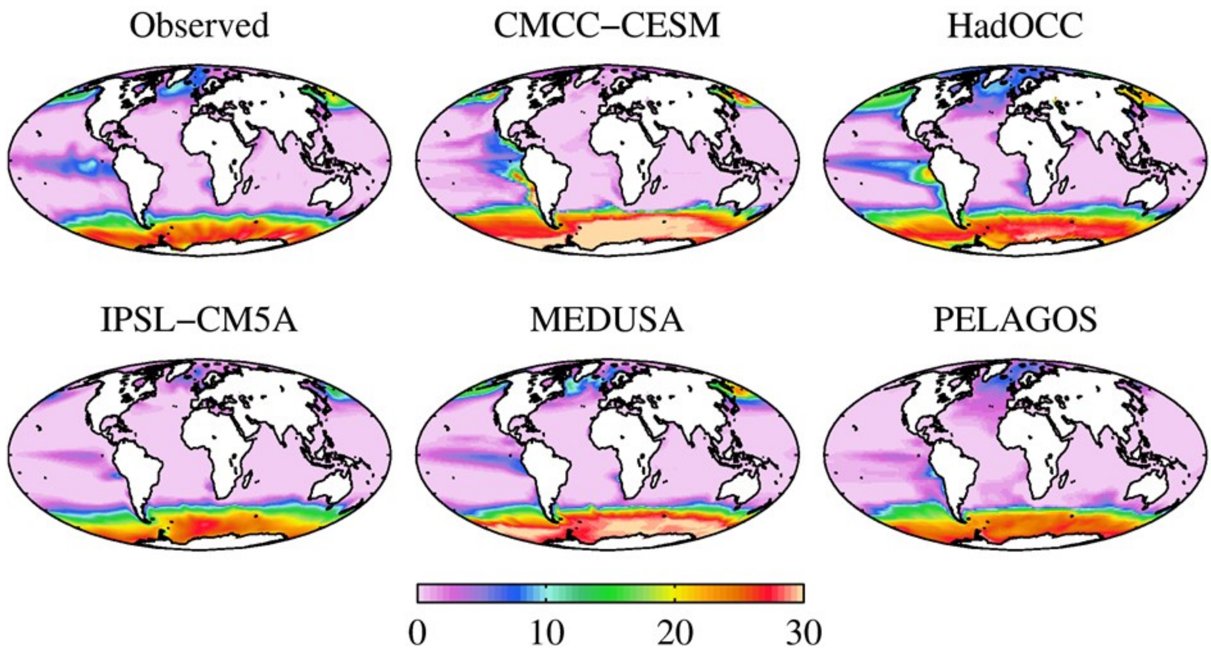


Fig.1 (a) Dissolved inorganic nitrogen (mmol N m^{-3})

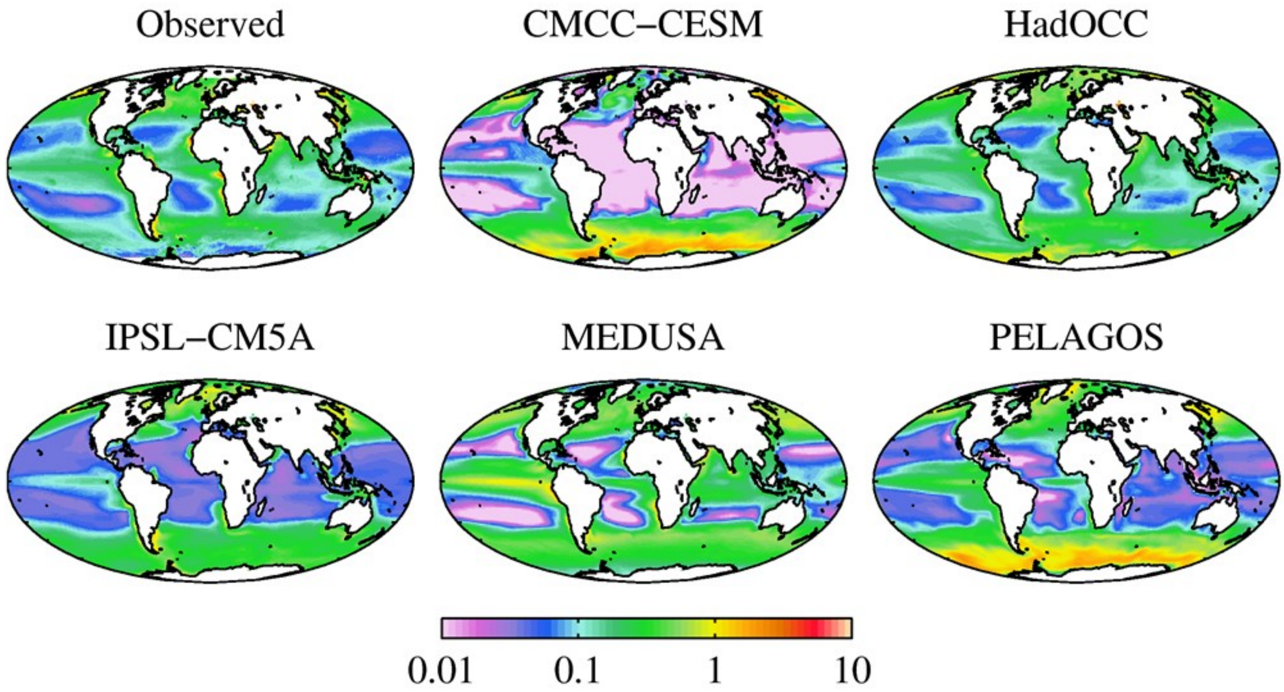


Fig. 1(b) Surface chlorophyll (mg chl m^{-3})

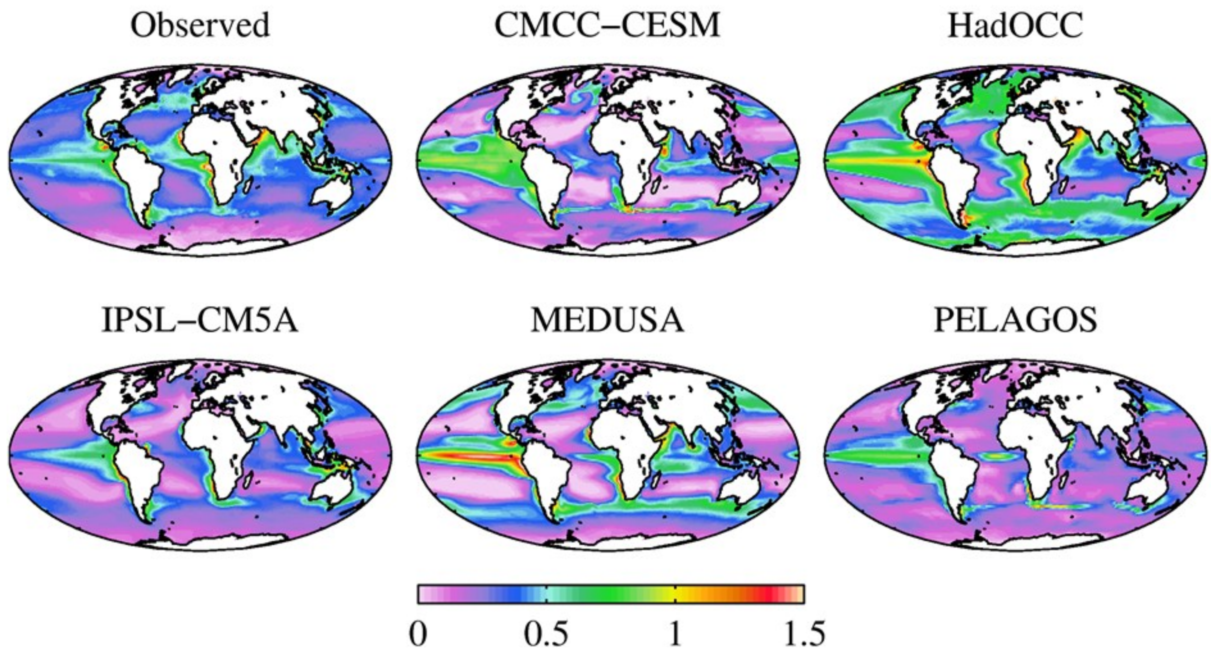


Fig. 1(c) Integrated primary production (g C m^{-2} d^{-1})

Figure 1 : Model output from physical-biogeochemical simulations with BFM/PELAGOS as the biogeochemical component of the CMCC Earth system model (CMCC-ESM), HadOCC embedded in the pre-operational version of FOAM with data assimilation, PISCES as a component of the IPSL Earth system model (IPSL-CM5A), as well as MEDUSA and BFM/PELAGOS in forced model configurations. Model output is displayed as the 5-year mean over 2001-2005 for (a) surface dissolved inorganic nitrogen (DIN); (b) surface chlorophyll; and (c) vertically-integrated net primary production (NPP). The World Ocean Atlas 2009 climatology (Garcia et al., 2010) for DIN, as well as chlorophyll and NPP from satellite-derived observations for the same period of time as model output are included for comparison.

DIN is the reservoir of nitrogen nutrient species (nitrate, nitrite, and ammonium) available to oceanic “plants”, phytoplankton, and plays a critical role in regulating the distribution of productivity in the ocean. DIN is consumed in the sunlit surface ocean by phytoplankton – which ultimately provide a source of food for biological resources such as fish and shellfish – and replenished by ocean circulation via the upwelling of deeper waters in which sinking organic matter has been regenerated back to DIN. Low levels of DIN prevail in permanently stratified oligotrophic gyres, high levels are associated with upwelling areas and areas with strong seasonal mixed layer dynamics. Maximum levels of DIN are typically found in the North Pacific and the Southern Ocean – so-called High Nutrient Low Chlorophyll (HNLC) regions – where primary production is limited not by nitrate but by the micronutrient iron. As such, large-scale patterns of DIN availability are influenced by both the biogeochemical and physical components of models. As Figure 1a illustrates, while there are discrepancies in some regions, such as the Equatorial Pacific and the Southern Ocean, the model fields generally compare well with observations.

Surface chlorophyll and vertically-integrated primary production are related biogeochemical quantities that respectively represent the standing stock of phytoplankton (more accurately their pigments) and the quantity of carbon dioxide fixed by them into organic molecules such as sugars. The former can be observed at the large-scale by satellite-mounted ocean colour sensors, while the latter is estimated from surface chlorophyll and other ocean properties using empirical algorithms. Global estimates of primary production range from to 40 to 60 Gt C y^{-1} (Carr et al., 2006), and here a simple average of three such algorithms – VGPM (Behrenfeld & Falkowski, 1997), Eppley-VGPM (Carr et al., 2006) and CbPM (Westberry et al., 2008) – has been used. As Figure 1b shows, while the models have broad similarity with observed chlorophyll, there are significant differences at the regional scale. BFM (CMCC-CESM and PELAGOS) shows significant excess chlorophyll in the Southern Ocean, while MEDUSA is systematically higher at the equator and lower in the subtropics. As expected, the agreement is greatest with HadOCC, which utilizes observational chlorophyll as part of its data assimilation. Perhaps unsurprisingly, model agreement on ocean productivity is similarly mixed. The models mimic the large-scale patterns estimated by the empirical algorithms, but detailed correspondence is weaker. Of particular note is that HadOCC significantly over-estimates productivity – most notably in the Southern Ocean – in spite of assimilating observed chlorophyll. Table 2 provides a summary of global averages and totals for the properties in Figures 1a to 1c.

	Observations	BFM/PELAGOS (CMCC-CESM)	HadOCC	PISCES (IPSL-CM5A)	MEDUSA	BFM/ PELAGOS
Mean surface DIN	5.23 mmol N m^{-3}	7.52	7.11	4.66	6.15	4.90
Mean surface chlorophyll	0.220 mg chl m^{-3}	0.234	0.234	0.178	0.258	0.310
Total primary production	46.0 Gt C y^{-1}	35.5	63.8	33.0	43.4	32.4

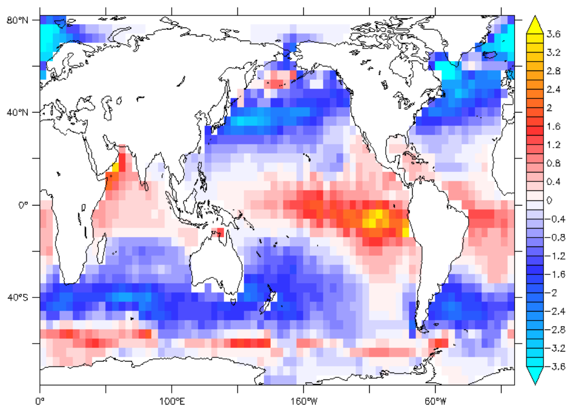
Table 2: Overview of model-observation comparison.

Climate research

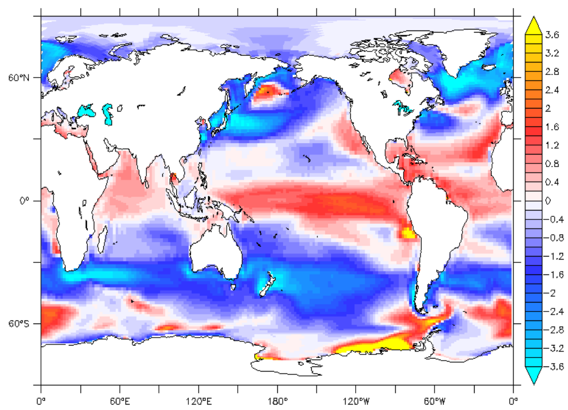
The PISCES and BFM/PELAGOS models (coupled to OPA) are components of Earth system models (ESMs) that have contributed to the Climate Model Intercomparison Project Phase 5 (CMIP5; http://pcmdi-cmip.llnl.gov/cmip5) to the ongoing IPCC Assessment Report (AR5). The BFM model in its global PELAGOS configuration is part of the CMCC-INGV ESM (Vichi et al., 2011), and its CMIP5 model identifier is CMCC-CESM. PISCES is the marine biogeochemical component of two French ESMs, specifically IPSL-CM5 and CNRM (Séférian et al. 2012). These Earth system models are used to investigate projected trends of ocean biogeochemistry and associated feedbacks to the Earth's radiative budget under different representative concentration pathways (RCP; Moss et al., 2008). While IPCC AR5 is still ongoing, previous modeling studies including OPA/PISCES, respectively OPA/PELAGOS focused on projected trends in primary and export production (Schneider et al., 2008; Steinacher et al., 2010; Vichi et al., 2011; Patara et al., 2012a, b), as well CO_2 exchange fluxes with the atmosphere (Roy et al., 2011) and ocean acidification (Orr et al., 2005; Gehlen et al., 2007).

sea to air flux of CO_2

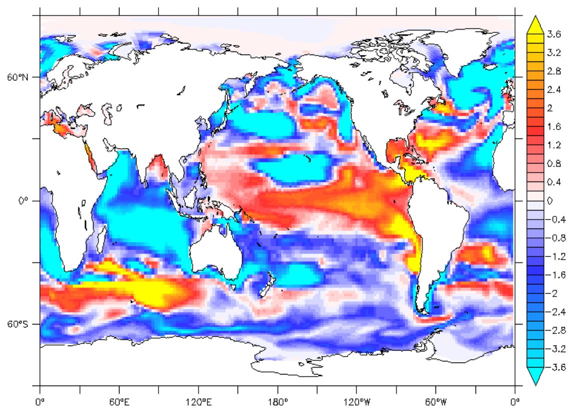
mol m^{-2} yr^{-1}



(a) data-based sea to air fluxes (Takahashi et al., 2009)



(b) 1996-2005 mean fluxes IPSL-CM5A



(c) 1996-2005 mean fluxes CMCC-ESM

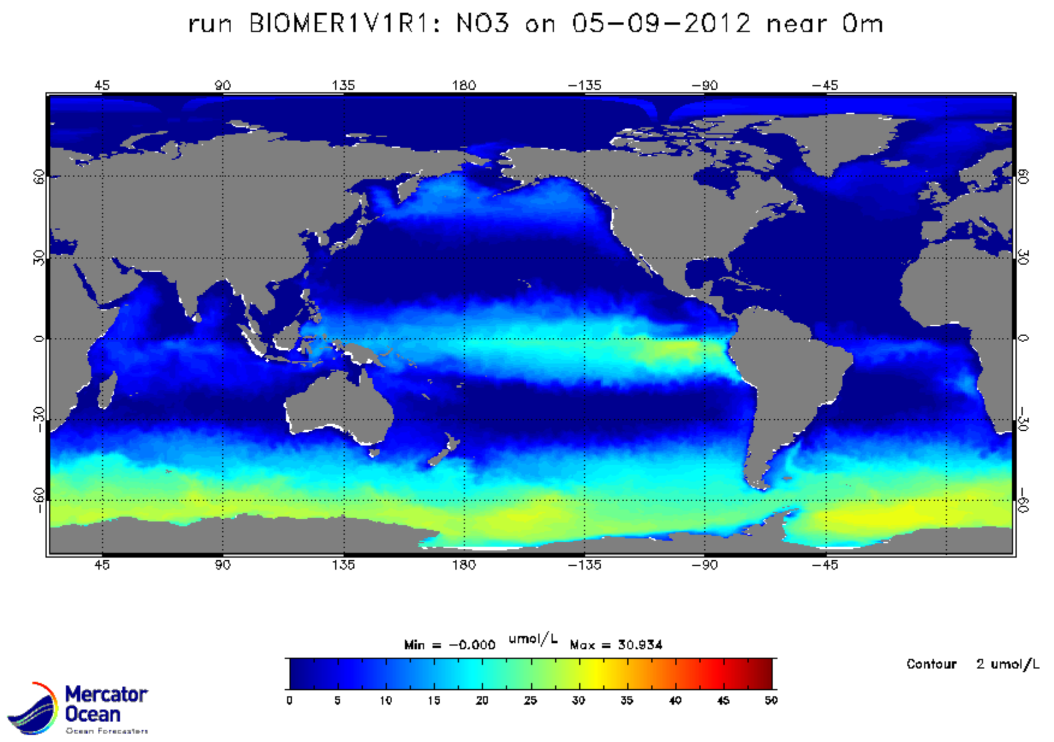
Figure 2 : Comparison of computed distributions of sea to air fluxes of CO_2 for (b) IPSL-CM5A, (c) CMCC-ESM and (a) the data base by Takahashi et al. (2009).

Figure 2 compares yearly mean sea-to-air fluxes of CO_2 averaged over 1996 to 2005 (positive values for outgassing) for IPSL-CM5-LR and CMCC-ESM to a data compilation by Takahashi et al. (2009). The large scale pattern of source and sink regions for CO_2 reflects the combination of ocean circulation, thermodynamics of the CO_2 system, biological production and the increasing concentration of atmospheric CO_2 (Sarmiento and Gruber, 2006). Both models reproduce major sink regions associated with areas of intermediate and deep water formation (e.g. Antarctic convergence and the North Atlantic), as well as source regions associated with upwelling (e.g. Equatorial upwelling, Antarctic divergence). However, there remain significant biases in model results. For example, both data and IPSL-CM5-LR agree on a source region linked to the Somali / Arabian Sea upwelling, while this region is a sink in CMCC-ESM. This feature reflects the lack of upwelling in CMCC-ESM which probably explained by the low resolution of the atmospheric model and highlights to role of ocean physics as an underlying control of biogeochemical distributions.

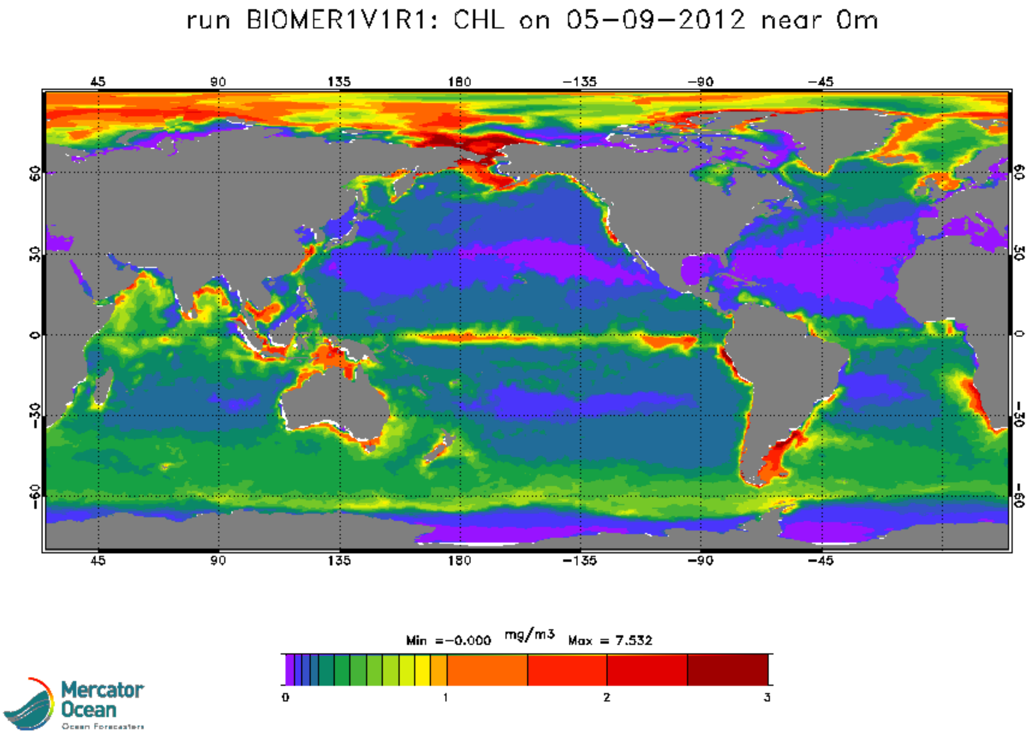
Physical-biogeochemical model applications for operational oceanography

The vast increase in computing power in recent years has made the on-line coupling of physical-biological models possible on a routinely basis and, together with advances in the modeling of biological processes, has led to the development of numerous operational and pre-operational applications, although most of these are currently being used in coastal waters. These applications range from aiding the design of observational networks (Barciela and Brasseur, 2012) to fisheries management. The latter is an application which has evolved towards an ecosystem-based approach, where initial attempts are being made to exploit routinely available environmental data in annual fisheries stock assessments (Berx et al., 2011), monitoring fish migration (Hobday and Hartman, 2006) and providing advice on pelagic fisheries like tuna (Lehodey et al., 2010). The dissemination of freely available biological products, for all users, is also becoming a reality through initiatives such as the FP7 MyOcean project (www.myocean.eu.org), whose champion users include the European Environment Agency and the UK's Centre for Environment, Fisheries and Aquaculture Science (Cefas). Frameworks like FOAM and Mercator Ocean provide a significant number of these products for the global ocean and the shelf seas.

The FOAM framework consists of a suite of models run operationally at the Met Office on a daily basis, producing analyses and six-day forecasts. For the deep ocean, it is run globally at 1/4° resolution (the ORCA025 configuration), and in three 1/12° regional configurations, covering the North Atlantic Ocean, Indian Ocean and Mediterranean Sea. There is also a FOAM configuration run operationally for the coastal waters, the 7KM Atlantic Margin Model (AMM7), coupled on-line to the ERSEM model (Edwards *et al.*, submitted). FOAM has a long tradition of applications in operational oceanography, initially developed to meet the requirements of the UK's Royal Navy, but its product portfolio has broaden in recent years to also provide operational biological products to various users, such as the Environment Agency and to a wider international network via the Marine Core Service of the MyOcean project (http://www.myocean.eu/).



(a)



(b)

Figure 3 : Near-real time output for surface ocean (a) NO_3 and (b) chlorophyll. For this operational application, the biogeochemical model PISCES is run off-line at 1° spatial resolution forced with physical fields from the Mercator Ocean operational system PS3V3.

Since the beginning of 2012, the French center for operational oceanography Mercator Océan has added near real time assessment of ocean biogeochemistry called BIOMER to its suite of products (delivered by the MyOcean website). BIOMER is based on the ecosystem model PISCES forced off-line with ocean physical fields provided by the global operational system PSY3V3 at ¼° spatial resolution (NEMO 3.1, 50 vertical levels, atmospheric forcings from ECMWF operational analysis at 3h, CORE bulk formulation), with assimilation of temperature, salinity and sea level data via the SEEK method (Brasseur and Verron, 2006) and an Incremental Analysis Update (Bloom et al., 1996). To decrease the computational burden, the spatial resolution of physical fields is degraded to 1° and temporal output is averaged over one week (El Moussaoui et al., 2011). At present, the system does not assimilate biogeochemical data. Model output is made available in near real time with a lag of two weeks for the following tracers: NO_3, PO_4, O_2, net PP, Chl. Figure 3 illustrates output for week 36 of 2012. Distributions are not directly comparable to those shown previously, as they represent weekly snapshots compared to five year averages (Fig. 2). Nevertheless, the large scale patterns are in agreement: low chlorophyll levels associated to well-stratified oligotrophic gyres and increased chlorophyll levels linked to Eastern boundary upwelling regions and areas with strong seasonal mixed layer dynamics. At latitudes around 60° S, the on-set of austral spring goes along with suitable conditions for phytoplankton development, as testified by increased chlorophyll concentration. This stands in contrast to conditions prevailing at the end of summer in the North Atlantic where the mixed layer is low in nutrients after spring and summer blooms.

Conclusion

Biogeochemical ocean modeling is a rapidly expanding field of marine research contributing to a diversity of scientific questions. Coupled physical-biogeochemical models are run routinely within NEMO and have proven skill for applications within biogeochemical and climate research (e.g. Séférian et al., 2012), as well as operational oceanography (Brasseur et al., 2009). The development of the later is made possible by a significant increase in computing power, along with the growing availability of real time and near-real time data. It is foreseeable that operational systems including biogeochemical variables will gain of importance in the context of marine environmental management. The qualitative comparison between biogeochemical model output obtained for various model configurations (coupled Earth System models, forced on-line and off-line configurations, with and without data assimilation) and climatological data demonstrates the capability of models to reproduce large scale features and highlights the importance of the underlying physical model. Obviously, model-data comparison goes beyond the climatological mean state and should include temporal variability from seasonal to inter-annual timescales. The biogeochemical models presented in this paper differ in the level of complexity of the representation of first levels of the marine ecosystem. The level of complexity needed for capturing the main features of marine biogeochemistry and ecosystems is an open question. The computational cost increases rapidly with model complexity and in particular for high resolution operational applications it is important to identify the minimal needed complexity. Model data shown in Fig. 1 and 2 have been generated with different biogeochemical components coupled to different versions of NEMO-OPA. The variability in underlying physics precludes a detailed attribution of causes and effects of between model differences to either biogeochemistry or physics. Having NEMO as a common, unifying framework to which the biogeochemical components are embedded, it would be straightforward to set up coupled on-line physical-biogeochemical simulations using an identical physical model and atmospheric forcing. This approach would allow assessing model skill in terms of complexity of the biogeochemical model.

Acknowledgements

MG, AE, CP and CE acknowledge financial support provided by the French Green Mercator project (INSU/LEFE/GMMC). MV wishes to thank the GreenSeas project no. 265294 funded by the EU FP7-ENV-2010. AY gratefully acknowledges the financial support of the Natural Environmental Research Council (NERC).

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TOWARD A DATA ASSIMILATION SYSTEM FOR NEMO

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Abstract

In this note, we discuss the project that has been conceived and the first achievement steps that have been carried out to set up a data assimilation system associated to NEMO. Of specific interest here are applications to operational oceanography. This data assimilation system is schematically made of three subcomponents: Interface Components, Built-in Components and External Components. Several elements of this NEMO data assimilation system have already been developed by various groups in France and in Europe and several of them could be introduced in the system (the linear Tangent and Adjoint Model, TAM, is one of the most important of them as far as variational assimilation is concerned), some others will require specific developments. Finally, we introduce the SEABASS reference configuration that is proposed to be the NEMO data assimilation demonstrator and the experimentation and training platform for data assimilation activities with NEMO. These various thoughts take advantage of the advances and discussions that have been carried out by the NEMOASSIM working group.

Introduction

Other contributions of this issue discuss how the NEMO modeling platform can be used to simulate the time evolution of the ocean circulation including its variability from global to regional scales. Due to the non-linearity of the equations governing the ocean dynamics, a wide range of such temporal and spatial scales interact together in such a way that the ocean evolution is partly chaotic and beyond some limit, unpredictable. Therefore, the routine monitoring and forecasting of oceanic variables, which is the essential goal of Operational Oceanography, must be treated as a series of inverse problems that require observed data at regular intervals to re-initialize the model state "close" to the observed ocean using all available data combined with the latest model predictions. In this respect, operational ocean monitoring is similar to numerical weather forecasting.

The terms "Data Assimilation" (DA) designate the range of objective methods enabling optimal combination of observations, model simulation and error statistics, in order to reduce as much as possible the uncertainty of ocean state estimations involved in short-term predictions or more or less long-term reanalyses. Very significant progress has been accomplished in ocean data assimilation during the past 20 years in the framework of a variety of pre-operational projects, such as the French SIMAN/QADRAN program in the nineties (*e.g.* Blayo et al., 1994), the DIADEM, TOPAZ (Brusdal et al., 2003), ENACT (Davey et al., 2006) and MERSEA European projects (Brasseur et al., 2005), and more recently the GMES My-OCEAN and on-going MyOCEAN2 and SANGOMA projects. The choice made in Europe to routinely monitor the ocean down to the meso-scales has strongly guided the first stages of the assimilation strategy in place today in most operational centres. At international level, the effort of the nations involved in the development of DA for Operational Oceanography were coordinated in the framework of GODAE (Cummings et al., 2009), demonstrating the relevance of the concept which is further developed in the framework of the on-going GODAE Oceanview.

Briefly speaking, two different categories of algorithms can be distinguished to solve the DA inverse problems: the optimal control approach, most often based on the variational adjoint method (Le Dimet and Talagrand, 1986) and the stochastic methods mostly derived from the Kalman filter concept. In its 4D-Var formulation, the variational method requires the adjoint of the linear tangent model to compute the gradient of the cost function to be minimized, and in that case can therefore be designated as a « model-dependent » DA method. By contrast, stochastic methods such as the Ensemble Kalman filter introduced by Evensen (1994) or the SEEK filter introduced by Pham et al. (1998) can be considered as « model-independent » DA methods which intensively use the direct model code to propagate ensemble statistics, while the update of these ensemble statistics requires additional « model-independent » algebraic operations. The EU SANGOMA project has been set up during the period 2012-2015 to advance stochastic assimilation methods, focussing on non-linear and non-Gaussian assimilation schemes to be used in the next operational systems of the GMES Marine Core Services.

Due to the fast evolution of ocean models during the past 20 years, thanks mainly to computer power increases, the flexibility of « model-independent » DA methods has been an asset to follow the successive updates of ocean model versions without much recoding. Today, the convergence of some of the oceanographic community in Europe toward the NEMO modeling platform provides the opportunity to revisit the overall assimilation strategy, since a more stable and smoother evolution of the model platform can be expected in the future. This is in essence the primary motivation of the project described in the present paper.

Despite some earlier attempts, no assimilation system had ever been formally included in the NEMO system so far. However, a number of DA frameworks already use NEMO as model component: e. g. SESAM (Brankart et al., 2001), SAM (Drillet et al., 2008), OPAVAR/NEMOVAR (Weaver et al., 2003, Mogensen et al., 2009), OceanVar (Dobricic and Pinardi, 2008) and many papers have been published discussing data assimilation results within OPA/NEMO. Since some common components are required by every system, there was therefore some duplication of efforts. In order to provide a more structured offer to a large number of users, CNRS proposed in 2009 to set up the so-called NEMOASSIM working group. This group gathers experts involved in the development of such systems (members of CERFACS, CNRS, ECMWF, INGV/CMCC, INRIA, MERCATOR and MetOffice), and members of the NEMO system team. This leads to sketch a strategy for implementation of an assimilation component associated to the NEMO code system and thereby make assimilation tools for NEMO more readily available to the user community.

In this note, we present the current status and perspectives of what could be the different components of a NEMO data assimilation system, which are categorized into Interface Components such as OBS, ASM components which make the link between observations and model-structured information, "Built-In" Components, such as TAM that is the linear tangent and adjoint models of NEMO, which are intrinsically linked to the direct NEMO code, and External Components to be included into NEMO DA system (4DVAR minimizer, square-root or ensemble analysis kernels, singular value decomposition), which are technically independent from NEMO, but nonetheless essential to build a stand-alone assimilation system. All these components (Interface Components, Built-in Components and Externals Components) are thus needed together to implement the NEMO DA system. Then, SEABASS, an academic NEMO configuration will be proposed as NEMO benchmark basis and demonstrator for DA. A number of perspectives will be discussed regarding the future of the NEMO DA system as a conclusion to this note.

NEMO Data Assimilation: Interface Components

The interface components are the modules that are NEMO-dependent, and which connect NEMO to external information independent from the model output.

The first two components to be included in the standard release of NEMO (from version 3.3 onward) were the *observation operator* (OBS) and the *application of the analysis increment* (ASM) since they represent the common interfaces needed to most assimilation schemes relevant to systems like NEMO. Indeed, the fundamental input to any assimilation kernel is the vector of differences between the observations and the reference state. This vector is usually known as the *innovation vector*, and is a direct product of OBS. On the other hand, the fundamental output of any assimilation kernel is a vector of corrections to the background state on the model grid (known as the *analysis increment*). Typically, it consists of corrections to the model current state but may also include corrections to other fields such as the surface forcing fields, model tendencies, or system parameters. The analysis increment is used to initialize or correct the model trajectory, and this is done through the ASM component.

The main purpose of observation operators is to transform model variables on grid points into quantities which can be directly compared with observations. For example, for in situ observations this can simply be interpolation from the model grid to observation points, but more complicated operators involving non-linear transformations of model variables to produce the observable quantity are also possible. Observation operators are mostly independent of the assimilation kernel. Moreover they are also valuable as a diagnostic tool for evaluation of model performance, since they provide the possibility of comparing model variables with observations. The choice proposed by the NEMOASSIM working group was to include, as a first version, the OBS module coming from NEMOVAR. It came in the NEMO 3.3 reference version as a contribution from the MetOffice (which is also a member of the NEMOVAR consortium) along with full documentation (Lea et al., 2012a).

There are several issues to deal with when developing such operator, namely what input file format should be available, how the output will be handled over any assimilation or diagnostic tool and how and where the observation operators are called. For the latter, two choices are available: either it is done off-line, once the model has finished its time integration, but that would potentially require a tremendous amount of extra I/O, or it can also be done on-line, for an extra computing time during the model integration, and that is the adopted solution in NEMO. In the current version, OBS is able to read data such as profiles of temperature and salinity from CORIOLIS or ENACT/ENSEMBLE database, GRHSTT or Reynolds sea surface temperature, AVISO sea level anomaly, sea ice concentration, and TAO/PIRATA/RAMA velocity, both in their original format and in the NEMOVAR feedback format. In the future it is likely that only the latter (with some improvement if needed) will be available in order to avoid maintaining many possible formats. A set of converting tools to produce feedback formatted observation files is already available in the NEMO reference version. The feedback format is also used as the output of the OBS module where the model equivalent to observation at the same time and place is also present, along with all associated information (position, time, QC flags, observation type and instrument, etc). This format represents the interface on the model side, it is then up to the user to build the interface between feedback files and the desired assimilation scheme or diagnostic package.

In most of the assimilation methods relevant to NEMO, the trajectory is controlled by introducing a correction to the model state. This correction, or *increment* is produced by the *analysis step* on variables linked to a control vector. The increment updates the model trajectory either directly, or in a gradual manner over a time period around the analysis date. This latter approach, usually referred to as the *Incremental Analysis Updates* (IAU) methodology (Bloom et al., 1996), tends to reduce shock in the model restart stage and to minimize spurious adjustment processes. From a technical point of view, this latter concept of a correction introduced progressively during the model run is not closely linked to the assimilation methods and could also be seen or interpreted as a use of forcing terms. In practice, these forcing terms correspond to 2D and/or 3D fields (*e.g.* temperature, salinity, or currents) and are applied directly as additional terms in the equations of the NEMO code (Ourmières et al., 2006).

As for the OBS module, the first version of ASM was imported from NEMOVAR as a Met Office contribution (Lea et al., 2012b). Both these choices were driven by the fact that the NEMOVAR code is sufficiently compatible with the NEMO code (same coding convention and practices and limited modification required to the standard reference).

Several possible further developments and improvements to the interfaces (OBS and ASM) are considered today. For instance, for the ASM module, new specificities will be introduced such as new fields (*e.g.* ice concentration), new IAU weight functions and memory usage optimisation. It would also be appreciated that ASM could manage several increments at the same time (as it is done in SAM). The supervision of their development is under the responsibility of the MetOffice.

Regarding the OBS module, its evolution goes through adding new types of observations. Special care should be devoted to ensure that OBS remains flexible enough to easily include both simple or sophisticated new operators.

NEMO Data Assimilation: Built-In Component

The other current key element of the NEMO DA system is NEMOTAM (stands for NEMO Tangent and Adjoint Model) or simply TAM. The development of tangent and adjoint models is an important step in addressing variational DA problems. In such methods, one minimizes a cost function that is a measure of the model-data misfit, and the adjoint variables are used to build the gradient for descent algorithms. Similarly the tangent model is used in the context of the incremental algorithms to linearize the cost function around a background control. During the ANR–funded project VODA, specific effort was dedicated to the development of the TAM for the ocean engine component of NEMO.

The only needed interface between the direct model and the TAM is the handling of the non-linear trajectory (required for differentiating around). So, once available, the inclusion of the TAM within the NEMO framework is straightforward. A version of TAM was released along with NEMO 3.2.2 and made available to the users on the NEMO website, although it was not fully part of the standard release due to lack of resources. With the support of CNRS, recent efforts have been dedicated to this point that will allow TAM to be soon part of the standard release as of NEMO 3.4 (Bouttier et al., 2012).

Assimilation-wise Tangent-linear and Adjoint Models are mainly used for variational assimilation applications. However they are also powerful tools for the analysis of physical processes. They can indeed be used for sensitivity analysis, parameter identification and for the computation of characteristic vectors (singular vectors, Lyapunov vectors, etc), which in their turn can be used for defining reduced order assimilation schemes.

Sensitivity analysis for instance is the study of how model outputs vary with changes in model inputs. The sensitivity information is given by the adjoint model, which provides the gradient of the outputs w.r.t. the inputs. One can find an example of application of such methods in the study conducted by Vidard et al. (2010) on the GLORYS ¼° global ocean reanalysis. The initial objective was to estimate the influences of geographical areas to reduce the forecast error using an adjoint method to compute sensitivities. They conducted a preliminary study by considering the misfit to observations as a proxy of the forecast error and sought to determine the sensitivity of this misfit to changes in the initial condition and/or in the forcing fields. Without going into the details of this study, one can see an example of sensitivity to initial temperature (surface and 100m) as shown in the two bottom panels of Figure 1. In this example it is clear that the SST misfit (top left) is highly sensitive to changes in surface temperature (bottom left) where the initial mixed layer depth (top right) is low. The opposite conclusion can be drawn from the sensitivity to the initial temperature at 100m (bottom right). This is obviously not a surprise, and is more useful here for the assessment of the model (more precisely of the tuning of vertical mixing) rather than to the original goal of assimilation system improvement.

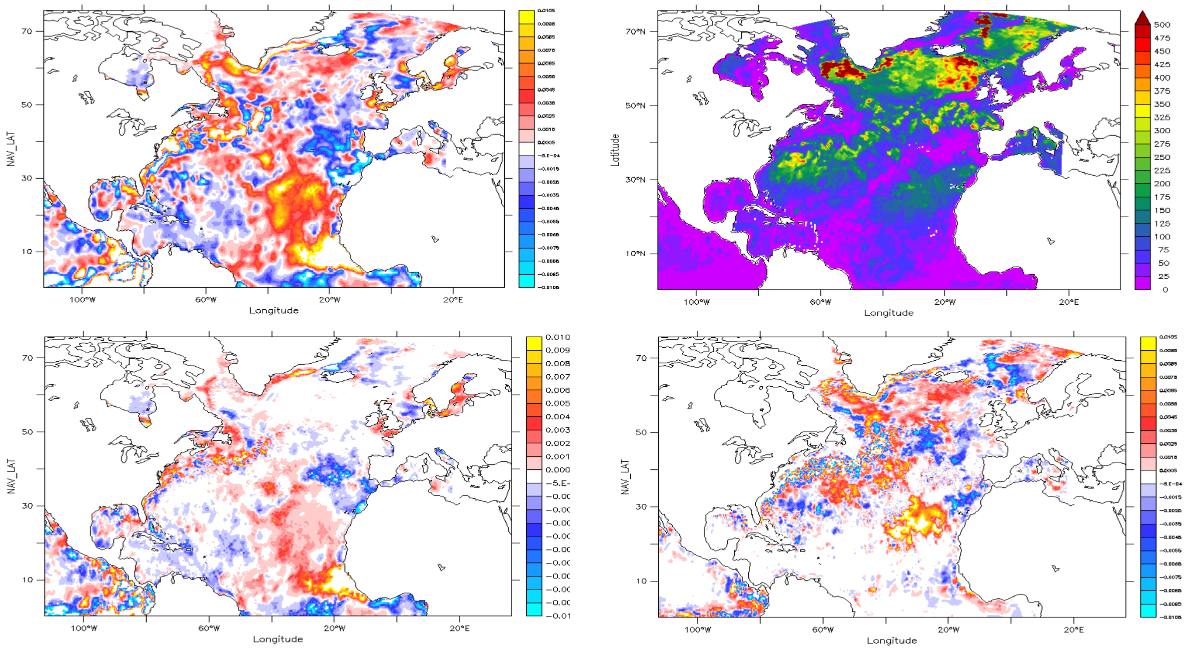

Figure 1: Top: misfit between forecast and observed SST (left) and mixed layer depth (right). Bottom: sensitivity to one-week lead-time SST error with respect to variations in initial surface (left) and 100m (right) temperature.

TAM and associated minimization tools have originally been developed for DA purposes. However, as mentioned above, they could be used for improving the understanding on the model behaviour as well. For example, they can be used to diagnose the differences between model simulations and ocean measurements and to provide valuable information on the robustness of numerical schemes. They can also be used to improve the balance in initial conditions, particularly for shelf-seas models or to assess the structures of the fastest growing instabilities in any flow.

For the future, it is expected that a number of further developments should be added. Several NEMO functionalities (for example AGRIF or Open Boundary Conditions), are not available yet in the current development of TAM. They will be under consideration for next versions of TAM. Estimation of error statistics is a key product of data assimilation and is not readily (and simply) available in variational schemes. There are some potentialities from the hybridization of variational and stochastic methods to bring some solutions. This should be studied further in the future. In addition, one could think that diagnostic tools should be made available in a coordinated way to the users of the NEMO data assimilation system. Note that many of such tools have already been developed in various groups. Built-in components would include physical diagnostic tools whereas specific methodological diagnostics should be in the following external components.

NEMO Data Assimilation: External Components

The NEMO data assimilation interfaces described before has been developed seeking generality and hopefully should be usable easily by any modular-enough assimilation engine. These interfaces have already been used by at least two major complex DA systems: NEMOVAR and SESAM (precursor of Mercator-SAM2). Although they are not part of the NEMO system per se, they are distributed under the same Cecill licence and can therefore be used in conjunction with NEMO.

These two External Components are quite different in their concept; therefore it is a good illustration of the generic aspect of the interfaces. On the one hand NEMOVAR is based on optimal control techniques where the model trajectory is kept close to the observation through the minimization of an objective function, using a descent algorithm. It uses the so-called incremental formulation where the minimization of the full problem is approximated by a succession of simpler problems, assuming that the evolution of the increment follows the tangent linear model. The algorithm is composed of sequences of two-stage processes: an integration of the non-linear direct model that computes the misfit to observations and possibly outputs the non-linear trajectory (outer iteration) and a minimization of the linearized problem (inner loop). The non-linear trajectory is then updated applying the computed increment during a new outer iteration possibly followed by another inner loop, and so on and so forth. In NEMOVAR, outer iterations and inner loops are separate executables. The outer loop is a standard NEMO model integration making use of OBS (resp. ASM) output (resp. input) files to communicate with the inner loop, while the inner loop is a specific program including the multiplication by the error covariance matrices, the computation of the cost function and its gradient thanks to a tangent-linear and adjoint models integrations and several minimization drivers. Note that NEMOVAR can also perform a 3D-FGAT-type assimilation where the evolution of the increment is assumed stationary in the inner loop, avoiding the need for the tangent and adjoint models integrations.

On the other hand, SESAM is a toolbox of assimilation modules originally developed to implement the SEEK filter algorithm (a reduced rank Kalman filter developed by Pham et al., 1998). In sequential methods, the assimilation algorithm consists of two successive operations: a forecast step to propagate in time the initial probability distribution for the state of the system and an analysis step to update this distribution using available observations. The forecast step is performed using the NEMO model, either by propagating the initial covariance using a linearized model operator (as in the original SEEK algorithm) or by producing an ensemble of model forecasts starting from a sample of the initial probability distribution. The analysis step is implemented in SESAM using the SEEK observational update algorithm, which is especially efficient with large observation vectors and low rank covariance matrices. Moreover, the original algorithm is now extended to work efficiently with localization of the forecast error covariance matrix, non-diagonal observation error covariance matrix and adaptive forecast and observation error statistics. It is still a linear algorithm, but extensions exist in SESAM (providing that an ensemble forecast is available) to account for non-Gaussian distributions using anamorphosis or a truncated Gaussian assumption. From a practical point of view, there is a clear separation between the forecast step, only involving NEMO model integrations, and the analysis step, implemented in the SESAM software. The overall system can thus be written as a master program (a shell script for instance) cycling forecast and analysis steps with quite simple interfaces between them.

For some scientific applications, especially for academic process configurations, it is sufficient to use simple error covariance matrix definitions. The so called B matrix required by 4D-VAR DA can thus be defined more simply than going through NEMOVAR: a simple tool should be developed for this. In the same way, a simplified version of the error observation definition routine (the so-called R) is under consideration.

CNRS manpower could be devoted together with other partners, to work toward the integration of these external components within the overall NEMO DA system.

SEABASS: a NEMO reference configuration for data assimilation

In the same way than the NEMO code has some reference demonstrating configuration (such as ORCA2, GYRE, etc …), it is proposed here to set up a reference assimilating configuration that can be used as a first demonstrator of several assimilation methodologies applied to NEMO. In this first stage, such a configuration has to be flexible, easy to manipulate and to maintain. Physically, it has to represent some key ocean dynamical processes. Moreover, its numerical cost must be reasonable.

An academic ocean basin double-gyre configuration is proposed. The rectangular domain of this configuration, now called Sea Box for Assimilation (SEABASS) extends from 24°N to 44°N and over 30° in longitude. Any horizontal resolution can be simply specified. For a 1/4° horizontal resolution, the grid contains only 121 points in longitude and 81 points in latitude. The ocean is sliced into 11 verticals levels, from surface to 4000 meters, described with a z-coordinate. The domain is closed and has a flat bottom. Lateral boundaries conditions are frictionless and bottom boundary condition exerts a linear friction. The circulation is only forced by a zonal wind. Lateral dissipation is performed on dynamics and tracers with a biharmonic diffusion operator. The salinity is constant over the whole domain and the initial stratification is produced using an analytical temperature profile. Details can be found in Cosme et al. (2010), for example.

Actually, this type of configuration has a long story that comes from ancient QG models implemented earlier to mimic the Gulf Stream system (e. g. Holland & Lin, 1975) and serve as a common basis through years to exemplify dynamical processes typical of the mid latitude like the Gulf Stream system with an unstable central jet, presenting meanders and eddies, as illustrated on Figure 2. Even very simplified, it is statistically meaningful regarding the eddy activity and the non-linearity amplitude of the actual Gulf Stream system. Clearly, the horizontal resolution of SEA-BASS configuration can be simply modified. As seen on Figure 2, which shows instantaneous relative vorticity at surface for three different horizontal resolutions (1/4°, 1/12° and 1/24°), increases in resolution allow stronger evidence of mesoscales and smaller scales activities.

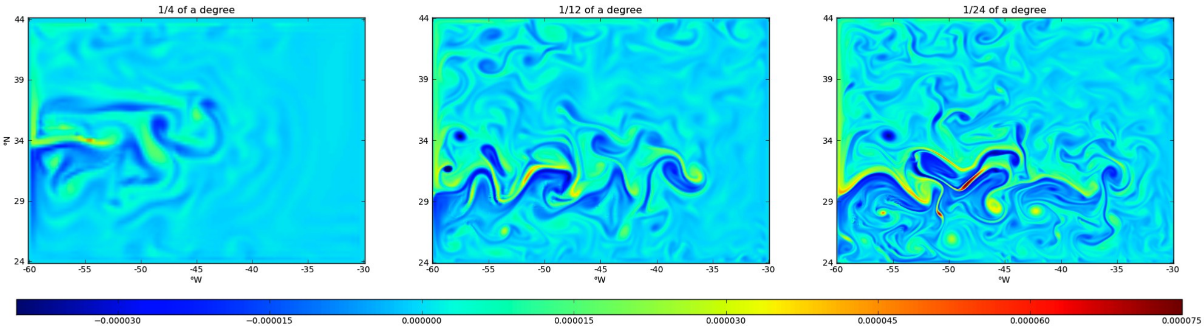

Figure 2: Instantaneous relative vorticity fields from SEABASS configuration, taken at different horizontal resolutions (from left to the right 1/4°, 1/12°, 1/24°)

SEABASS is a compromise between simplicity and a good representation of non-linear dynamical processes, increasing with its horizontal resolution. From a practical point of view, this configuration is easy to maintain across NEMO evolutions. This simplicity ensures that results obtained with different DA systems will probably be robust to most possible numerical evolutions of the NEMO code. In addition for variational DA, this configuration is fully differentiable, which ensures that Tangent and Adjoint Models do not contain approximations of the direct model. Several DA methods have also already been studied and tested on this configuration: SEEK filter and smoother, variational DA methods, nudging, Back-and-Forth nudging, ...

The ambition for SEABASS within NEMO is to have this simple model configuration together with the above DA methodologies and the associated tools and interfaces freely available to users.

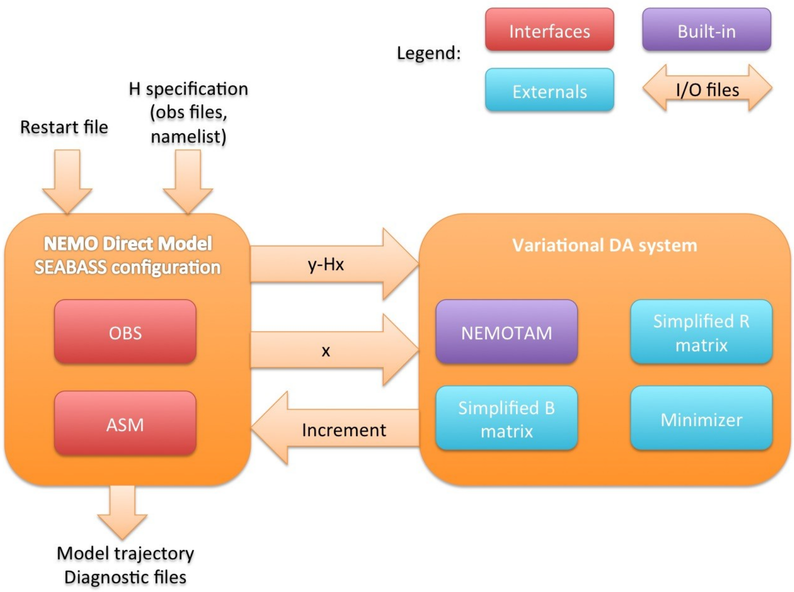

Figure 3a

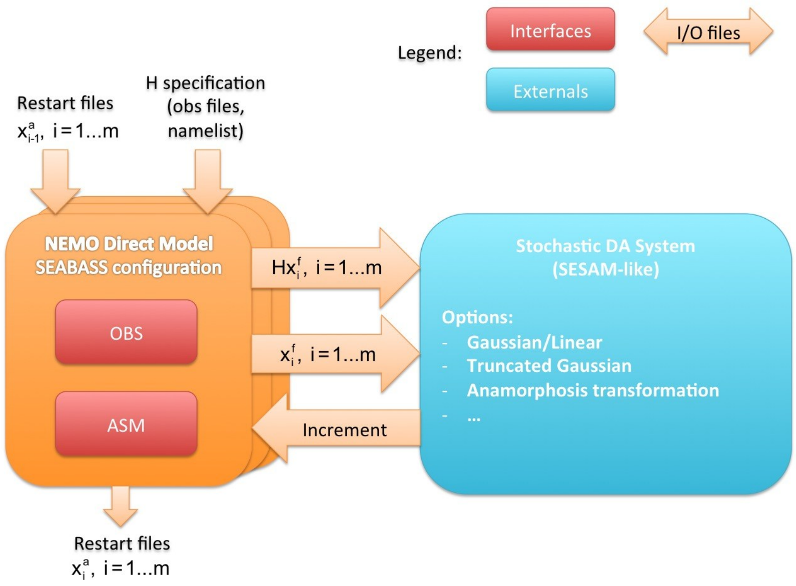

Figure 3b

Figure 3: Sketch of a data assimilation system for the SEABASS demonstrator: a) for a variational DA system, b) for a stochastic DA system

Figure 3 intends to show in a schematic representation how the NEMO data assimilation system presented here could be set up with the present SEABASS demonstrator in the case of a variational DA system (Figure 3a) and of a stochastic DA system(Figure 3b). Note that in this simplified SEABASS test case, some external components have been added: a minimizer, simplified error covariance matrices (B and R) and a stochastic analysis tool.

Conclusion

The goal of this paper was to set up some proposals to rationalize the developments related to data assimilation in NEMO and with the aim of building progressively a flexible data assimilation component designed for the NEMO system. In addition and most importantly, there is the willingness to make all of these freely available to all interested users.

There is a real diversity of data assimilation methods, addressing different scientific and operational challenges. In the future, the accumulated experience in inverse methods and the growing amount of computing resources will even accentuate the use of these different data assimilation methods for multiple applications: operational forecasting, parameter estimation, sensitivity analysis, design of new parameterizations… New observations from space or in-situ will also be a strong incentive for these developments. This will result in a number of new challenges, among which some can probably be anticipated.

From a methodological point of view, it appears clearly that Ensemble approaches encounter increasing interest, either for operational oceanography, for research studies, or for climate prediction. These Ensemble approaches can be either purely stochastic, as EnKF and its derivatives, or hybrid methods, as En-4DVAR under present development in several meteorological operational centres (Buehner et al., 2010).

Another important aspect of future data assimilation systems will be their capacity to take into account totally new types of observations and/or a dramatically higher flux of information. This will be the case with the advent of high resolution altimetry satellites such as with the NASA-CNES SWOT satellite mission project that should be launched around 2019. Relatively new sensors such as gliders also offer prospects that have not been carefully explored. Also, one can question the optimality of the use of existing sensors in assimilating mode, e. g. ocean colour satellite data. The increasing flux of information of SWOT type for example may raise new methodological issues for data assimilation, e.g. in the direction of image data assimilation or of multi-incremental approaches.

In the future the scope of ocean applications making use of data assimilation will broaden. For example, biogeochemical models bring their own specificities to data assimilation. They are generally highly non-linear and statistically not well conditioned (e. g. non-Gaussianity) and include a number of poorly known parameters. In this context, data assimilation tools may not only be used to perform state estimation but also to calibrate those parameters and validate model outputs. The expertise gained on these topics with NEMO will be a valuable asset when going toward more integrated Earth systems, coupling the ocean to components (atmosphere, ice, hydrosphere, …). In this prospect, the NEMO data assimilation environment should be adaptive enough to help the users to properly cope with these present and future scientific and operational issues.

Acknowledgement

Many points presented in the present paper were discussed within the NEMOASSIM working group (M. Bell, S. Drobicic, D. Lea, C. Lévy, M. Martin, K. Mogensen, C. E. Testut and A. Weaver).

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NEMO IN MYOCEAN MONITORING AND FORECASTING CENTERS (MFCS)

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Introduction

During the MyOcean project, all the Monitoring and Forecasting Centers (MFCs, delivering services each in one region as shown in Figure 1) have implemented operational model configurations in order to cover the global ocean with a focus on the European waters. These numerical model configurations are used to provide real-time forecasts of the physical state of the ocean.

Figure 1: The MyOcean MFCs geographic service coverage. The arrows show the boundaries between these domains. Note that these domains do not correspond to the model domains as described in Table 1.

Most MFCs have also used these OGCM (Ocean General Circulation Model) configurations to couple with Biogeochemical (BGC) model that provide real-time forecast for the major BGC variables. Within NEMO, several options are possible with respect to the use of BGC models: The use of BGC codes that are embedded into NEMO (including PISCES) that can be coupled with the OGCM (OPA), the coupling could be online (both component being integrated simultaneously) or offline (the BGC uses the physics produced by a previous run). If offline coupling is selected, the horizontal and temporal resolution can be degraded. This is the approach used by Mercator (see table 4, and Gehlen et al., 2012, this issue) for the global model configurations. For the IBI region Mercator is presently developing R&D that will enable to do online coupling at 1/12°. Other groups using NEMO within MyOcean have taken a different approach, e.g. the Met Office is using a version of ERSEM (European Regional Seas Ecosystem Model) (developed by PML (Plymouth Marine Laboratory)) which is coupled online with the NWS (North Western Shelves) model, the Med group (led by Italy) is using the Biogeochemical Flux Model (BFM) coupled with a specific transport model (OPATM) that uses off-line ocean physics from the Med MFC degraded in horizontal resolution.

Also, most MFCs have used model configurations derived from the real-time ones to produce reanalysis of the past observations over the recent decades. This is true for the Global Ocean where Mercator has used a 1/4° global configuration developed together with CNRS in the DRAKKAR context, used also by the University of Reading in the UK and CMCC in Italy to provide an ensemble of global reanalysis over the modern altimeter period (from 1992, see Ferry et al., 2012, this issue). This is also true for the Med, the Arctic, the Baltic and the Black seas for which reanalysis have been produced with configurations derived from the real-time systems. The reanalysis produced for the NWS differs from this as it has been produced by 2 groups using their own OGCMs configurations (namely based on POLCOMS and HYCOM).

Finally, all the MFCs are working on R&D mode on upgrading these OGCM configurations for further releases. This is illustrated in the tables 1 to 4.

Most MFCs are using NEMO or have plans to use NEMO as the baseline for their OGCM component configuration in the near future.

This has been the case since the beginning of MyOcean with the global ocean (Lellouche et al., 2012), the Mediterranean sea (Tonani et al. 2008 and Oddo et al. 2009), the IBI (Cailleau et al 2012, Maraldi et al. 2012) and NWS regions (O'Dea et al. 2012) as illustrated in the tables 1, 2 and 3. The corresponding working groups, namely Mercator Ocean, the Met Office, INGV and CMCC, together with CNRS and NERC form the working force of the NEMO consortium as discussed in Lévy and Benshila, 2012 (this issue).

In addition, for global model configurations, the Met Office people are concentrating their efforts towards the development of coupling with the atmosphere at eddy permitting resolution for the ocean (namely at 1/4°), while Mercator Océan people are concentrating their efforts on forced configurations at higher resolution (1/12°), in order to better resolve the meso-scale. In the MyOcean 2 project, the development of a coupled prediction system based on NEMO at 1/4° has started at the Met Office in R&D mode, and ocean products obtained from a coupled prediction system are planned to be disseminated through MyOcean catalogue at 6 month prior to the end of the MyOcean 2 project (end of 2013).

There are several developments on NEMO tests implementations conducted in R&D mode by most MFCs that currently use other OGCM. This is the case for the Baltic and the Black sea (see below). The work on the black sea is well advanced, most R&D tasks have been done within the MyOcean project (the configuration has been developed, has been tested), while the work for the Baltic has not started yet, which explains that plenty of the options are still to be defined (TBD) in the tables 1 to 4. Only the Arctic MFC has no plans yet to transition to NEMO. This is discussed in more details in the conclusions of this paper.

Finally NEMO has been considered as a potential OGCM to be used to implement a regional configuration for the Marmara Sea to connect physically the Black and Med seas through the Dardanelles and Bosphorus straits. For the moment the two MFCs dealing with these two seas are disconnected. This work is planned to be done within the MyOcean 2 project. The final choice of the OGCM will take into account the fact that the straits are very narrow (below 1km in some places), and the choice of a finite volume/elements OGCM will probably be preferred to NEMO which is implementing finite differences on the horizontal. The final choice of the OGCM that will be used has not been made yet.

MFC	Domain	OGCM version	Usage	Horizontal grid	Vertical grid
GLO	Global ocean	NEMO 3.1	R/T	1/12° - 1/4° ORCA	50 z-levels
		NEMO 3.2	Reanalysis	1/4° ORCA	75 z-levels
		NEMO 3.4	R&D	1/12° - 1/4° ORCA	50 – 75 z-levels
ARC	North Atlantic	HYCOM 2.2.37	R/T	~ 1/8° (10-15 km)	28 hybrid layers
		HYCOM 2.2.12	Reanalysis	~ 1/8° (10-15km)	28 hybrid layers
		HYCOM 2.2.37	R&D	~ 1/8° (10-15 km)	28 hybrid layers
BAL	North and Baltic Sea	HBM (MyO V2)	R/T	~1 to 6 km	109 z-levels
		HBM (MyO V1)	Reanalysis	~6 to 12 km	50 z-levels
		HBM (MyOV3) - NEMO	R&D	~ 2 km	122 layers (HBM) – *TBD (NEMO)*
NWS	North western Atlantic shelves	NEMO 3.2	R/T	1/15°x1/9°	34 s-levels
		NEMO 3.4	R&D	1/15°x1/9°	34 s-levels
IBI	IBIROOS domain	NEMO 2.3*	R/T	1/36°	50 z*-levels
		NEMO 2.3*	Reanalysis	1/12°	75 z*-levels
		NEMO 2.3* – NEMO 3.4	R&D	1/12° – 1/36°	50 z*-levels
MED	Mediterranean	NEMO 2.3 **	R/T	1/16°	72 z levels
		NEMO 2.3 **	Reanalysis	1/16°	72 z levels
		NEMO 2.3 ** - NEMO 3.4	R&D	1/16°	72 z levels
BS	The black sea	MHIC***	R/T	0.061°x0.044° (~5x5km)	38 z-levels
		POM	Reanalysis	1/10°x1/16 (~7x8km)	26 σ-surfaces
		NEMO 3.3	R&D	0.061°x0.044° (~5x5km)	38 full step z-levels

Table 1: the MFCs major OGCM geographical characteristics. z-levels indicate coordinates for which the total column depth is varying with time (following the total sea level, developed for and used on IBI configuration), while z-levels denotes fixed depth levels and s-levels terrain following levels. All the z-level and z*-levels configurations use partial cells (Barnier et al. 2006) at the bottom.*

** NEMO 2.3 has been used as the base line for the IBI configuration development several years ago, a large part of the NEMO code has been rewritten to improve the numerical core on this shelf tidal open ocean region. These developments were done on NEMO2.3 at the origin, and most of them are currently being transferred to more recent NEMO version (namely version 3) by the IBI group (in France) in collaboration with the NWS people (in the UK).*

*** NEMO 2.3 has been also been used as the baseline for the Med configuration development several years ago. Several adaptations have been done to the code to allow scientific performances in the Mediterranean Sea, the R/T system is made from this updated NEMO 2.3 version.*

**** MHIC is an OGCM developed by the Marine Hydrophysical Institute (Demyshev and Korotaev, 1992)*

MFC	Usage	Forcing fields	Freq of forcing	Analytical Daily cycle	Atm pressure forcing	Tides	Using Bulk	Vertical mixing scheme
GLO	R/T	ECMWF	Daily - 3 hourly	No - No	No - No	No - No	CLIO - CORE	TKE
	Reanalysis	ERA-interim	3 hourly	Yes	No	No	CORE	TKE
	R&D	ECMWF	3 hourly	Yes	No	No	CORE	TKE
ARC	R/T	ECMWF	6 hourly	Yes	No	No	Kara *et al*. 2000	GISS (Canuto)
	Reanalysis	ERA-Interim	6 hourly	Yes	No	No	Kara *et al.* 2000	GISS (Canuto)
	R&D	ERA interim	6 hourly	Yes	No	No	Kara *et al.* 2000	GISS (Canuto)
BAL	R/T	DMI– Hirlam & DWD	Hourly	No	Yes	Yes	Neutral Kara *et al.* 2000	K-omega (Canuto) part 2
	Reanalysis	DMI and SMHI – Hirlam, ERS-40	Hourly	No	Yes	Yes	Neutral Kara *et al* 2000	K-omega
	R&D	AS in R/T and reanalysis	Hourly	No	Yes	Yes	Neutral Kara *et al* 2000 (HBM) - *TBD (NEMO)*	K-omega (HBM) - *TBD (NEMO)*
NWS	R/T	Met Office	Hourly	No	Yes	Yes	Flux driven*	K-Epsilon
	R&D	Met Office	Hourly	No	Yes	Yes	CORE	K-Epsilon
IBI	R/T	ECMWF	3 hourly	Yes	Yes	Yes	CORE	K-Epsilon
	Reanalysis	ERA-interim	3 hourly	Yes	Yes	Yes	CORE	K-Epsilon
	R&D	ECMWF	3 hourly	Yes	Yes	Yes	CORE	K-Epsilon
MED	R/T	ECMWF	6 hourly	No	No	No	MFS	Packanowski and Philander (1981)
	Reanalysis	ECMWF	6 hourly	No	No	No	MFS	Packanowski and Philander (1981)
	R&D	ECMWF	6 hourly	No	No - Yes	No	MFS	Packanowski and Philander (1981)
BS	R/T	Skiron**	6 houly	No	No	No	Flux driven	Mellor and Yamada
	Reanalysis	ECMWF	6 hourly	No	No	No	Flux driven	Mellor and Yamada
	R&D	RNMA ***	6 hourly	No	No	No	Flux driven	Mellor and Yamada

Table 2: OGCM atmospheric forcing and vertical physics characteristics. Note that for the global R&D configuration, the table describes only the forced configurations maintained at Mercator Océan, not the coupled configuration developed at the Met Office. We note also that K-epsilon vertical mixing has been adopted on the two tidal domains on the European shelf: NWS and IBI.

** the NWS NEMO configuration operated in real-time do not use any classical bulk formulation to recompute interactive fluxes, but forces the ocean with fluxes computed by the UKMO UM atmospheric model, using COARE3.0 bulk formulae, assuming a zero motion ocean with a SST equal to OSTIA products (derived from observations)*

*** These are fields of the Atmospheric Modeling and Weather Forecasting Group, University of Athens, Greece, developed during the MFSTEP project*

**** RNMA is the Romanian National Meteorological Agency. The AGCM is Alladin (Stefanescu et al., 2004).*

MFC	Usage	Free surface type	Tracer advection scheme	Momentum advection scheme
GLO	R/T	Implicit filtered *	TVD	Vector form – een**
	Reanalysis	Implicit filtered	TVD	Vector form – een
	R&D	Implicit filtered	TVD	Vector form – een
ARC	R/T	Explicit time split	FCT2	4th order
	Reanalysis	Explicit time split	FCT2	2nd order
	R&D	Explicit time split	FCT2	4th order
BAL	R/T	Explicit	TVD	Vector upwind
	Reanalysis	Explicit	TVD	Vector upwind
	R&D	Explicit (HBM) - *TBD (NEMO)*	TVD (HBM) – *TBD (NEMO)*	Vector upwind (HBM) - *TBD (NEMO)*
NWS	R/T	Explicit time split	TVD	Vector form – een
	R&D	Explicit time split	TVD/PPM	Vector form – een
IBI	R/T	Explicit time split	Quickest	Vector form – een
	Reanalysis	Explicit time split	Quickest	Vector form – een
	R&D	Explicit time split	Quickest	Vector form – een
MED	R/T	Implicit filtered	MUSCL + upwind	Vector form – een
	Reanalysis	Implicit filtered	MUSCL + upwind	Vector form – een
	R&D	Implicit filtered - Explicit time split	MUSCL + upwind	Vector form – een
BS	R/T	Implicit***	TVD	Vector form - een
	Reanalysis	Explicit time split	2nd order centered	2nd order centered
	R&D	Implicit filtered *	MUSCL	Vector form - een

Table 3: some numerical aspects of the OGCM

**NEMO Implicit filtered free surface is schematically a free surface without variation of the top level thickness (see Roullet and Madec, 2000) while explicit time split means that the free surface is explicitly resolved (see Madec et al. 2008), using time splitting method (different time steps for the external and internal modes). NEMO implicit filtered free surfaces are used in domains where the tidal elevations + high frequency signals are not considered (GLO, MED and BS).*

*** een stands for Energy and Enstrophy conserving schemes*

**** For the current R/T implementation of the BS, they use an implicit scheme for the free surface which differs from the one used in NEMO. See Demyshev and Korotaev, 1992.*

MFC	Usage	Ice model (code/ rheology)	BGC model	Wave model coupled	Atmospheric model
GLO	R/T	LIM2/VP – LIM2 /EVP	No – Yes PISCES offline at 1° weekly physics	No	No
	Reanalysis	LIM2/EVP	PISCES offline at 1° weekly physics	No	No
	R&D	LIM2/EVP (forced con-figs) – CICE/EVP (coupled configs)	PISCES offline at 1/4° weekly physics (forced configs) – no BGC (Coupled configs)	No***	No (forced configs) – Met Office UM, fully coupled, COARE3.0 based
ARC	R/T	NERCS 1 cat/EVP	Norwecom online	No	No
	Reanalysis	NERSC 1 cat/EVP	Norwecom online (at ½° horiz resol)	No	No
	R&D	NERSC 5 cat/EVP	Norwecom online	Wave in ice *	No
BAL	R/T	Thermodynamic only	DMI ERGOM	No	No
	Reanalysis	Thermodynamic only	No	No	No
	R&D	New developments (HBM) - *TBD (NEMO)*	DMI-ERGOM and SMHI -SCOBI	In test mode	No
NWS	R/T	Non applicable	PML ERSEM online		No
	R&D	Non applicable	PML ERSEM online		No
IBI	R/T	Non applicable	No	No	No
	Reanalysis	Non applicable	No	No	No
	R&D	Non applicable	PISCES online (at 1/12° horiz resol)	No **	No
MED	R/T	Non applicable	OPATM BFM offline at 1/8° biweekly	WAM	No
	Reanalysis	Non applicable	OPATM BFM offline at 1/8° biweekly	No	No
	R&D	Non applicable	OPATM BFM offline at 1/8° biweekly	WAM- Wa-vewatch	No
BS	R/T	No	MHI Biogeochemical model v1	No	No
	Reanalysis	No	MHI Biogeochemical model v1	No	No
	R&D	No	No	No	No

Table 4: the model coupled to the OGCMs. Note that all the regions concerned by Ice NEMO-based configurations are coupled to a prognostic ice model, either from Louvain la Neuve (LIM) or Los Alamos (CICE). Note that the Arctic region is covered by a "home-made" ice model, the Arctic R&D group is working on a more sophisticated version of the ice model implementing more ice categories. Finally, note that there is a great variety of BGC model used.

** Waves taken into account in the ice model of the ARC MFC, see Dumont et al. 2011*

*** Some tests are planned to implement mixing parameterizations using outputs of wave models. This is not fully coupling, but will test the impact of waves on the ocean vertical mixing. This work will follow some successful test (that have already been done within in a R&D MyOcean sub project led by Met No) to test the impact on the ocean of wind stresses coming from an atmospheric model coupled with waves in forced mode.*

**** There will ultimately be coupled with wave model in the coupled global modeling system, but for the moment, there is no coupling to any wave models applied, and the future is not yet defined.*

NEMO for the global and basin-scale ocean

The global ocean forecasting system operated by Mercator Océan and available through MyOcean data server is based on the NEMO ocean model since the first version which was operated in real time in 2001. The current global system is based on two global configurations at 1/4° and 1/12° of horizontal resolution and a regional one at 1/12° which cover the North Atlantic and the Mediterranean Sea. The main characteristics of these configurations are described in the Tables 1 to 4. They have been developed at Mercator Océan and through several collaborations with research partners especially with the DRAKKAR project as said above, and so have used state of the art parameterization for global ocean configurations. The first global 1/4° simulation performed with NEMO is described in Barnier et al. (2006), authors show that this model simulation has already a high level of quality especially concerning the level of eddy kinetic energy and the position of the main currents. Several other recent studies, based on NEMO global ocean configurations, have proved the importance of the model resolution to improve the realism of the ocean circulation, for example with the Gulf Stream pathway in Hulburt et al., (2011), the ability of a model to forecast oceanic structures (Hulburt et al., 2009) and also for several applications as for the oil spill drift (Law Chune et al., 2012) or the transfer time of eel larvae across Atlantic Ocean (Blanke et al., 2012). In the operational system the impact of a higher resolution is less clear than in a forced simulation because the data assimilation constrains the meso scales field which is mainly observed with the current observation network thanks to the altimetry satellites. As an example, a zoom on the south Atlantic along the African coast is presented in Figure 2, the top panel shows the observed sea level anomaly (black contour) for August 15th 2011 delivered by MyOcean. This field is assimilated (not directly the map but the along track observations which are also used to produce this map) in the global 1/12° system (bottom panel, Figure 2). The main meso scales structures are well represented in the model solution, with several eddies at the same place in the model and in the observations. The color field on the top panel (Figure 2) is the satellite observed chlorophyll distributed by MyOcean, this field exhibits more small scale structures as smaller eddies or filaments which are not assimilated in the global system . The sea surface salinity and the velocity fields (Figure 2, bottom panel) show also smaller structures which can be simulated thanks to the high resolution of the global system. More details and analysis performed with the global operational system are presented in the quarterly validation Quo Va Dis bulletin (http://www.mercator-ocean.fr/eng/science/qualification) and the performance of the future release of the system are described in Lellouche, et al (2012).

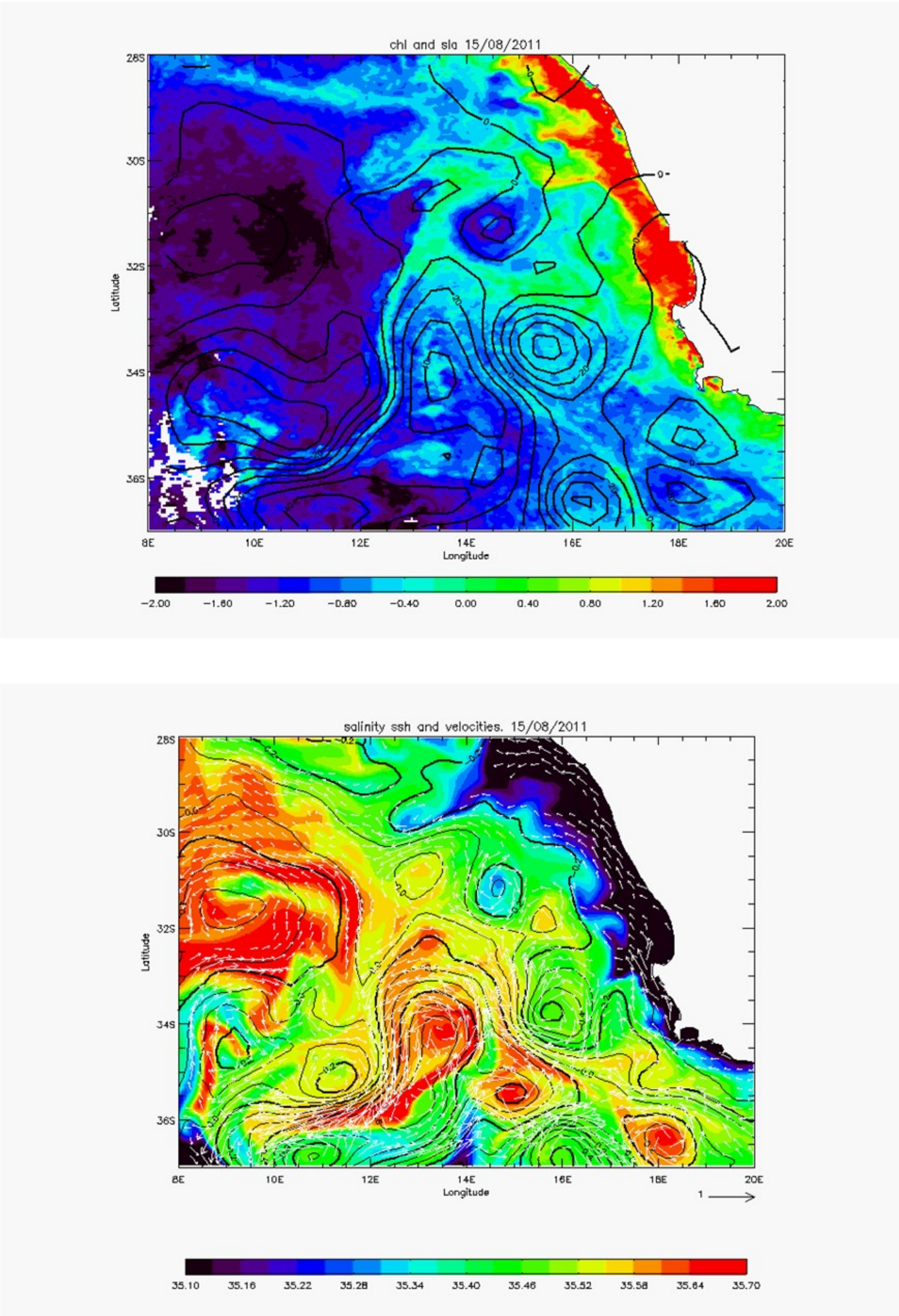

Figure 2: top panel: observed log of Chlorophyll-A chl-a (color) and Sea Level Anomaly sla (contour) for August 15th, 2011. Bottom panel: analysis produced with the global 1/12° system for 15/08/2011, sea surface salinity (color field), sea surface height (contour) and surface velocity (white arrows)

NEMO in tidally dominated Seas

Common to NWS and IBI (Iberian Biscayan and Irish Seas) MFCs domain are the wide and shallow (200m) continental shelves where dynamics are largely dominated by tidal motions. Tides provide there the bulk of turbulent mixing through their dissipation over the rough bottom, shaping bottom layers over a large part of the water column. A spectacular manifestation of this process is the occurrence of vertically homogenized areas in spring/summer where surface thermocline is prevented to set up due to the amount of bottom mixing. This leads to sharp "tidal fronts" (which mean locations are depicted in Figure 3a, moving according to spring-neap tide variability.

Development of an accurate "tidal ready" NEMO code has certainly been one of the most time-consuming task for both NWS and IBI developers. This has been all the more the case since some required modifications to the numerical kernel where not fully developed or tested at MyOcean project start. Specific to both groups (Table 3) is the replacement of the "default" filtered free surface of Roullet and Madec (2000) by a "split explicit" free surface (otherwise, this would have led to an excessive damping of external gravity waves). Tidal range becoming large compared to the water depth, linear free surface approximation has been relaxed (in practice vertical grid is remapped according to the free surface elevation at each time step). The latter option however requires some care where tidal range exceeds the water depth since no "wetting drying" scheme is presently available (yet scheduled in MyOcean2). Also common in both groups is the use of a k-epsilon vertical mixing scheme. It is noteworthy that the implementation has been made in the generic form proposed by Umlauf and Burchard (2005), hence allowing retrieving other 2-equation closures such as the Mellor and Yamada (1982) scheme used by BS MFC. Numerous studies have shown that the k-epsilon model has good performances in river plumes, estuarine processes and more generally tidally dominated environments. Combined with Canuto A (Canuto et al., 2001) stability functions as it is the case in both groups, Holt and Umlauf (2008) further demonstrate an overall improvement in the location of tidal fronts compared to a 1.5 closure (the so-called TKE scheme commonly used in NEMO belong to the latter class of closures).

A major difference in NWS and IBI MFC concerns the vertical coordinate choice. The generalized vertical coordinate framework used in NEMO indeed allows to easily switch from "z" (geopotential), "zps" (z with partial bottom cells) to "s" (terrain following) vertical coordinate systems. Following the previous POLCOMS-based set-up over the North Sea, NWS kept a s-coordinate approach, which allows for a good resolution in the bottom boundary layer. To minimize pressure gradient errors, s-coordinates in NEMO are defined along "a smoothed bathymetry envelope", so that the vertical coordinate revert to z when the slopes become steep. This procedure is very similar to the "vanishing quasi-sigma" vertical coordinate used in NLOM (Dukhovskoy et al., 2009). Further efforts towards the reduction of these errors have lead to the implementation by NWS of a "pressure jacobian scheme" to compute hydrostatic pressure gradient on s-levels. Noteworthy is also recent research on alternative sigma distributions (Siddorn and Furner, 2012) that substantially improves hydrostatic consistency. On the other hand, IBI-MFC uses zps coordinates, keeping the consistency with the 50 levels grid distribution used in the global system. The relatively high resolution in the upper 100m (1m at the surface, at most 15m at 100m) allows to properly resolve the surface diurnal cycle but leads to much lower bottom resolution over the continental shelf than in the s-coordinate case. A 15m vertical resolution however allows for the representation of bottom mixed layers and marginally of log layers in these regions.

Even if the purpose here is a broad overview of the different contexts in which NEMO is used, we briefly address the question of the staircase representation of the lower most bottom cells in a tidal environment. This issue has indeed not received much attention so far, the use of z-coordinates being historically discarded in such circumstances. It has however been found that with a faithful and (an almost) continuous representation of the bathymetry thanks to partial bottom cells, the vertical mixing scheme accommodates the largely variable bottom thicknesses (Figure 3b)[1]. This leads to a smooth bottom stress distribution (Figure 3a) in the sense that it is not related to vertical discretization settings. As a consequence the model predicts pretty accurate frontal mean positions as in the NWS sigma based system. This somewhat restores the use of step coordinates on the shelf even if part of this success comes from the relatively gentle slopes there, well resolved at the high horizontal resolution used. Representing downslope flows over steeper bathymetries would still remain favorable to s-coordinate models unless extremely high vertical and horizontal resolutions are used (Winton et al., 1998).

[1] One subtle requirement for this is the use of a logarithmic formulation for bottom stress coefficient. Logarithmic or constant quadratic bottom drags are often seen as interchangeable formulations in ocean modeling. Here, highly variable bottom thicknesses due to partial bottom cells reveals the need for consistency between the assumed law of the wall boundary condition in the vertical mixing closure and bottom stress formulation.

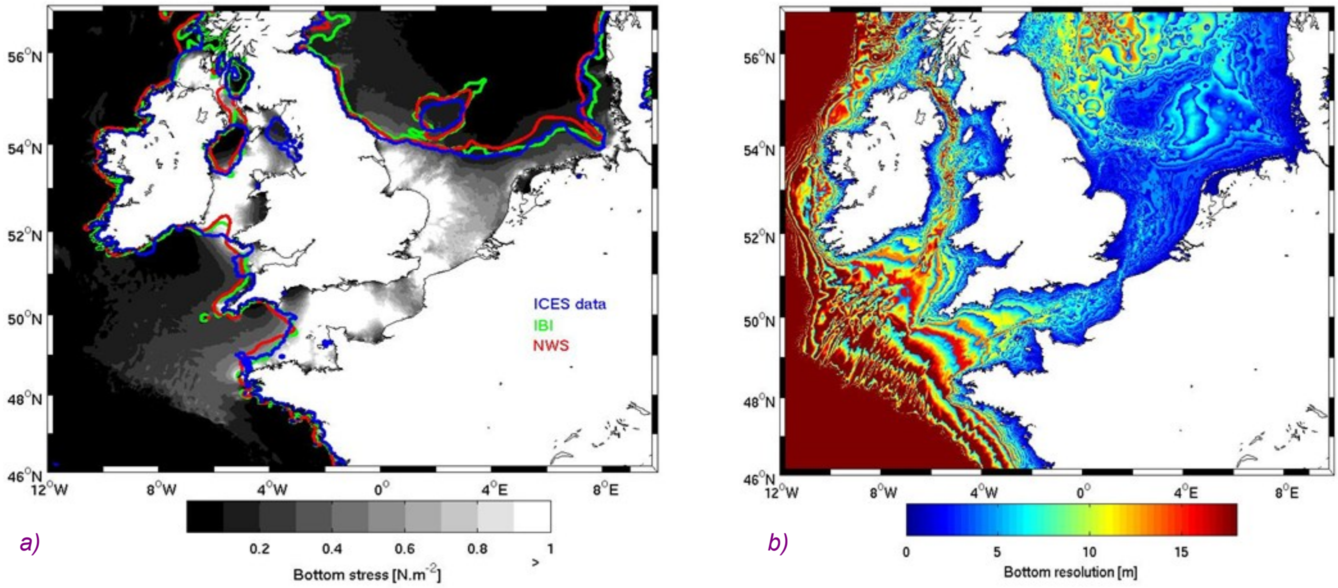

Figure 3: a) Colored lines: summer frontal positions deduced from surface to bottom temperature difference (ΔT=1°C) in IBI and NWS models versus ICES in-situ data (Jun-Aug 2008 average). Background: Averaged bottom stress in IBI system. b) Partial bottom cell thicknesses in IBI model.

NEMO in the Mediterranean Sea

The physical component of MFS (Mediterranean Forecasting System) is composed of two elements: an Ocean General Circulation Model (OGCM) and a Wave Model. The OGCM code is NEMO-OPA version 2.3 (Madec et al. 2008). The Wave Model is based on the WAM (Wave Analysis Model)-cycle 4 code (Komen et al. 1994). NEMO-OPA has been implemented in the Mediterranean at 1/16° x 1/16° horizontal resolution and 72 unevenly spaced vertical levels (Oddo et al. 2009). The off-line coupling between NEMO and WAM is done as follows. The NEMO model provides a first guess of SST and surface currents, which are used by the WAM model. The neutral drag coefficient computed by WAM is used by the NEMO model and modified in order to take into account the stability conditions at the air-sea interface. The two models cover the entire Mediterranean Sea and also extend into the Atlantic in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar.

The wave model takes into consideration the surface currents for wave refraction but assumes no interactions with the ocean bottom. The model uses 24 directional bins (15° directional resolution) and 30 frequency bins (ranging between 0.05Hz and 0.7931 Hz) to represent the wave spectra distribution.

The hydrodynamic model is nested, in the Atlantic, within the monthly mean climatological fields computed from ten years of daily output of the 1/4° x 1/4° degrees global model (Drevillon et al., 2008). Details on the nesting technique and major impacts on the model results are in Oddo et al., 2009. The model uses vertical partial cells to fit the bottom depth shape.

The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the 6-h, 0.25° horizontal-resolution operational analysis and forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the model predicted surface temperatures (details of the air-sea physics are in Tonani et al., 2008). The water balance is computed as Evaporation minus Precipitation and Runoff. The evaporation is derived from the latent heat flux while the precipitation and the runoff are provided by monthly mean datasets: the Climate Prediction Centre Merged Analysis of Precipitation (CMAP) Data (Xie and Arkin, 1997); the Global Runoff Data Centre dataset (Fekete et al., 1999) for the Ebro, Nile and Rhone and the dataset from Raicich (Raicich, 1994) for the Adriatic rivers (Po, Vjosë, Seman and Bojana). The Dardanelles inflow is parameterized as a river and the climatological net inflow rates are taken from Kourafalou and Barbopoulos (2003). The data assimilation system is the OCEANVAR scheme developed by Dobricic and Pinardi (2008). The background error correlation matrix is estimated from the temporal variability of parameters in a historical model simulation. Background error correlation matrices vary seasonally and in 13 regions of the Mediterranean Sea, which have different physical characteristics (Dobricic et al. 2007). The mean dynamic topography used for the assimilation of SLA (Sea Level Anomaly) has been computed by Dobricic (2005). The assimilated data include: sea level anomaly, sea surface temperature, in situ temperature profiles by VOS XBTs (Voluntary Observing Ship-eXpandable Bathythermograph), in situ temperature and salinity profiles by argo floats, and in situ temperature and salinity profiles from CTD (Conductivity-Temperature-Depth). Satellite OA-SST (Objective Analyses-Sea Surface Temperature) data are used for the correction of surface heat fluxes with the relaxation constant of 40 W m^{-2} K^{-1}.

The biogeochemical component of MFS is off-line coupled to MFS, which provides the physical forcing in terms of velocity, temperature, salinity, irradiance, eddy diffusivity and wind speed fields (Teruzzi et al. 2011, Lazzari et al. 2010). The OPATM-BFM model of Med-biogeochemistry is a transport-reaction model that deals with the time evolution of chemical and biological state variables in the marine environment. It is based on the

OPA Tracer Model version 8.1 (Madec et al. 1998) coupled with the Biogeochemical Flux Model (BFM; Vichi et al. 2007a,b), an evolution of ERSEM (European Regional Sea Ecosystem Model). BFM is based on fluxes of elements (carbon, phosphorous, nitrogen and others) among chemical functional families and living functional groups. BFM is targeted on the phytoplankton/nutrients and microbial loop trophic level. Key aspects of the BFM are its potential for limitation by macronutrients (nitrogen, phosphate and silicate), the use of adjustable C:N:P:Si ratios in zooplankton and phytoplankton compartments, and the chlorophyll to carbon variable dependency.

The Med-biogeochemistry provides 10 days of forecast preceded by 7 days of simulation driven by a) physical forcings extracted from the analyses produced by the INGV Med-MFC_Current system, and b) assimilation of available surface chlorophyll field derived by satellite observations at the first day of such simulation.

The assimilation is made by means of a 3DVAR scheme which uses the method of the error covariance matrix decomposition described in Dobricic and Pinardi (2008). In particular, the approach provides that the error covariance matrix is decomposed in a series of different operators (Vi), and that the assimilation solution is found in a reduced dimension control space. Then the solution for the state vector (biogeochemical variables) is obtained by the sequential application of the Vi operators.

NEMO in the Black Sea

The NEMO model configuration developed and tested

Major aspects of this configuration are given in tables 1 to 4. Additional information regarding this setup is provided here:

- z-levels are calculated according to the hard-wired hyperbolic tangent stretching function proposed by Madec et al. (1998). The time step is set to 10 minutes.
- The bathymetry used is based on the data prepared in MHI with maximum depth of 2202 m. Nine major rivers (Danube, Dnestr, Dnepr, Kodori, Inguri, Rioni, Eshil, Kizil and Sakarja) are taken into account. The Kerch strait is considered as a river in the current model configuration
- Climatic volume discharges through the river and Kerch Strait mouths (Knysh et al. 2008) converted to the values of downward water flux are used according to the procedure described in Madec et al., 2008. Climatic temperature and salinity (Knysh et al. 2008) are specified in the mouths.
- The Bosphorus strait is considered as an open boundary. Thus profiles of temperature, salinity, meridional velocity (zonal velocity is assumed zero) are specified. The procedures described in Treguier et al., 2001 and Madec et al., 2008 for open boundary conditions are applied.
- The initial conditions are derived from the analysis for 31/12/2006 provided by the BS MFC model (Ratner et al., 2006) interpolated to the z-levels of the NEMO configuration.
- Fourth order bilaplacian operator is used for the parameterization of the diffusion on momentum and tracer. Values of the horizontal eddy viscosity and diffusivity are assumed constant in time and space and equal 5.10^8 and -4.10^8 m^4/s respectively.
- Stability function from Galperin et al. (1988) (nn_stab_func=0) is used in the Mellor and Yamada vertical scheme.
- The model is time-stepped using modification of leapfrog-asselin filter scheme proposed by Leclair and Madec (2009).

Prognostic calibration of the designed configuration

Several prognostic simulations were carried out for the period 2007-2008 for preliminary model calibration. It is shown that basic elements of the Black Sea circulation such as the Rim Current with a large number of on shore mesoscale anticyclones are resolved by NEMO (Figure 4). The Rim Current jet is present in the simulation, is more pronounced in winter-spring period, whereas it almost vanishes during the summer.

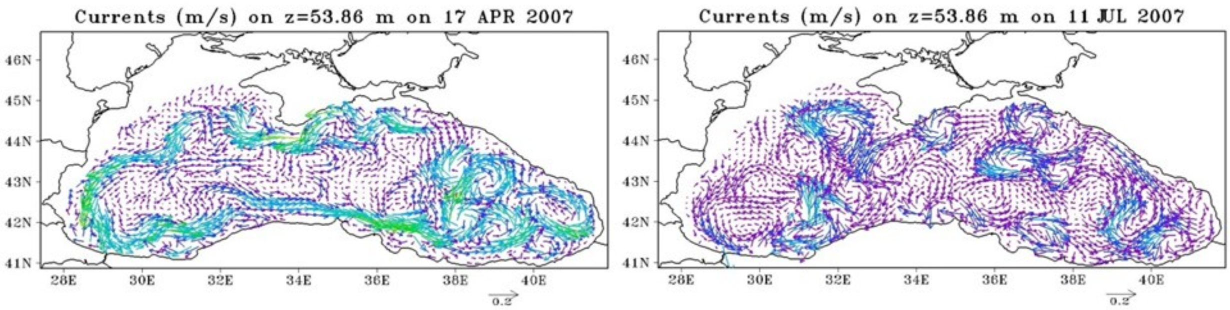

Figure 4: Currents reconstructed in the NEMO 2007-2008 prognostic runs for the black sea. Left April 17th 2007, right July 11th 2007

Vertical temperature cross sections along 43.7°N (Figure 5) and salinity fields are used for preliminary evaluation of the tuning quality of the current configuration. Comparison of the results from the current NEMO configuration and MHIC (Marine Hydrophysical Institute) runs shows that the upper mixed layer has approximately the same depth in both models. At the same time the cold Intermediate Layer (a layer where temperature is below 8°C) intensity is lower in NEMO than in MHIC simulations. It even may have breaks in the summer.

Additional tuning of the NEMO model is on the way. Some tests (not shown) have been already made including the Azov Sea and data assimilation based on the 3D-Var procedure (Weaver et al., 2005). The salinity is specified as a basic variable. The reference level for the balanced SSH evaluation is set at 500m. The SSH assimilation procedure assumes extraction of the basin averaged sea level before assimilation. Profiling floats data are assimilated as separate profiles, without any additional preliminary interpolation to evaluate the assimilation procedure skill.

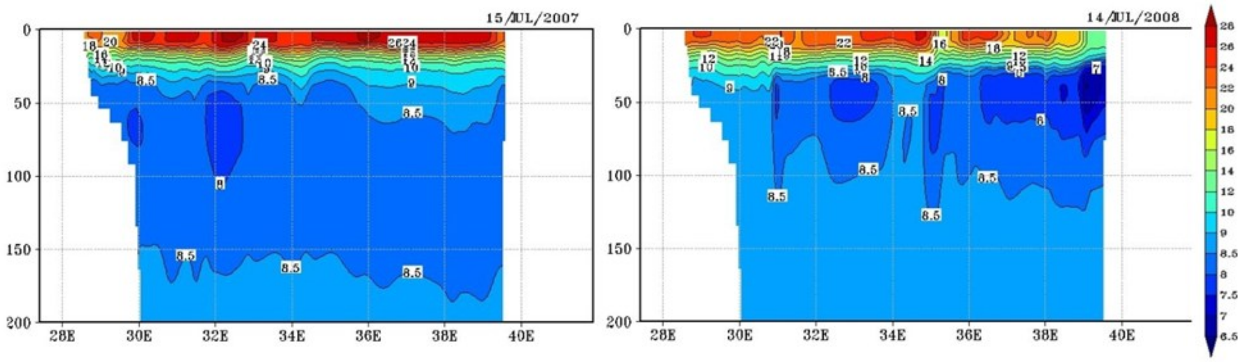

Figure 5: Summer temperature sections along 43.7°N in the Black Sea from Nemo simulations. Left: mid July 2007, right: mid July 2008

NEMO in the Baltic Sea

The Baltic MFC group uses the common developed HBM (HIROMB-BOOS-Model) code as operational model system (Berg and Poulsen, 2012; Poulsen and Berg, 2012). HBM was developed from the BSH-Cmod ocean circulation model, the development of which started in the beginning of 1990 at Bundesamt für Seeschifffahrt und Hydrographie (BSH) in Germany. The current HBM is considered to be a very reliable, accurate, computational efficient, well-tested and well-documented model. Over the years the model-development has been partially financed by a number of EU projects, such as FP6 Mersea, FP6 Ecoop, FP7 MyOcean.

The Baltic group and especially the Baltic nominal and backup production units at DMI and BSH, respectively, will continue to develop the HBM code during MyOcean 2 as the Baltic operational model system.

In addition to this development a test set up of NEMO will be implemented in the Baltic group to investigate the feasibility of using NEMO operationally for the Baltic Sea. FMI will lead this implementation. Several features, for example the ice module, require additional research effort before NEMO can match the performance of current Baltic forecasting systems. FMI will work in close co-operation with other Baltic partners and stakeholders to develop the Baltic NEMO.

Tests to address the quality of NEMO and HBM will be initiated during MyOcean 2. The long term goal is that NEMO results will be part of the multi model ensemble product from the Baltic group. The benefit of multi model ensemble forecasts has become evident in the everyday forecasting duties of the Baltic partners, and a new ensemble member is expected to provide additional value. The NEMO set up will be used by SMHI to produce a new 20 years Baltic reanalysis product within the MyOcean 2 project.

Conclusions

We see that NEMO is largely used by MyOcean MFCs. Mercator Ocean has used this code since its beginning (thanks to strong links with the scientific community led by CNRS) and ran the first NEMO based forecasting system in 2001. The Met Office leading NCOF (National Center for Ocean Forecast) in the UK has successfully transitioned most of their model developments (for the global within FOAM and for the NWS within NOOS) to NEMO, it was an active player for the creation of the NEMO consortium, and is an active member of it since its beginning. The group of people (led by INGV) dealing with the Med Sea have successfully transitioned to the use of the ocean part of NEMO (OPA) several years ago now, in the MFS context, and INGV and CMCC entered the NEMO consortium more recently. The group dealing with the Black sea has successfully implemented a NEMO based OGCM configuration in the black sea during the MyOcean project, and is now considering operating a transition towards NEMO in the future. The group is currently working on research and development tasks to accomplish this within the MyOcean 2 project.

In the Baltic, the group plans to setup NEMO in a test version and make a thorough comparison of existing operational models (HBM and HIROMB). This comparison will evaluate issues such as the quality of model forecasts, model development potential and computational efficiency.

The Nansen Center leading the Arctic MFC in MyOcean has no plans to transition from HYCOM to NEMO in the near future, which does not mean that there are impermeable walls between the models. HYCOM is presently the only mature model using an advanced hybrid vertical coordinate system (Bleck 2002) but NEMO is also actively developing its Arbitrary Lagrangian Eulerian (ALE) vertical coordinate of clear scientific benefit (Leclair and Madec, 2011). This ambitious transition will represent a major step for the whole MyOcean community. The Arctic MFC can then contribute more than ten years of expertise in hybrid coordinate modeling and data assimilation that would otherwise be lost for MyOcean, should HYCOM be abandoned.

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NEMO: THE MODELING ENGINE OF GLOBAL OCEAN REANALYSES

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Abstract

We illustrate here the use of NEMO ocean engine in three eddy permitting global ocean reanalyses and one reference simulation of the altimetric era (1993-2009) carried out in the framework of the MyOcean EC funded project. The ORCA025 model configuration (1/4° horizontal resolution) of the NEMO code is used both for the reanalyses and the non-assimilative reference simulation. Complimentarily to these reanalyses, a multivariate ocean state estimation based on observations only is also included is that study. The main differences between the reanalyses comes from the data assimilation scheme implemented to control the ocean state with delayed time reprocessed observations of sea surface temperature (SST), in situ temperature and salinity profiles and sea level anomaly (SLA). After presenting each reanalysis system and the reference simulation, we present various diagnostics showing the skills of the different simulations. Most of the results show that the reanalyses are consistent between each other and are able to reproduce known climate signals. We also investigate the idea that a multi model ensemble of reanalysis may provide uncertainty estimates and we illustrate this with the Atlantic Meridional Overturning Circulation (AMOC) for which the ensemble mean has more skill than any individual reanalysis member.

Introduction

The description of the past climate is an important challenge for meteorologists, oceanographers and biosphere scientists. A way to describe the past climate from its smallest space and time scales to the largest ones is to produce reanalyses of the state of the atmosphere, the ocean and the biosphere which depict the full three dimensional state of the planet as a function of time. Meteorologists have the largest experience in that research field and have been producing atmospheric reanalyses for about 2 decades (e.g. ERA-15, NCEP-NCAR I, ERA-40, NCEP-DOE II, ERA-Interim, see http://reanalyses.org/atmosphere/overview-current-reanalyses for an extensive list of atmospheric reanalyses). The production of ocean reanalyses is a more recent activity which started at the beginning of years 2000 (Lee et al. 2009). The first ocean reanalyses were assimilating only one kind of observations, like in-situ observations or altimetric sea level anomaly (Ferry et al., 2007), often in conjunction with nudging approaches for SST. The resolution was coarse (1°~2°) with no mesoscale. Progresses made in the field are such that today's reanalyses use advanced multivariate data assimilation schemes that allow assimilation of most available type of observations. However, many reanalyses are still conducted at coarse resolution (~1°) and only few propose a realistic description of the mesoscale eddy field. Thanks to satellite altimetry, sea level displacements associated to ocean eddies have been observed with a few centimeter accuracy for more than two decades and there are evidences both from observations and modeling studies that they play a role on the meridional heat transport (e.g. Souza et al., 2011, Smith et al. 2000). There is also evidence that ocean mesoscale features have an impact on the atmospheric winds (e.g. Chelton et al., 2004, Maloney and Chelton, 2006). That is why including mesoscale features in ocean reanalyses is an important issue and contributes to improve our understanding of ocean and climate variability. Nevertheless, one has to keep in mind that ocean observations are scarce before the 2000s (i.e. prior to the full deployment of Argo floats) and that large uncertainties may still exist in the ocean reanalyses. A way to have access to both the eddy variability and uncertainty estimates of reanalyses is to perform a multi-system ensemble of ocean reanalysis at eddy-permitting resolution, which by construction sample the uncertainties related to the data assimilation schemes. As it is explained later in the text, the reanalysis systems that are members of the ensemble only differ by the data assimilation scheme. The free run could in some cases be considered as a member of the ensemble having a very crude assimilation scheme.

In this study we present the results from 3 eddy permitting global ocean reanalyses, one simulation without data assimilation (reference simulation hereafter) and one multivariate ocean state estimation based on observations only, all covering the altimetric era (1993-2009). The whole dataset thus allows appreciating the impact of different assimilation schemes on the relevant climate signals, as well as the impact of the observations themselves (with respect to the reference simulation) and the impact of having a physically consistent ocean state (with respect to observation-only statistical estimates).

These simulations have been produced in the framework of the 3-years (2009-2011) MyOcean1 EC funded project. The reanalyses and reference simulation use the ORCA025 model configuration (1/4° horizontal resolution) of NEMO forced by ECMWF ERA-Interim atmospheric surface variables. Reanalyses and free run have been produced in a coordinated way between Mercator Océan in France (GLORYS2V1 reanalysis), CMCC in

Italy (C-GLORS), University of Reading in United Kingdom (UR025.4) and CNRS-LEGI in France (reference simulation MJM95). The additional reprocessed data set based on observations only was produced by CLS in France (ARMOR3D) without information from any prognostic ocean model. We present hereafter the skills of these reanalyses for some particular ocean diagnostics. The results show that the reanalyses carried out with the NEMO ocean engine have common robust patterns in their description of a wide range of physical processes. We also investigate the possibility of producing ensemble based estimates to improve the description of the ocean variability. In a first part we describe the various reanalyses, their common features with an emphasis on the configuration of NEMO and their specificities (data assimilation used). Then, we present and discuss the results for some particular diagnostics. The last section draws conclusions and perspectives.

NEMO ocean engine in MyOcean global ocean reanalyses

NEMO ocean engine is a key component of the MyOcean near real time global ocean monitoring and forecasting system. From the early beginning of the MyOcean project, it was decided that all global ocean reanalyses would be carried out with the ORCA025 model configuration of NEMO forced with ERA-Interim surface atmospheric parameters. Groups involved in this global ocean reanalysis effort are Mercator Océan, CMCC and University of Reading for ocean reanalyses, CNRS-LEGI for the reference simulation and CLS for the multivariate reprocessed observations (without prognostic ocean model).

The guiding line of the reanalysis group was to use as much similar as possible ocean model and surface forcing and when possible the same observations (for assimilation) to produce global ocean syntheses spanning the altimetric era (1993-2009). Main differences between ocean reanalyses come from the differences in the data assimilation methods. As a result one has a small reanalysis ensemble sampling the uncertainty related to the data assimilation methods used (including the case when no data assimilation is used). Another important issue of the reanalysis activity is the validation process. A common validation protocol for the global reanalyses has been defined which relies on the previously defined MERSEA-GOADE metrics, CLIVAR/GSOP diagnostics along with other metrics defined in the framework of MyOcean quality control for operational forecasting systems.

We present hereafter the ocean model configuration used in the different simulation as well as the different reanalyses features. A synthetic view of MyOcean reanalyses using NEMO is given in Table 1.

System name	Domain Resolution	Model version	Data Assimilation	Assimilated observations
GLORYS2V1	Global, ¼°, 75 vertical levels	ORCA025 LIM2 EVP NEMO 3.1, 3-hourly atmospheric forcing from ERA-Interim, including SW+LW corrections	SAM2 (SEEK Kernel) + IAU and bias correction (Testut et al., 2003, Ferry et al., 2012)	Reynolds 0.25° AVHRR-only-SST, DT SLA from all altimetric satellites, in situ T, S profiles from CORIOLIS CORAv2.3 data base
CGLORS	Global, ¼°, 50 vertical levels	ORCA025 LIM2 NEMO 3.2.1; 3-hourly atmospheric forcing from ERA -Interim, including SW+LW and PRECIP corrections	Global OceanVar (3DVAR) (Dobricic and Pinardi, 2008, Storto et al. 2011a)	Reynolds 0,25° AVHRR+AMSR-E SST, in situ T, S profiles from EN3_v2 with bias correction for XBT
UR025.4	Global, ¼°, 75 vertical levels	ORCA025 LIM2 NEMO 3.2, forced with ECMWF ERA-Interim reanalysis + bulk fluxes	Met Office FOAM – NEMO assimilation system (Storkey et al. 2010, Martin et al., 2007)	EN3_v2 with bias correction for XBT/MDT, in situ + satellite SST, AVISO SLA, EUMETSAT OSISAF sea ice concentration
MJM95	Global, ¼°, 75 vertical levels	ORCA025 LIM2 EVP NEMO 3.2, 3-hourly atmospheric forcing from ERA-Interim, including	Restoring of the sea surface salinity (timescale: 60 days / 10m layer)	Levitus 2009 Monthly sea surface salinity climatology
ARMOR3D	82°N/82°S, 1/3° 24 vertical levels (0-1500m)	Statistical method (Guinehut et al., 2012, Mulet et al. 2012)		Reynolds 0,25° AVHRR-only/ AVHRR-AMSR-SST/, DT SLA from all altimetric satellites, in situ T, S profiles from CORIOLIS CORAv2.3 data base

Table 1: Features of the 3 reanalyses, 1 reference simulation and 1 observation-only based ocean syntheses.

Ocean model

All ocean simulations (with and without data assimilation) are performed with the ORCA025 global configuration of the NEMO numerical framework (i.e. free surface, primitive equation ocean/sea-ice general circulation model, version 3, Madec 2008). Most features described in this section are common to the models used by each reanalysis center. Some differences may exist which are specified in corresponding reanalysis description sections.

The version of ORCA025 used here has many common features with the ORCA025 model developed by the European DRAKKAR consortium (Drakkar group, 2007), the numerical details of which are given in Barnier et al. (2006). The ¼° horizontal grid is defined as a generic tripolar 'ORCA' type mesh ranging from 8km resolution in the Canadian Archipelago to 28km at the equator. The geographical domain extends from 77°S to the North Pole. The bathymetry is the combination of the 2-minute bathymetry file (ETOPO2) of NGDC from Smith and Sandwell (1997) for the deep ocean below 300m depth and the GEBCO 1-minute bathymetry for the shelves (above 300m depth). The z vertical levels grid uses partial cells parameterization for a better representation of the topographic floor. The sea ice component is the Louvain-La-Neuve thermodynamic-dynamic ice model version 2 (LIM2) (Fichefet and Maqueda, 1997, Timmermann et. al., 2005) and is coupled to the ocean. Following options are implemented in the model configurations: momentum advection is computed with the EEN scheme (energy and enstrophy conserving) advection of tracers (temperature and salinity) is computed with a total variance diminishing (TVD) scheme, the free surface algorithm is filtering out the high frequency gravity waves (Roullet and Madec, 2000), lateral diffusion for tracers is laplacian isopycnal (300 $m^2 s^{-1}$), horizontal viscosity for momentum is biharmonic (-1×10^{11} $m^4 s^{-1}$). Vertical mixing is parameterized according to a turbulent closure model (order 1.5). Barotropic mixing due to tidal currents in the semi-enclosed region of the Indonesian throughflow is parameterized following Koch-Larrouy et al. (2008). The lateral friction condition is a partial-slip condition at the wall.

The monthly runoff climatology is built from coastal runoffs and 99 major rivers (Bourdalle-Badie and Treguier, 2006) together with an annual estimation of the Antarctica ice sheets melting. Atmospheric forcing fields are issued from the ERA-Interim reanalysis (Simmons et al. 2007, Dee and Uppala, 2009). We use a 3 hours sampling to reproduce the diurnal cycle, concomitant to the use of the 1m thickness of the uppermost level. Freshwater and radiative fluxes have on the contrary daily temporal frequency. Momentum and heat turbulent surface fluxes are computed with the bulk formulae proposed by Large and Yeager (2009) using the usual set of atmospheric variables: surface air temperature at 2m height, surface humidity at 2m height, mean sea level pressure and the wind at 10m height. Daily downward longwave (LW) and shortwave (SW) radiative fluxes and rainfalls (solid + liquid) fluxes are also used in the surface heat and freshwater forcing. An analytical formulation (Bernie et al., 2007) is applied to the shortwave flux in order to reproduce ideally the diurnal cycle.

GLORYS Reanalysis system

Ocean model and surface forcing

GLORYS2V1 ocean model specificities are the following. The ORCA025 configuration is customized as follows. The NEMO engine is version 3.1. It has a high resolution vertical grid of 75 vertical levels ranging from 1m at the surface to 200m at the bottom. The Elastic-Viscous-Plastic rheology formulation (Hunke and Dukowicz, 1997) for the LIM2 ice model (hereafter called LIM2_EVP) is used in conjunction with a computation and spatial smoothing of the ocean-sea ice stress at each oceanic time step. For the surface forcing, errors in the ERA-Interim clouds are known to induce large errors in both radiative fluxes and rain rates. Therefore, a method to correct these large scale radiative flux biases towards Gewex (Global Energy and Water cycle Experiment; http://www.gewex.org/) fluxes has been developed and applied (Garric and Verbrugge, 2011). Following Lupkes (2010), the warm ERA-Interim surface air temperature was also cooled by 2°C and the surface humidity was dried by 15% over sea ice and north of 80°N. Despite the correction of the SW and LW fluxes, hindcasts experiments performed without data assimilation revealed an underestimation of the Antarctica sea ice extent during summer. In order to avoid correcting this, we arbitrarily decreased by 20% the downward SW flux southward south of 65°S. No attempt was made to correct ERA-Interim rain rates. Consecutively the freshwater budget is far from equilibrium. In order to avoid a mean sea surface height drift and to reduce errors in the SLA assimilation, the surface mass budget is set to zero at each time step with a superimposed seasonal cycle. We have implemented a 3D (Temperature, Salinity) restoring towards the climatology produced by Gouretski and Koltermann (2004) in the Southern ocean (south of 60°S) and under 2000m depth to stabilize the mass adjustment and the Antarctica Circumpolar Current transport (the reason for this is a recognized deficiency of ORCA025 to generate realistic Antarctic Bottom Water AABW). The model initial condition (5 December 1991) is taken from climatological fields from Levitus (1998) with an ocean at rest. The sea ice fraction is issued from the mean December 1991 NSIDC satellite dataset (Comiso et al., 2008).

Data assimilation

Data assimilation is performed with Mercator Assimilation System version 2 (SAM2). It relies on (i) a reduced order Kalman filter based on the SEEK formulation introduced by Pham et al. (1998) missing ref in conjunction with a 3D-Var temperature and salinity bias correction scheme.

The Kalman filter was implemented in a realistic framework by Testut et al. (2003) and is used for several years at Mercator in an operational context. The forecast error covariance is based on the statistics of a collection of 3D ocean state anomalies (typically a few hundred) and is seasonally variable (i.e. fixed basis, seasonally variable). This approach comes from the concept of statistical ensembles where an ensemble of anomalies is representative of the error covariances. This approach is similar to the Ensemble optimal interpolation (EnOI) developed by Oke et al., (2008) which is an approximation to the EnKF that uses a stationary ensemble to define background error covariances.

A bias correction scheme has been implemented in order to correct temperature and salinity biases when enough observations are present. The bias correction will correct the large scale slowly varying error of the model whereas the SEEK filter will correct the smaller scales of the model forecast error.

After the analysis, the increments are applied using an Incremental Analysis Update (IAU) method (Bloom et al., 1996, Benkiran and Greiner, 2008). In the variant of the IAU used at Mercator, the model integration over the assimilation window is performed a second time with the increments applied with the IAU technique. This allows to reduce spin up effects and ensures a continuous trajectory of the analyzed model. More details about GLORYS2V1 can be found in Ferry et al. (2012a).

Assimilated observations

Assimilated observations are sea surface temperature (SST) maps, delayed time (DT) along track sea level anomalies (SLA), and in situ temperature and salinity profiles. The SST comes from the daily NOAA Reynolds 0.25° AVHRR-only product (Reynolds et al., 2007) and is assimilated once per week at the analysis time (day 4 of the assimilation window). The DT along-track SLA data are provided by AVISO (SSALTO/DUACS Handbook, 2012) and benefit from improved DT corrections. The various satellite altimetry data assimilated in GLORYS2V1 come from Topex/Poseidon, ERS-1/2, GFO, Envisat and Jason-1/2. Assimilation of SLA observations requires the knowledge of a Mean Dynamic Topography (MDT) and we used the MDT referred to as CNES-CLS09 (Rio et al., 2011). In situ temperature and salinity profiles come from the CORA-3 in situ delayed time data base provided by CORIOLIS data centre and available through MyOcean service (http://www.myocean.eu/). This in situ data base includes profiles originating from the NODC data base, from the GTS, from national and international oceanographic cruises (e.g. WOCE), from ICES data base, TAO/TRITON and PIRATA mooring arrays, and Argo array. The temperature and salinity profiles have been checked through objective quality controls but also visual quality check. Following the first quality check done by CORIOLIS data centre, additional quality check and data thinning is performed.

CGLORS reanalysis system

CGLORS consists of a weekly three-dimensional variational analysis (3DVAR), followed by a 1-week Ocean General Circulation Model (OGCM) integration, which brings the analysis forward to the next assimilation step. The three-dimensional variational data assimilation system is a global ocean implementation (Storto et al., 2011) of OceanVar (Dobricic and Pinardi, 2008), the assimilation system used within the MyOcean Mediterranean Sea Monitoring and Forecasting Center.

Ocean model and surface forcing

The OGCM is NEMO 3.2 (Madec, 2008) in its ORCA025 configuration, coupled with the Louvain La Neuve Sea-Ice model (LIM2, Fichefet and Morales Maqueda, 1997).

All the forcing fields are provided by the European Center for Medium-Range Weather Forecast (ECMWF) ERA-Interim atmospheric reanalysis project (Simmons et al., 2007). The same corrections than GLORYS2V1 for large-scale short-wave and downward long-wave radiation fluxes have been used; precipitation fields were corrected by using a climatological coefficient derived from the REMSS/PMWC dataset. In order to avoid artificial drifts of the globally-averaged sea-surface height due to the unbalanced fresh water budget, the evaporation minus precipitation minus runoff has been set equal to zero at each model time-step. The runoff used in CGLORS has been compiled by Bourdalle-Badie and Treguier (2006): it is a monthly climatology that includes 99 major rivers and coastal runoffs.

The strategy for initializing the reanalysis has been chosen as follows: a 1979-1989 assimilation-free run initialized with: I) monthly climatology of temperature and salinity fields from the NODC World Ocean Atlas 1998 Series (Levitus et al., 1998) blended with the PHC2.1 climatology for the Arctic region; ii) sea-ice parameters (se-ice cover and ice temperature) from the ERA-Interim reanalysis. From 1990 onwards, the data assimilation was switched on.

Data assimilation

The analysis step is used to correct three-dimensional fields of temperature and salinity. The observations are compared to the background field closer in time to the observations within 3-hourly time slots of the weekly assimilation time-window. The background-error covariance matrix is modeled through a linear decomposition onto two linear terms accounting, respectively, for vertical covariances and horizontal correlations. In CGLORS, vertical covariances are represented by a 1-degree resolution set of 10-mode seasonal bivariate Empirical Orthogonal Functions (EOFs) of salinity and temperature at full model vertical resolution. Horizontal correlations are modeled by means of a four-iteration first-order recursive filter, with three-dimensional, parameter- and direction- dependent correlation length-scales. Both the vertical EOFS and the correlation length-scales were calculated from the seasonal anomalies (with respect to the climatology) of a non-assimilative OGCM run for the same reanalysis period.

Assimilated observations

CGLORS assimilates all the in-situ observations of temperature and salinity from moorings, ARGO floats, Expandable Bathy Termographs (XBTs) and Conductivity-Temperature-Depth (CTDs). The data used in this reanalysis are collected, quality-checked and distributed by the U.K. Met Office Hadley Center. The dataset is called EN3 and the version used is the v2a. XBTs fall rates are corrected according to the time-dependent bias-correction scheme of Wijffels et al. (2008). CGLORS also assimilates SST observations from the NOAA high-resolution daily analyses, which uses AVHRR and (from 2002) AMSR-E radiances. In addition, CGLORS includes a nudging assimilation to sea-ice concentration data from NOAA AVHRR daily analysis at high-resolution (1/4 degree) with 15 days restoring. The observational errors for in-situ observations were initially set equal to those found by Ingleby and Huddleston (2007) and subsequently tuned via the Desroziers' method (Desroziers et al., 2005). CGLORS also assimilates along-track sea level anomaly observations from AVISO through local hydrostatic adjustments (Storto et al., 2011a).

Known problems of CGLORS include i) a bug in the sea-ice nudging, causing an over-estimated melting of the sea-ice and a consequent over-warming in the polar regions, and ii) spurious vertical correlations at depth (~1000 m) that induce both temperature and salinity model drifts over the reanalysis period and visible at most depth ranges.

UR025.4 reanalysis system

Ocean model and surface forcing

UR025.4 ocean model specificities are the following. The numerical model used in UR025.4 is the global ocean model ORCA025 based on the NEMO modeling framework version 3.2. There are 75 vertical depth levels with separations varying smoothly from 1 *m* at the surface to 200 *m* at the bottom. The ocean is fully coupled with the Louvain-la-Neuve Ice Model version 2.

Surface atmospheric forcing for the period of 1989 to 2010 is obtained from the ECMWF ERA-Interim atmospheric reanalysis (Simmons et. al., 2007; Dee and Uppala, 2009). The ERA-Interim reanalysis provides 10 m wind, 2 m air humidity and air temperature to compute 6-hourly turbulent air/sea fluxes during model integration, using the bulk formula proposed by Large and Yeager (2009). Downwelling short and long wave radiative fluxes and precipitation are also provided by ERA-Interim. There is no sea surface salinity restoring in UR025.4.

Data assimilation system

The assimilation system used in UR025.4 is based on the UK Met Office operational FOAM–NEMO system (Storkey et al., 2010; Martin et al., 2007). A complete description of the system is provided by Storkey et al. (2010) and references therein. Here we summarize the main characteristics.

The data assimilation methodology is an Optimal Interpolation (OI) type scheme (Lorenc et al., 1981) with assimilation increments calculated using a first-guess-at-appropriate-time (FGAT) scheme every 5 days (73 assimilation cycles per year) and introduced evenly over the period in an incremental analysis update (IAU, [Bloom et al. 1996]) step. For all data types (apart from sea ice), the analysis is separated into horizontal and vertical parts. The SST increments are applied over the model mixed layer down to a maximum depth of 660 m. Mesoscale SLA increments are projected to depth using a version of the Cooper and Haines (1996) scheme. Synoptic scale SLA increments are applied directly to the model SLA field. For profile data, a vertical analysis is first performed at each observation point, followed by a horizontal analysis at each model level. After 3D temperature and salinity increments have been derived, geostrophic balancing increments are applied to the baroclinic velocity field, poleward of 5° ramping down to zero at 1°. Surface salinity increments are calculated to balance sea-ice increments and mesoscale surface height increments are recalculated using hydrostatic balance.

The model and observation spatial error covariance matrices are univariate, with cross-correlations between state variables being provided by dynamical balancing relationships as described above. A number of bias correction schemes are used to deal with systematic errors in the model and observations. The scheme of Bell et al. (2004) adds a correction term to the subsurface pressure gradients in the tropics to counter errors in the wind forcing or/and deficiencies in the vertical mixing of momentum. Errors in the mean dynamic topography (MDT) field are corrected using the method described by Lea et al. (2008).

Assimilated observations

UR025.4 assimilates *in situ* and satellite SST data, satellite sea level data, satellite sea ice concentration data, and *in situ* temperature and salinity profile data.

The satellite SST data includes level 3 data from the Advanced Very High Resolution Radiometer (AVHRR) sensor on board the NOAA series of satellites, processed by the Pathfinder project at version 5.0 (NODC, 2009), and sub-sampled level 2 data from the (Advanced) Along-Track Scanning Radiometer ((A)ATSR) sensors on board the ERS-1, ERS-2 and ENVISAT satellites, re-processed using the operational processor used in 2007 to form a consistent data-set (NEODC, 2011). The *in situ* SST data are taken from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS, Worley et al. 2005; Woodruff et al. 2011). Sea-ice concentration data are from a re-processed version of the Special Sensor

Microwave/Imager (SSM/I) data provided by the EUMETSAT Ocean and Sea-Ice Satellite Application Facility (OSI-SAF; available from http://osisaf.met.no). These SST and sea-ice concentration data-sets are the same as those used in a reanalysis of the Operational SST and Sea-Ice Analysis (OSTIA) system (Stark et al. 2007; Donlon et al., 2011). After 31st December 2007, near-real time versions of the NOAA AVHRR, AATSR, *in-situ* SST and OSI-SAF sea-ice concentration data are used for assimilation as the gridded observational analysis data are not available.

Altimeter SLA data is along-track data processed by the Collecte Localisation Satellite (CLS) and distributed by Aviso, which includes data from the Jason-1, Jason-2, Topex/Poseidon, ERS, and Envisat platforms at various times. The mean dynamic topography (MDT) field is the Rio et al. (2005) climatology.

In situ temperature and salinity observations are obtained from the UK Met office quality controlled ENACT/ENSEMBLES dataset (Ingleby and Huddleston, 2007). This dataset is largely composed of observations from the World Ocean Database 2005 and supplemented by data from the GTSPP (Global Temperature and Salinity Profile Program) and Argo. As such, the dataset includes all available hydrographic observations, including those from shipboard Expendable Bathythermographs (XBTs) and Conductivity-Temperature-Depth (CTD) measurements, as well as observations from mooring arrays (such as TAO and PIRATA). The operational quality control system used for the FOAM assimilation products (Martin et al., 2007) is used to perform a number of consistency checks on the data. These include buddy checks, track checking, testing for density inversions and thinning of the data. The version of the dataset used in UR025.4 (EN3_v2a_NoCWT_LevitusXBTMBTCorr) differs from the previous version assimilated in UR025.3 (EN3_v2a) as it includes bias corrections for XBT and MDT data (Levitus et al., 2009).

Experimental Design

The entire period of the reanalysis covers 1989 – 2010. Initial conditions for temperature and salinity are derived from the ENACT/ENSEMBLES climatology. The run and post-processing were both carried out on the UK Met Office MONSOON system. The model outputs have been saved as 5-day, monthly and annual means in NetCDF format files.

Free (Reference) simulation MJM95

MJM95 is a hindcast model simulation with no data assimilation that covers the whole period of the reanalysis (1993-2009). It has been carried out with the same ORCA025 configuration used by the various groups with the objective to provide the reference model solution forced by atmospheric reanalysis. It can be used by the other groups to evaluate the benefit of the data assimilation.

The ocean and sea ice model configuration used to produce this reference simulation is exactly the same as the one described for the GLORYS2V1 reanalysis. The atmospheric forcing fields and the bulk formulation used are the same.

The only differences between GLORYS2V1 and MJM95 settings are that MJM95 *(i)* relaxes the model sea surface salinity to climatological values, and *(ii)* uses a mean seasonal cycle of chlorophyll from SeaWifs in the parameterization of the absorption of SW fluxes in the upper ocean.

(i) The sea surface salinity restoring uses a time scale of 60 days/10 meters. The restoring is identical for the open sea and ice covered areas. It is enhanced by a factor of 5 in the Mediterranean Sea. The restoring term is bounded to a maximum absolute value of 4 mm/day (not in the Med Sea). No restoring is applied in region of runoff and to the south of 30°S where a freshwater flux is added to account for the melting of icebergs. In this run, we implemented 2 changes to the standard SSS restoring: (a) coastal areas remain free of restoring. A fading coefficient (function of the distance to coast) is used, with a characteristic length scale of 150 km. (b) In the restoring term, the SSS difference between model and observation climatology (Levitus et al. 1998) is computed using a spatially filtered model field. The filtering is achieved with a shapiro filter applied 100 times.

(ii) The parameterization of the light penetration in the ocean is implemented and a monthly chlorophyll surface concentration climatology deduced from SeaWIFS ocean color product is used.

ARMOR3D

ARMOR3D is an ocean synthesis based on a multivariate combination of several observation data sets (without the use of any prognostic ocean numerical model) in order to provide the temperature, salinity, horizontal geostrophic velocity and absolute height fields on a weekly time period. Data and method are fully described in Guinehut et al. (2012) and Mulet et al. (2012) but the main features are recalled here.

Method

For the temperature (T) and salinity (S) fields, the method has been first developed using simulated data sets (Guinehut et al. 2004), then observations at a regional scale (Larnicol et al. 2006) and it is now applied to the global ocean and it has two steps (Guinehut et al., 2012).

The first step of the method consists in deriving synthetic temperature profiles from the surface down to 1500-meter depth from altimeter and SST data through a multiple linear regression method and covariances calculated from historical data. For synthetic salinity profiles, the method uses only altimeter data. Pre-processing of altimeter SLA includes the extraction of the steric part of the SLA using regression coefficients deduced from an altimeter/in situ comparison study (Dhomps et al. 2011).

The second step of the method consists in combining the synthetic profiles with in situ temperature and salinity profiles using an optimal interpolation method. To gain maximum benefit from the qualities of both data sets, namely the accurate information given by in situ T/S profiles and the mesoscale variability given by the T/S synthetic profiles, a precise statistical description of the errors of these observations has been introduced in the optimal interpolation method. For the in situ profiles, since these observations are considered almost perfect, a very low white noise is applied. For the synthetic profiles, simulating remote-sensing (altimeter and SST) observations, since these observations are not direct measurements but are derived from the regression method, correlated errors have to be applied to correct long-wavelength errors or biases present in the synthetic fields and introduced by the regression method.

First and second steps of the method are implemented as anomalies from the Arivo monthly climatology (Gaillard et al. 2008).

Absolute height and geostrophic current fields are then calculated using the thermal wind equation with a reference level at the surface to combine absolute current fields at the surface from satellite altimetry with the combined T/S fields (Mulet et al., 2012). As the CNES-CLS09 Mean Dynamic Topography (MDT) used to calculate the absolute current fields at the surface is not defined for the Mediterranean, Black and Red Seas (Rio et al, 2011), the 3D geostrophic current fields are also not defined for those areas. Finally, as the geostrophic formulation is not applicable at the equator, the 3D current fields are also not defined between 5°S and 5°N.

Temperature, salinity, absolute height and horizontal geostrophic velocity fields are available at a weekly period on a 1/3° Mercator horizontal grid on each Levitus vertical level from the surface down to 1500-meter depth and for the 1993-2010 periods.

Input data

Three sources of data are used. In situ T and S profiles are from the Coriolis centre (http://www.coriolis.eu.org/) which is also the MyOcean in situ TAC (Thematic Assembly Center), including Argo profiling floats, XBT, CTD, moorings (Cabanes et al., 2011 & 2012). Altimeter sea level anomalies (SLA) are from the SSALTO/DUACS centre (MyOcean sea level TAC) and are weekly combined maps of all processed altimeters (currently: Jason-1, Jason-2 and Envisat for the NRT products) with a 1/3° horizontal resolution; absolute geostrophic current fields at the surface calculated from the combination of the SLA and a Mean Dynamic Topography (Rio et al., 2011) are also from the SSALTO/DUACS centre (SSALTO/DUACS Handbook, 2012). SST data are from daily Reynolds analyses with a 1/4° horizontal resolution, combining AVHRR, AMSR and in situ observations and distributed by the National Climatic Data Center at NOAA (http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php, Reynolds et al., 2007).

Results

We present here different diagnostics for the different global ocean reanalysis products. The objective is to evaluate the robust features of these reanalyses and also where the largest uncertainties are found. We selected 3 diagnostics which are the sea level trend, the surface heat flux and the Atlantic meridional overturning circulation (MOC) at 26.5°N.

It should be noted that the results presented here are a subset of a large amount of diagnostics which were produced as part of the MyOcean common validation protocol for reanalyses. This protocol relies on previous initiatives like MERSEA-GODAE metrics, CLIVAR/GSOP diagnostics, along with new metrics defined in the framework of MyOcean quality control for operational forecasting systems. These diagnostics are routinely used to assess and check the reanalysis skill. The results are presented in MyOcean Scientific Validation Reports (Ferry et al., 2012b, Storto et al., 2012 , Valdivieso et al., 2012, Barnier et al., 2012, Guinehut et al., 2012) which extensively describe the validation of MyOcean reanalysis products against data being assimilated and other observation-based products. It also helps to identify the robust results among the reanalyses.

Sea Level trend

Global mean sea level (GMSL) time series and sea level trend maps over the 17-year reanalysis period are presented in Figure 1 and Figure 2 respectively. There is a good capability of the ocean reanalyses to simulate the GMSL rise. This good skill is related to the assimilation of altimetric sea level data. The reanalysis ensemble mean (yellow line, ensemble from CGLORS, GLORYS2V1 and UR025.4) realistically reproduces the observations from AVISO (black line). The observation-only ARMOR3D product also fits well the observations as the sea level is mainly constrained by the altimetric observations. Only the reference simulation (MJM95, grey line) fails in simulating the observed sea level rise. This is due mainly to the lack of constrain on the net surface water flux. The global mean water budget is not closed in atmospheric reanalyses (precipitation suffers form very large errors) and this impacts the global mean sea level.

The good skill of the ocean reanalyses in reproducing SLA trends is confirmed by the 17-year sea level trend maps (Fig. 2). GLORYS2V1 and UR025.4 have a good skill in representing the spatial distribution of the trends when compared to AVISO. The reference simulation exhibits the correct large scale patterns because a very large part of the sea level variability is governed by the winds (e.g. ENSO variability in the tropics). Nevertheless, because the surface net water budget is not closed, unrealistic variations of the GMSL contaminates regional SLA trends in MJM95.

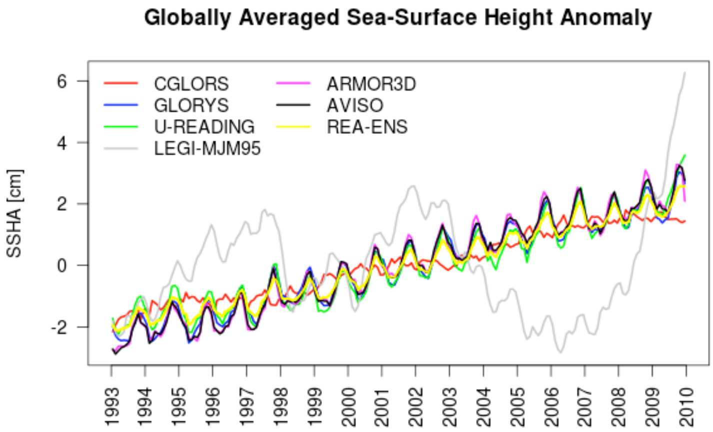

Figure 1. Global mean sea level (GMSL) estimates in the 5 reanalyses products together with the observation (AVISO).

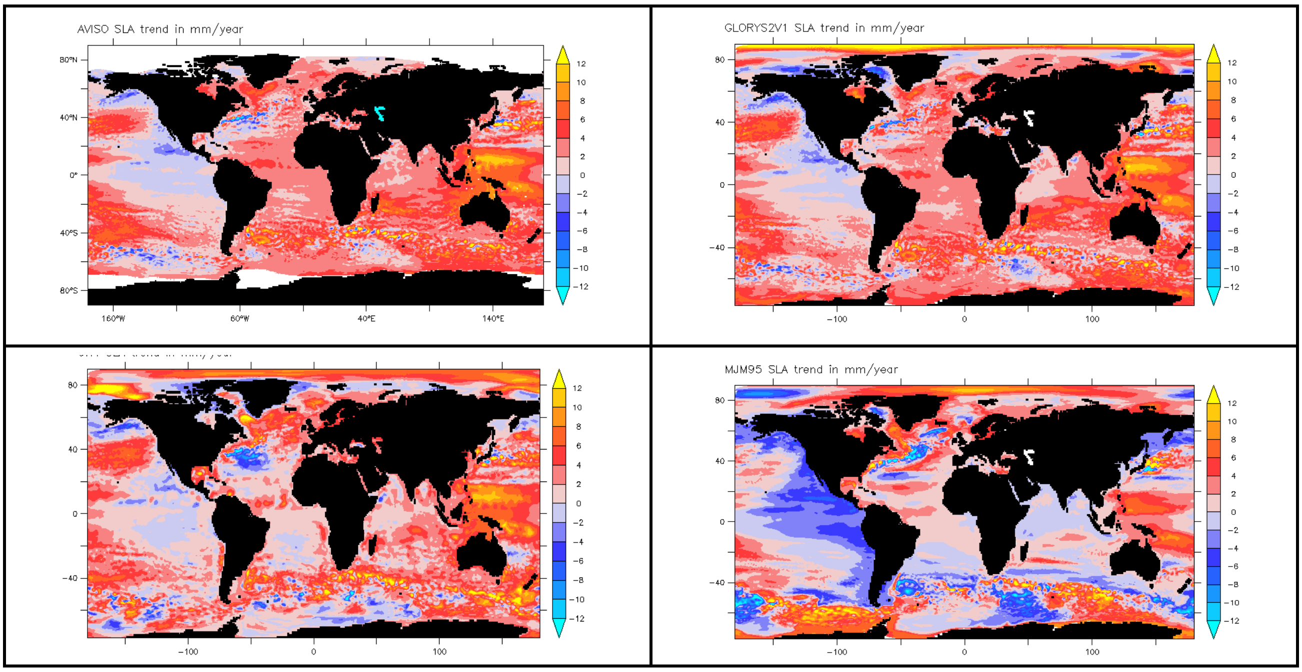

Figure 2. Regional sea level trend in AVISO (upper left), GLORYS2V1 (upper right), UR025.4 (lower left) and MJM95 (lower right). Range is [-10; 10] cm.

Surface heat flux

We present here maps (Fig. 3) and zonal averages (Fig. 4) of the 17-year average net surface heat flux in GLORYS2V1, C-GLORS, UR025.4 and MJM95 runs. It is worth noting that the surface heat flux presented here does not include the correction provided by data assimilation. Differences between simulations are therefore principally driven by differences in SST.

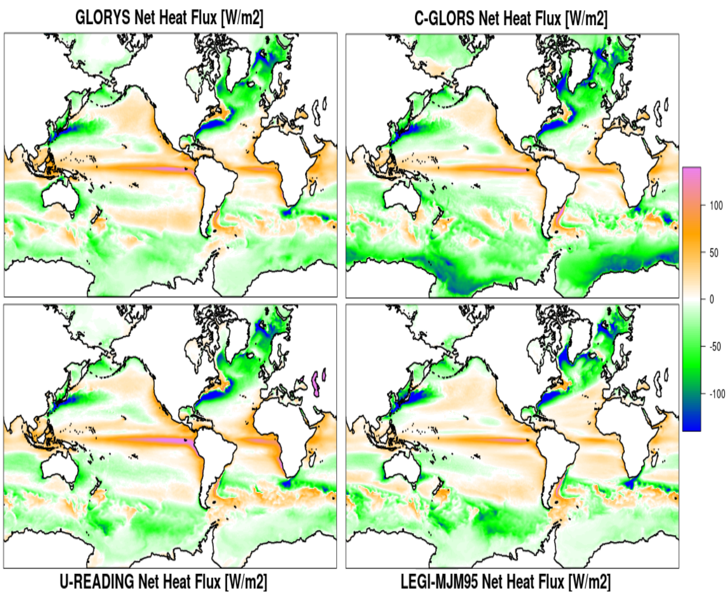

Figure 3. 17-year average net surface heat flux in GLORYS2V1, C-GLORS, UR025.4 and MJM95 simulations (in W/m^2).

The maps of net heat flux (Fig. 3) show that there is a good consistency between the various estimates. The largest differences are found at high latitudes, especially south of 40°S. The largest differences between the reanalyses (C-GLORS vs. the three other estimates) are found in ice covered regions, especially around Antarctica. This difference comes from a limitation of the ice model configuration used in C-GLORS which was run without dynamics (thermodynamics only). This clearly shows that ocean-ice processes play a key role for ocean-atmosphere heat exchanges at high latitudes.

The zonal average heat flux (Fig. 4) reveals that there is an overall good agreement between the reanalysis ensemble mean and ERA-Interim except at high latitudes (>50°) where the ocean reanalyses tend to have more heat transfer from the ocean to the atmosphere. It can be noted that the reanalysis ensemble mean (which includes the free run here) agrees much more with ERA-Interim estimate than with OAFlux estimate (Yu and Weller, 2007) that blends data from different sources (satellites, insitu, reanalyses). Differences with OAFlux exceed +20 W/m2 (OAFlux provides more heat to the ocean) on the global scale.

The reanalysis ensemble spread is quite small, less than ±10 W/m^2 between 60°S and 60°N. This is partly explained by the data assimilation of an observed SST by all reanalyses (except in reference simulation, see Table 1) and this helps to constrain the fluxes. The reduced spread is also related to the fact that all simulations are forced by the same surface atmospheric parameters coming from ERA-Interim. This means that the error bar provided by the ensemble spread does not include the errors from the surface atmospheric parameters (which are often quite large) but is representative of the uncertainty of the data assimilation method used. Fig. 4 suggests that there is an underestimation of the net heat loss at high latitudes in ERA-Interim, especially at high latitudes. The differences are significant between 45°S and 65°S with a gain of energy by the ocean in ERA-Interim whereas there is an energy loss in the reanalyses. The global net heat flux of each ocean synthesis and the ensemble mean is displayed in Table 2. Any of the ocean synthesis is closer to the equilibrium than ERA-Interim estimate and the ensemble mean, around 0.5 ± 1.4 W/m2 is in very good agreement with Levitus et al. (2012) estimate of the ocean global warming (+0.39 W/m2 in the top 2000m depth). We can note that the Reference simulation (MJM95) achieves a remarkable equilibrium without any data assimilation which demonstrates the good skill of NEMO engine in ORCA025 configuration forced with large scale bias corrected atmospheric surface parameters.

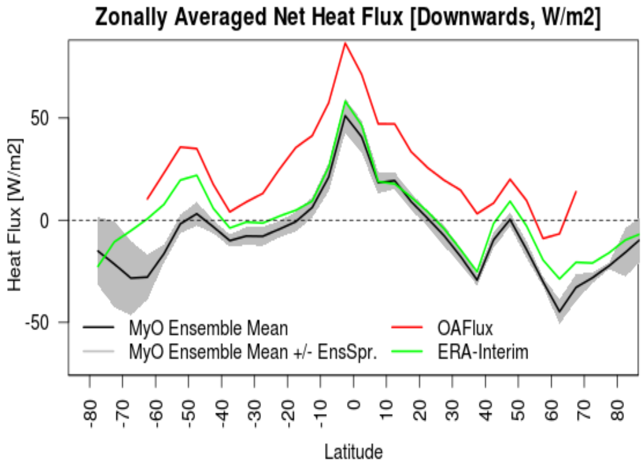

Figure 4. 17-year average zonal mean ocean-atmosphere heat flux in the Reanalysis ensemble mean (black) and in ERA-Interim (green). The grey-shaded area corresponds to ±1 standard deviation of the ensemble (GLORYS2V1, UR025.4, C-GLORS, MJM95). Unit is W/m^2.

Ocean Synthesis	Net surface heat global average (W/m^2)
C-GLORS	-5.9
GLORYS2V1	3.5
UR025.4	4.1
MJM95	0.6
ERA-Interim	8.6
MyO-Ensemble	0.6 ± 1.4

Table 2: Global net surface heat flux (W/m^2) estimated by the ocean reanalyses (positive means ocean heat gain).

Atlantic Meridional Overturning Circulation (MOC): comparison with RAPID

The Atlantic MOC is a key component of the ocean circulation as its strength directly modulates the meridional heat transport in the ocean. The RAPID-MOCHA array (Cunningham, 2007) allows since 2004 a continuous monitoring the MOC variability. We present here direct comparisons of Atlantic MOC estimates from MyOcean reanalyses with that of the RAPID array. Figure 5 displays the AMOC at 26.5°N as represented by the 5 ocean syntheses (the free run and ARMOR3D included) as well as by the ensemble mean. The seasonal cycle is clearly visible in the observations and most of the reanalyses reproduce it reasonably well. The associated correlation coefficients are given in Table 3. All correlation coefficients are statistically significant at the 0.95-level. One should however moderate these good correlations which are partly due to the fact that the ocean syntheses are able to reproduce the seasonal cycle of the AMOC. We can note that the best correlation is obtained with MJM95, the reference (free) simulation. It shows that the NEMO ocean model in ORCA025 configuration captures remarkably well the AMOC variability, provided that the surface atmospheric parameters are realistic. Two interesting comments can be made. First, none of the reanalysis is able to perform as well MJM95 (although GLORYS2V1 correlation is certainly not statistically different from that of MJM95). Our interpretation is that data assimilation, which modifies the ocean state by adding increments, breaks basin scale dynamical balances and impacts the AMOC variability. The mechanism behind this skill reduction in reanalyses is currently being investigated. The second comment concerns the reduced correlation of ARMOR3D with RAPID. Our explanation is that this ocean synthesis based on observations only does not have any global constrain on transports (i.e. no constrain on the currents divergence) and this may lead to errors in the transport, especially near the coast and / or western boundary currents. Adding an additional constrain on currents divergence could certainly improve its representation of the AMOC variability.

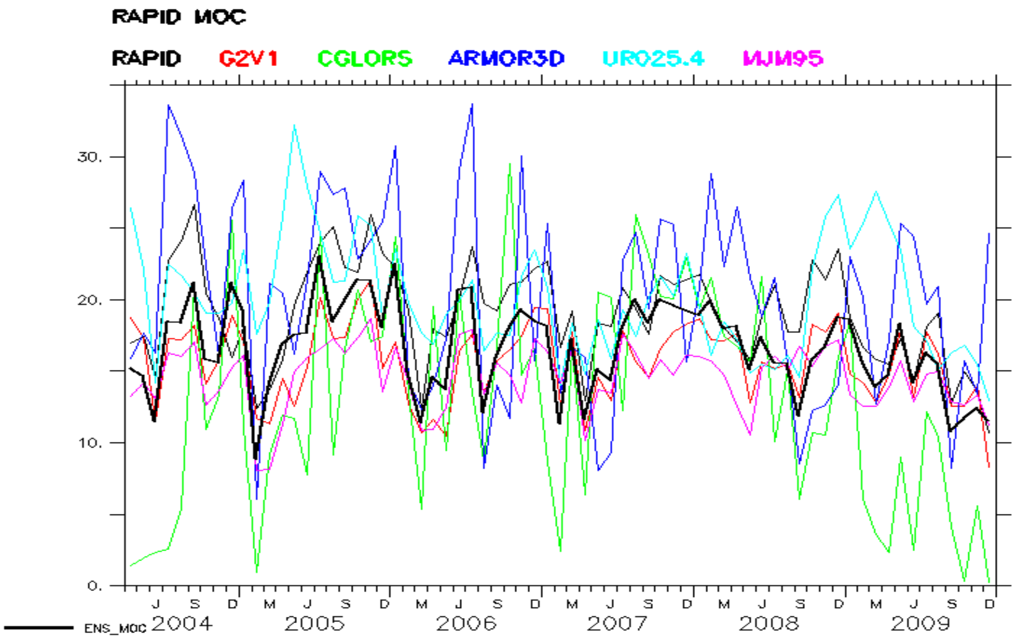

Figure 5: Atlantic MOC(Sv) at 26.5°N in RAPID (thin black) and in the 5 reanalyses (color). The ensemble mean is indicated by the black bold line.

Correlation with RAPID data	Full signal	Interannual anomaly (i.e. seasonal cycle removed)	
			ENSEMBLE MEAN with 4 members (i.e. 1 member removed)
GLORYS2V1	0.73	0.66	0.69
CGLORS	0.47	0.43	0.68
UR025.4	0.39	0.50	0.65
MJM95	0.77	0.69	0.68
ARMOR3D	0.47	0.39	0.72
ENSEMBLE MEAN	0.75	0.71	-

Table 3: Correlation of AMOC at 26.5°N between ocean syntheses estimates and RAPID data. The ENSEMBLE MEAN is constituted of the 5 ocean syntheses. In the last row, the ENSEMBLE MEAN is built with 4 members, the one being withheld corresponding to the reanalysis name of the line.

The most interesting part of the AMOC variability is the one associated to inter annual variations. The correlation of the 5 reanalyses and ensemble mean AMOC inter annual anomaly against RAPID is shown in Table 3. Most of the reanalyses (except UR025.4) have a reduced correlation for the anomaly compared to the full signal because the seasonal cycle is removed. More interesting is the correlation obtained with the 5-member ensemble (0.71) which is greater than any of the 5 members, showing that this small ensemble is able to better sample the true state than a single member (Murphy, 1988). In order to confirm this, we have also computed the correlation against RAPID anomalies with ensemble means having 1 member withheld, showing to what extent each member provides additional information to the ensemble mean. The last row of Table 3 reveals that all members of the ensemble provide useful information to the ensemble as the 4-member ensembles have reduced correlations (except ARMOR3D).

The advantage dealing with a multi model ensemble is that it is possible to estimate the uncertainties associated to the model used. In our case, the models (i.e. reanalysis systems) differ mainly by the data assimilation scheme (background error covariances, observations errors, bias correction scheme,…) as they share the same OGCM configuration (ORCA025) and code (NEMO) and the same surface forcing. As an illustration, the associated error of the AMOC estimated from MyOcean global ocean reanalyses is displayed in Figure 6. We can see that the error bar provided by the ensemble is quite realistic as the RAPID AMOC estimate is most of the time within the ± 1 ensemble standard deviation.

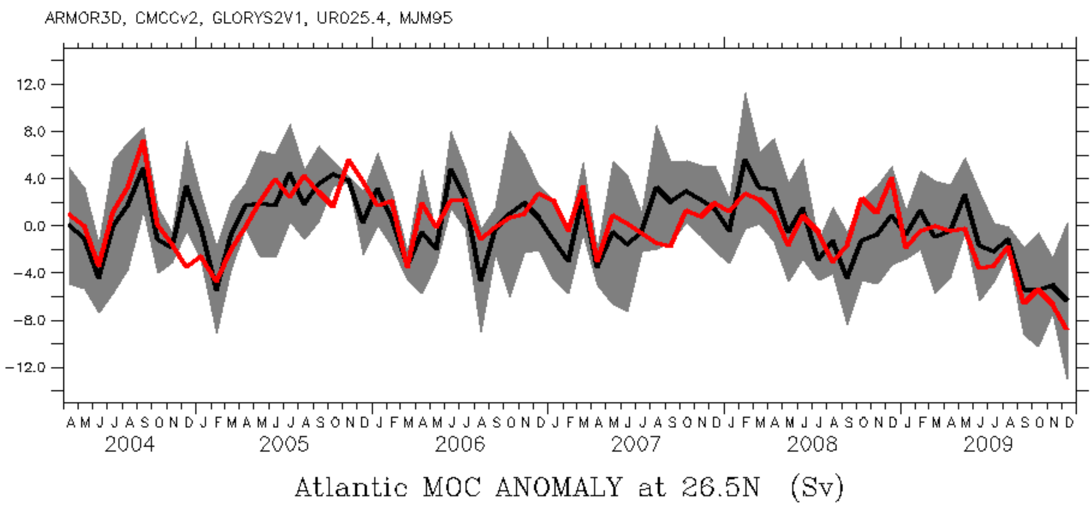

Figure 6: AMOC interannual anomaly at 26.5°N (Sv) from the ocean syntheses ensemble mean (black) and RAPID (red). The grey shaded area corresponds to ± 1 ensemble standard deviation (Sv).

Conclusions and perspectives

We described the setting of the NEMO ocean engine used in three eddy permitting global ocean reanalyses and one reference simulation of the altimetric era (1993-2009) carried out in the framework of the MyOcean EC funded project. The ORCA025 model configuration (1/4° horizontal resolution) of the NEMO code is used for both the reanalyses and the reference simulation without data assimilation which allows estimating the added value of data assimilation. Complimentarily to these reanalyses, a multivariate ocean state estimation based on observations only is also included in the present study.

The objective of the reanalyses carried within MyOcean project was to produce eddy-permitting ocean syntheses covering the altimetric era (1993-2009). Three global ocean and sea-ice reanalyses were produced (namely GLORYS2V1, C-GLORS, UR025.4), using the ORCA025 configuration of NEMO OGCM forced by ERA-Interim atmospheric parameters and assimilating altimetric SLA, in situ T/S profiles and SST. The 3 reanalyses differ mainly in the way data assimilation is performed. A simulation without data assimilation with the same ocean GCM (MJM95) was also performed.

The results presented here show that for a variety of ocean parameters (sea level, surface heat fluxes, Atlantic MOC), there is a good consistency between the different reanalyses. Robust features are present in MyOcean reanalysis products, which tend to show that eddy-permitting ocean reanalysis have become mature. Part of this success is related to the use of NEMO ocean engines which includes advanced numerical schemes that allow describing the ocean physics accurately, as proven by the results of the free run. Data assimilation was found crucial in correctly simulating some parameters such as GMSL variability and regional trends of sea level. The main advantage of having access to several reanalyses differing in the way data assimilation is performed is that it becomes possible to sample the uncertainty due to the data assimilation methods used. This uncertainty changes a lot from one ocean parameter to another but the main conclusion from that study is that multi model ensemble of the past ocean state would be able to efficiently sample the true ocean state, and hence provide more accurate ocean state estimates than any single reanalysis. Further work is needed to fully validate this approach but in the light of the results presented here, the methodology seems quite promising. This work will be continued in the framework of MyOcean2 EU funded project (2012-2014) and in the recent CLIVAR/GODAE-OceanView joint reanalysis intercomparison initiative.

Acknowledgements

The research leading to these results has received funding from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement n°218812 (MyOcean). GLORYS reanalysis also received support from INSU-CNRS, Mercator Océan and Groupe Mission Mercator Coriolis. Some computations presented in this study were performed using HPC resources from GENCI-CINES. The Florida Current cable and section data are made freely available on the Atlantic Oceanographic and Meteorological Laboratory (www.aoml.noaa.gov/phod/floridacurrent/) and are funded by the NOAA Office of Climate Observations. Data from the RAPID-WATCH MOC monitoring project are funded by the Natural Environment Research Council and are freely available from www.noc.soton.ac.uk/rapidmoc.

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MED12, OCEANIC COMPONENT FOR THE MODELING OF THE REGIONAL MEDITERRANEAN EARTH SYSTEM

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Introduction

MED12 [Lebeaupin-Brossier et al., 2011, 2012a; Beuvier et al., 2012] is the new regional configuration of the Mediterranean Sea of the ocean general circulation model NEMO [Madec and the NEMO Team; 2008]. The MED12 grid has been extracted from the 1/12° global operational Mercator model [Lellouche et al. 2012]. The development of MED12 is made in the continuity of the evolution of the French modeling of the Mediterranean Sea, following OPAMED16 [Béranger et al., 2005], OPAMED8 [Somot et al., 2006] and NEMOMED8 [Beuvier et al., 2010]. The MED12 domain covers the entire Mediterranean Sea and a part of the Atlantic Ocean, until 11°W. MED12 does not cover the Black Sea. With a horizontal resolution of 1/12°, MED12 is an eddy-resolving model in the major part of the domain. The vertical resolution uses 50 unevenly spaced vertical levels with the partial-cells parameterization for the bottom layer. The time step is 12 minutes.

The bathymetry comes from the 10th version of the Mercator-LEGOS bathymetry at a resolution of 30''x30'', composed of the merging between the GEBCO-08 database, the MEDIMAP bathymetry [Medimap Group, 2005] and the Ifremer bathymetry of the Gulf of Lions [Berné et al., 2004]. The initial states come from the MEDATLAS-II climatology [MEDAR/MEDATLAS Group, 2002] in the Mediterranean domain and from the climatology of Levitus et al. [2005] in the Atlantic domain. MED12 includes a new parameterization of the Atlantic inputs modelled through damping of 3D-temperature, 3D-salinity and sea surface height climatologies. The sea surface height climatology is built with GLORYS-1 data [Ferry et al. 2010] to conserve the ocean volume in a regional configuration using the filtered sea surface parameterization of NEMO. The bottom turbulent kinetic energy background in the bottom friction parameterization is a 2D field corresponding to the mean tidal energy computed from a tidal model [Lyard et al., 2006]. The river runoffs of Ludwig et al. [2009] and the Black Sea inputs are included following the method of Beuvier et al. [2010]. More details can also be found in Beuvier et al. [2012].

The MED12 model has been developed in the context of the SiMED and MORCE projects, in collaboration with Mercator Ocean teams and national laboratories. Several ongoing projects aim at coupling MED12 with atmospheric models and biogeochemical models. In the following, we present first results obtained with a free ocean simulation and with an ocean-atmosphere coupled simulation.

Ocean modeling

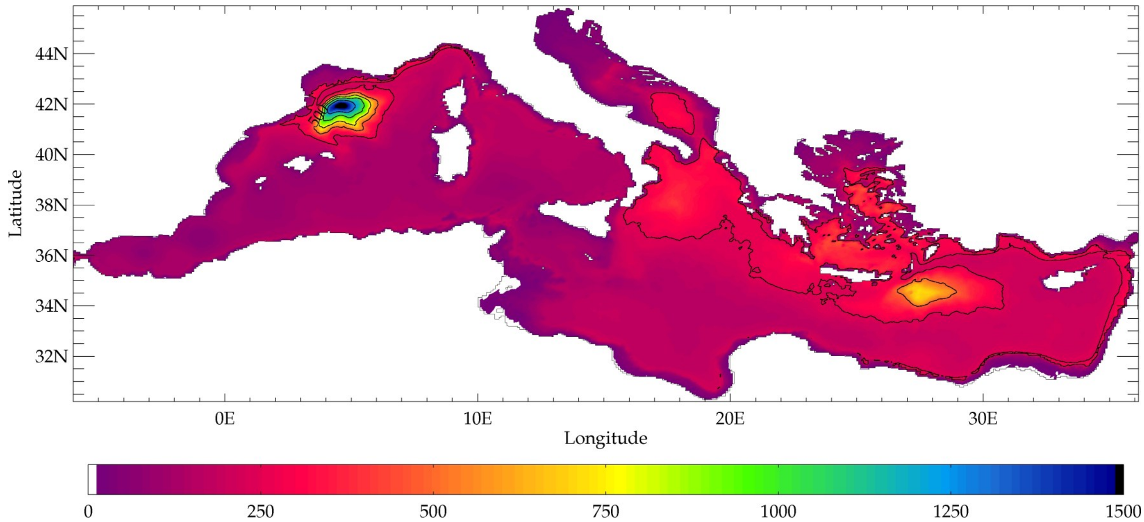
A 53-year simulation from 1958 to 2011, called hereafter MED12-long [Beuvier, 2011], was carried out. For the initial state, 3D temperature and salinity initial fields are weighted by a low-pass filtering with a time window of ten years of the MEDATLAS data covering the 1955-1965 period. The simulation starts in October 1958 with an ocean at rest. The atmospheric forcing is ARPERA [Herrmann and Somot 2008], a dynamical downscaling of the ERA40 reanalysis [Simons and Gibson, 2000] by the ARPEGE-Climate model [Déqué and Piedelievre, 1995].

The long-term variability of the Mediterranean Sea is illustrated by interannual variations of heat and salt contents between 1958 and 2011, expressed here by 3D-average temperature and salinity, T3D and S3D respectively (Figure 1). The model is compared with the two gridded climatologies IN3 [Ingleby & Huddleston, 2007] and MEDATLAS [Rixen et al., 2005]. The T3D and S3D of the whole water column (Figures 1a and 1b) are in good agreement with observations. The T3D is a little too high by 0.1°C in MED12-long while the S3D trend is well simulated, but with a lack of interannual S3D variations. In the surface layer (0-150m), the T3D is very well reproduced (Figure 1c), mainly thanks to the retroaction term relaxing the model sea surface temperature towards the “observed” sea surface temperature of Reynolds et al. [2002]. However, values of the surface layer S3D are too low by 0.04 to 0.28 psu (Figure 1d). In the intermediate layer (Figures 1e and 1f), values of both T3D and S3D are too high (+0.2°C for T3D, +0.02 to +0.08 psu for S3D). Nevertheless, the T3D interannual variations of the intermediate layer are well captured. In the bottom layer (Figures 1g and 1h), the T3D and S3D trends are a little higher than in the climatological datasets (+0.08°C, +0.03 psu) and no interannual variations are simulated. However, a large uncertainty exists for this layer, as both gridded datasets may over-estimate deep temperature and salinity interannual variations because of under-sampling (more pronounced for salinity).

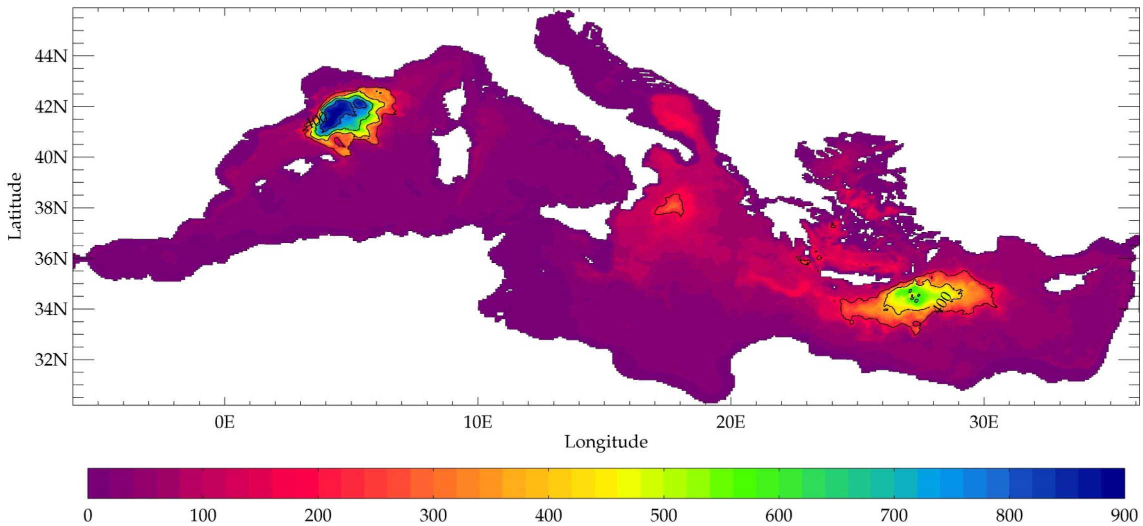
*Figure1: Mean potential temperature **T3D** (a, c, e and g) and mean salinity **S3D** (b, d, f and h) for different layers of the Mediterranean Sea: the whole water column (0 m–bottom, a and b), the upper layer (0–150 m, c and d), the intermediate layer (150–600 m, e f), and the deep layer (600 m–bottom, g and h), and, for differents datasets: the **MED12-long** simulation (blue solid line), the interannual gridded database of [Rixen et al., 2005] (black dashed lines, with the ±1 standard deviation interval in grey) and the EN3 interannual gridded database [Ingleby and Huddleston, 2007] (green solid line). The S3D scales are five times lower than the T3D allowing the representation of the same impact on potential density.*

Intermediate and deep convection regularly occur in specific areas of the Mediterranean Sea as illustrated in Figure 2. The turbocline depth is used to show the convection depth as it is a better criterion available in NEMO for the low stratified Mediterranean Sea than the criteria on the thermocline or the pycnocline depth. The 53-year mean of the annual turbocline depth maxima (Figure 2a) highlights well known areas of intermediate or deep convection, such as the Gulf of Lions (around 42°N - 5°E), the Rhodes Gyre in the Levantine sub-basin (around 34°N - 26°E), the southern Adriatic sub-basin and the Aegean sub-basin. A new area is also captured in the northern Ionian sub-basin. However, the values for the Adriatic sub-basin are not deep enough, barely reaching 300 m depth in average whereas observations show values reaching a maximum of about 1200 m depth during several years. Interannual variations (Figure 2b) are relatively high in the Gulf of Lions (standard deviation of 800 m). Interannual variations are also relatively high in the Levantine sub-basin (standard deviation of 500 m) and in the northern Ionian basin. According to the ratio between the standard deviation and the 53-year mean of turbocline depth (Figure 2c), values over 120% at the north-eastern and the south-western extremities of the convection area in the Gulf of Lions, indicate the maximum spatial extent of the deep water formation that can be reached during strong events. In the same way, high values in the Levantine area are relative to formation of Levantine Deep Water. And values around 80% in the northern Ionian sub-basin show intermediate water formation during very strong winters.

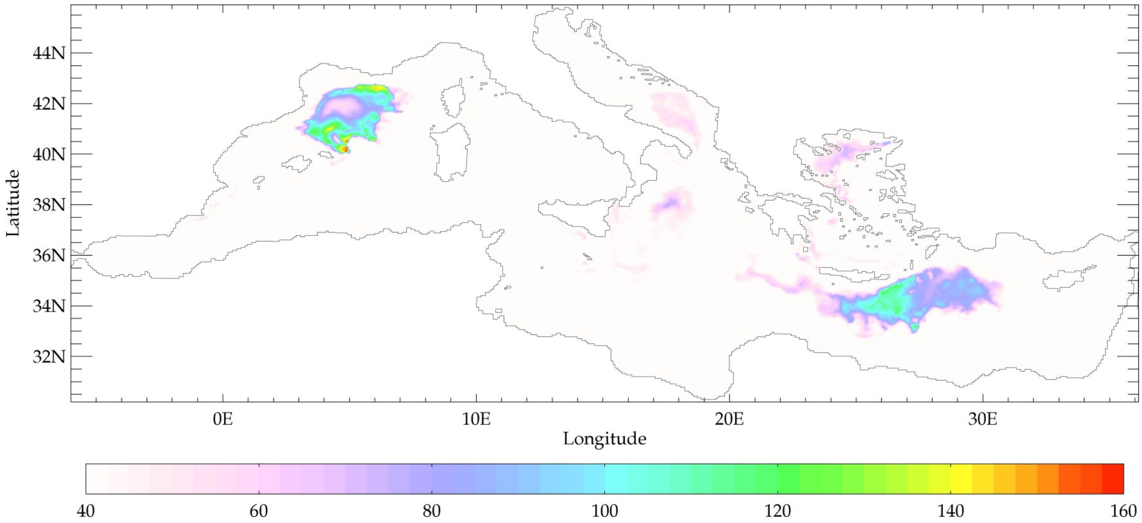
This MED12 configuration is devoted to be used soon in the reanalysis of the Mediterranean circulation driven by ALADIN-Climate atmospheric forcing from CNRM (horizontal resolution of 12 km). At the same time, new versions of Mediterranean configurations are being developed, using more 75 vertical z-levels or using a higher horizontal resolution MED36 (1/36°, horizontal resolution of 2.5 km).



(a)



(b)



(c)

Figure2: (a) Average of the yearly maximum turbocline depth over the period 1958-2011 (in meters, contours every 250 m), (b) standard deviation of the yearly maximum turbocline depth around the average in (a) (in meters, contours every 200 m), and (c) ratio (in %) between (b) and (a).

Ocean-Atmosphere Coupling

MED12 is the ocean compartment in the MORCE (*Model of the Regional Coupled Earth system*) system [Drobinski et al., 2012]. MED12 is coupled to the *Weather Research and Forecasting* (WRF) atmospheric model [Skamarock et al., 2008]. The WRF domain covers the Mediterranean basin [28°N-50°N, 13°W-42°E] with a 20-km horizontal resolution and has 28 sigma-levels in the vertical. Initial and lateral conditions are taken from the ERA-interim reanalysis [Simons et al., 2007] provided every 6 hours with a 0.75° resolution and a nudging towards the driving fields is applied with a coefficient of 5.10^{-5} s^{-1} for temperature, humidity and velocity components above the planetary boundary layer. The complete set of physical parameterizations chosen for the WRF model is detailed in Lebeaupin Brossier et al. [2012b].

Companion uncoupled and coupled simulations have been done. In the first one, MED12 is driven in surface with a 3-hourly frequency, by WRF fluxes extracted from the dynamical downscaling of the ERA-interim reanalysis obtained with WRF alone. And the coupled simulation runs with two-way interactive exchanges between the two compartment-models managed by the OASIS coupler [Valcke, 2006]. The exchanged variables are the sea surface temperature, the heat flux (solar Q_s and non-solar Q_{ns}), the water flux (F_w=E-P) and the momentum flux (tau). The coupling frequency is 3 hours. Both simulations run from January 1989 to December 2008 and start with an ocean at rest.

Focusing on the extreme 2005 deep convection event in the Gulf of Lions, the comparison between the uncoupled and coupled simulations is illustrated by the horizontal and vertical distributions of the convection in Figure 3. Deeper mixed layer is formed in the southern part of the Gulf of Lions (around 4°E-41°N) in the uncoupled simulation (Figure 3a) while the deep convection area is extended farther eastwards in the coupled simulation (Figure 3b). In particular, a larger turbocline depth is found in the Tyrrhenian sub-basin (Bonifacio gyre area) and in the Ligurian sub-basin. In the Ligurian sub-basin, the chronology of the convection events driven by strong winds is the same in the two simulations. But the saltier and colder intermediate layer is rapidly mixed on 15th February 2005 in the coupled simulation and then the mixed layer reaches the sea bottom of the Ligurian sub-basin (2200 m). In the uncoupled simulation, the turbocline depth reached only 450 m depth on 8th March 2005. The difference in the characteristics of intermediate and deep layers is the ocean response to the coupled mode, and is an integrated signature of the air-sea flux modulation by the coupling (for example, larger heat loss over the Ligurian and Bonifacio cyclonic gyres in winter 2005, Figure 3).

The coupling of MED12 with other atmospheric models is currently in development (COSMO-CLM at Frankfurt University, ALADIN-Climate at Météo-France), to be part of multiple-compartment regional climate systems over the Mediterranean region and to further investigate the interannual variability of strong air-sea exchanges that trigger in particular the deep ocean convection.

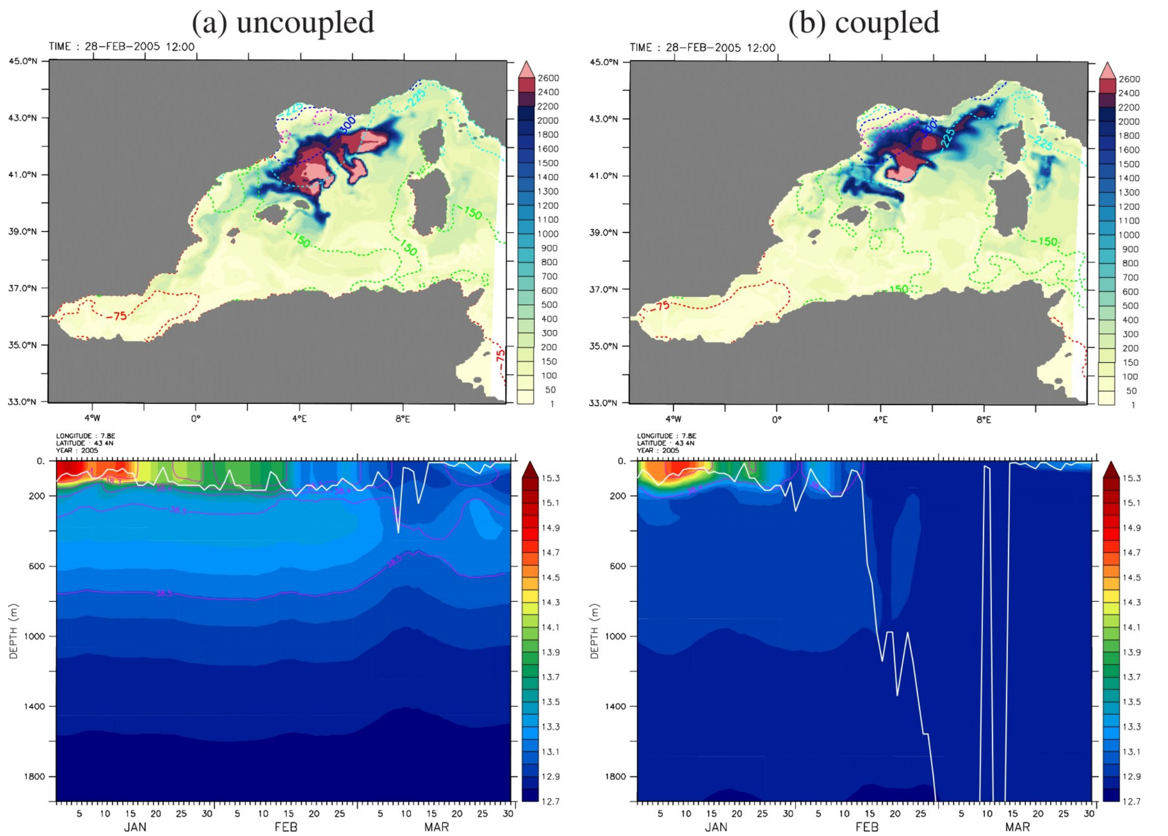


Figure3: Top panels: Depth of the turbocline for 28th February 2005 (in m, color) and monthly mean heat loss (W m $^{-2}$, dashed lines every 75 W m $^{-2}$). Bottom panels: for the period January to March 2005 at 7.8°E-43.4°N between 0 and 2000 m in the Ligurian sub-basin, Howmöller diagrams of temperature profiles (°C, color), salinity profiles (psu, purple contours every 0.1 psu) and turbocline depth (in m, white contour) - in the (a) uncoupled and (b) coupled experiments.

Conclusion

MED12, oceanic regional model based on the NEMO code, is an efficient numeric tool, dedicated to the study of complex oceanic processes and adapted to the specificities of the Mediterranean Sea. Driven by interannual atmospheric forcings, rivers and Black Sea freshwater inputs, exchanges with the Atlantic Ocean, for long-term runs, MED12 allows assessing the variability of processes such as the open sea convection. MED12 is also coupled to several atmospheric models in order to study the interactions between atmospheric and oceanic fine scale processes on long periods of time. Finally, note that coupling with biogeochemical models (*e.g.* Eco3M or PISCES) is underway. Added to the coupling of atmospheric models, including hydrological and vegetation models, MED12 is an important modeling component that fully completes several Regional Earth System configurations, and is thus a key model involved in several current projects that investigate the Mediterranean Sea climate system.

Acknowledgements

This work was granted access to the HPC resources of IDRIS (Institut du Développement et des Ressources en Informatique Scientifique) of the Centre National de la Recherche Scientifique (CNRS) under allocation 2010 and 2011 (project number 010227) made by Grand Equipement National de Calcul Intensif (GENCI). This work is a contribution to the HyMeX international program on the study of the water cycle in the Mediterranean Sea.

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NEMO FOR CLIMATE MODELING

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Background

The ocean is a central component of the climate system, providing long term memory and contributing to the variability of heat and CO2 uptake on a number of time scales. NEMO global configurations are used in coupled mode by a large fraction of the climate Modeling community. They distinguish themselves from the other uses in several ways: for instance local and global conservation constraints are key for long simulations and the coupling to the other climate components, most prominently with the atmosphere and sea-ice, offers specific challenges. Historically, the global ORCA configurations couple the three NEMO engines (ocean dynamics NEMO_OPA, sea-ice NEMO_LIM and biogeochemistry NEMO_TOP) to several atmosphere General Circulation Models (GCMs) to form global Earth System Models (ESMs). NEMO climate configurations span different uses as well as grid resolution and length of simulation, ranging from high resolution coupled models for short term predictability studies or process understanding (e.g. ORCA025 in SINTEX or GloSea5), to low resolution paleoclimate simulations (e.g. ORCA2 in IPSL) or control and historical multi-century simulations (e.g. ORCA1 in EC-Earth or CNRM-CERFACS) that contribute to international intercomparison projects such as CMIP (Taylor et al. 2012).

NEMO was first developed for global ocean and climate uses. The associated constraints have hence always been a driver for the basic numerical and physical choices in the code. The global ORCA2 configuration was first coupled in 1995 to the Météo-France/CNRM ARPEGE atmosphere GCM at CERFACS (Guilyardi and Madec 1997), where the OASIS coupler (Valcke 2006) was developed. Coupling to other atmosphere GCMs then followed: to LMD to form the IPSL model in 1996 (today IPSL-CM5B, Dufresne et al. 2012), again to ARPEGE to form the CNRM-CERFACS model (Voldoire et al. 2012), to ECHAM to form the SINTEX model in 1998 (which branched both into the SINTEX-F1 model run on the Earth Simulator, Luo et al. 2008) and in one of the current CMCC models (CMCC-MED, Scoccimarro et al. 2011), to HadAM3 to form HadOPA in 2001 (a precursor to the current HadGEM3, Hewitt et al. 2011), again to ECHAM to form KCM (Park et al. 2009), to IFS to form EC-Earth (Hazeleger et al. 2012, Sterl et al. 2012). Today NEMO is coupled through its OASIS interface to multiple atmosphere GCMs in Europe and worldwide. Hundreds of studies explore the role of the ocean in climate using NEMO and NEMO is the ocean/sea-ice components of several CMIP coupled models (some even including the biogeochemistry component like for the IPSL), which scenario simulations inform the IPCC process.

Being routinely coupled to different atmosphere, sea-ice (e.g. LIM, Fichefet et al. 1999, and CICE, Hunke and Lipscomb, 2008) and other biogeochemistry models (RCEM, MEDUSA, HADOCC, …) led to rethink and redesign the coupling interface, both physically and algorithmically, on a regular basis (e.g. Fig. 1). Today, the NEMO surface module encapsulates a set of different physical and numerical choices for coupling which presents a significant progress compared to the former more *ad-hoc* approaches.

Current and future challenges

More than fifteen years after the first use of NEMO in coupled mode, new challenges invite to revisit the science of coupling in the model in several directions. Indeed evolving physical and algorithmic interfaces of ocean/atmosphere and ocean/sea ice, the advent of new components, and the increase in resolution all require new coupling strategies. Examples include:

- The synchronous or asynchronous air-sea coupling has not evolved much since the 1990s and the vision laid out in Fig.1 has still to be fully explored. A notable recent development in the inclusion of the diurnal cycle in the coupling (Bernie et al. 2007) which required to revisit the mixed-layer physics and led to significant changes in the mean state and the coupled variability in the tropics (Bernie et al. 2008, Masson et al. 2012, Terray et al. 2012). Ocean currents are now taken into account when computing the surface wind stress which led to significant impacts in some coupled models (Luo et al. 2008).
- New research shows that the coupled interface has not numerically converge with this classical coupling (Lemarié et al. 2012). As implicit calculations are not yet possible from the bottom of the ocean to the top of the atmosphere, via the sea-ice, efficient numerical techniques have yet to be developed to account for this lack of convergence, which can presumably have large impacts in region where the ocean and the atmosphere are tightly coupled, like in the tropics.

- The addition of new components like surface waves, biogeochemistry in the sea-ice or under-ice shelf seas and icebergs will require to revisit the way the classical coupling is done, both between the ocean and the atmosphere and between the ocean and the continental ice shelves.
- Very high resolution configuration either global, regional or nested (Fig .2) will require revisiting the physical parameterizations to account for new physics and/or new coupled constraints (see for instance the CIRCE configuration, Gualdi et al. 2012).

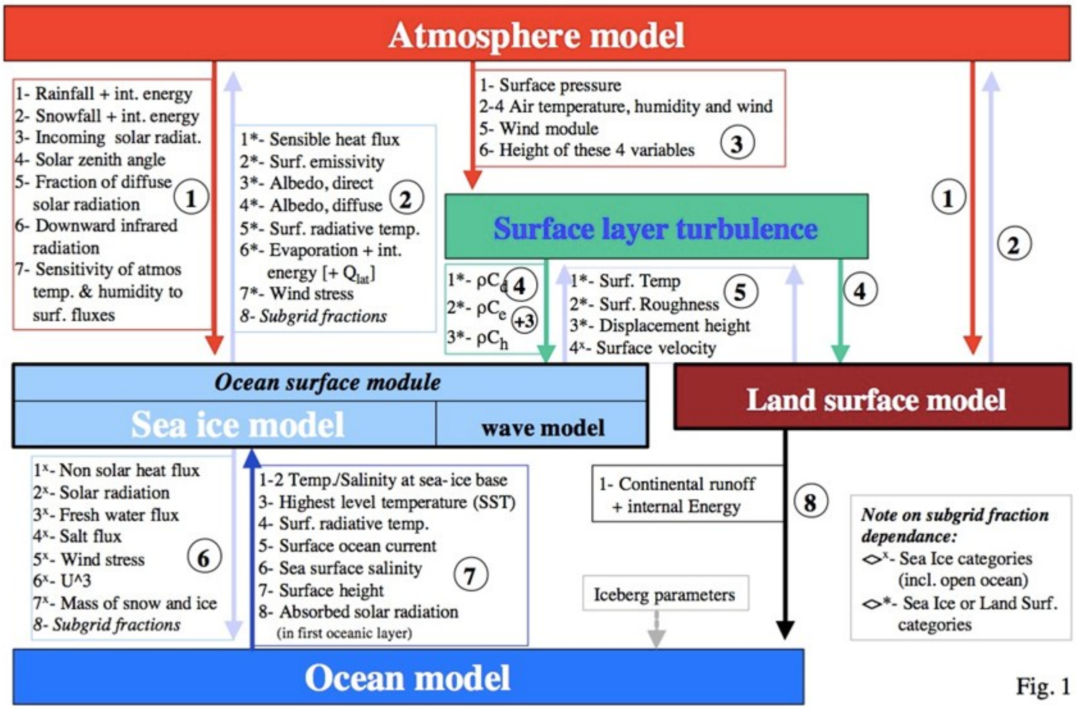

Figure 1. Proposed interfaces for Atmosphere/Ocean/Sea ice/Land Surface (unpublished manuscript by E. Guilyardi, G. Madec, T. Fichefet, O. Marti, J. Polcher and S. Planton, 2006). One main difference with classical interfaces is the introduction of new modules (e.g. ocean surface, surface turbulence). This added modularity simplifies the exchanges, ensures they are "process-based" and helps distinguish fast and slow processes. The exchanges are represented by groups of fields attached to solid colored arrows and numbered from 1 to 8. This thinking went into the design of the latest surface module of NEMO but the complete vision has still to be fully explored.

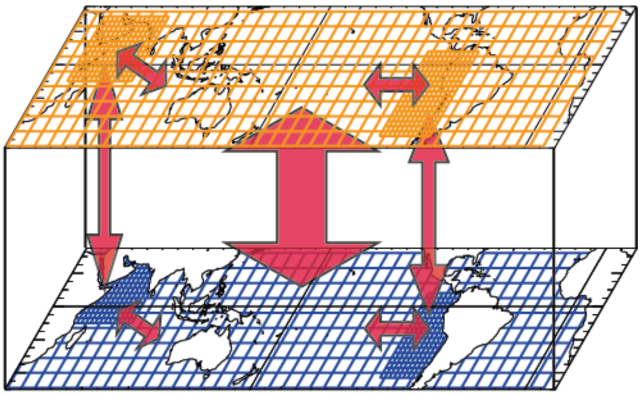

Figure 2. High resolution global-nested Ocean-Atmosphere coupling as planned with WRF/NEMO and AGRIF zooms (Courtesy Sébastien Masson, LOCEAN/IPSL).

Other challenges for NEMO for climate studies include the performance of smaller and hence less scalable, configurations (e.g. ORCA2 run at multi-millennia paleoclimatic time scales) on the new generation of massively parallel supercomputers. At the other end of the spectrum, very high resolution global configurations (e.g. ORCA 1/12th or higher resolutions) will need to run in Earth System mode, hence including biogeochemistry. Coarsening techniques, where the sea-ice and/or the biogeochemistry are computed less often and on less points than the ocean engine, are required to make this possible. Fueled by the community interest in multi-year to decadal predictability, the ocean components of climate model now need to be initialized. Ranging from simple nudging techniques to the more elaborate ecosystem of NEMO-based assimilation tools, there is a large spectrum of strategies currently being explored by the NEMO climate community (Koenigk et al. 2012, Swingedouw et al. 2012, Cassou et al. 2011) namely building on coupled ocean-atmosphere Seasonal Forecasting expertise (like System 4 at ECMWF or GloSea5 at the Met Office). No doubt this will also lead to new physical, algorithmic and computational developments in NEMO.

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