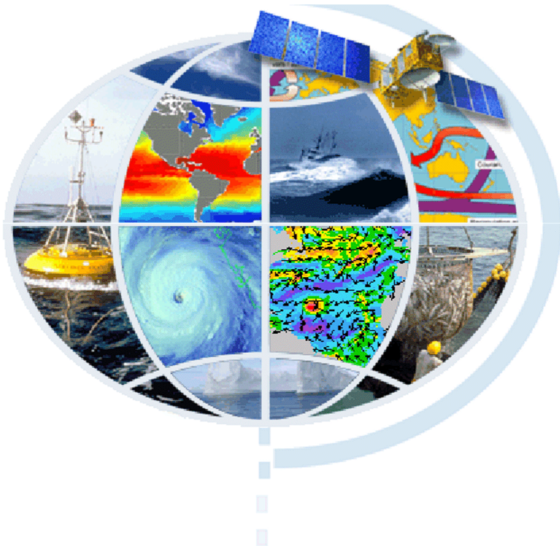
MERCATOR Quarterly Newsletter

Editorial – April 2008



Greetings all,

By the end of April 2008, the final meeting of the MERSEA European Project set up in Paris, in the Institut Océanographique.

The aim of the project was to develop a European system for operational monitoring and forecasting on global and regional scales of the ocean physics, biogeochemistry and ecosystems.

It was surely a challenge to get together many different partners to build the future European operational oceanography of tomorrow. It was also a challenge for the MERSEA teams to demonstrate their capacity to collect, validate and assimilate remote sensed and in situ data into ocean circulation models, to interpolate in time and space for uniform coverage, to run nowcasting (i.e. data synthesis in real-time), forecasting, and hind-casting, and to deliver information products. The project also had to develop marine applications addressing the needs of both intermediate and end-users, whether institutional or from the private sector

This Newsletter collects some of the many results obtained during this project. Several aspects are tackled: global and regional forecasting systems, observations, and applications.

The News is written by the Coordinator of the Project, Yves Desaubies. He draws MERSEA results up.

In a first article, Marie Drévillon et al. present the MERSEA/Mercator-Ocean V2 global ocean analysis and forecasting system. In a second one, Hervé Roquet et al. describe L3 and L4 high resolution SST products. The next article, written by Bruce Hackett et al., focuses on Oil spill applications. The article of John Siddorn et al. closes the issue by a description of the development of a North-East Atlantic tidal NEMO system.

Enjoy your reading!

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Mersea, a precursor to GMES Marine Core Service

By Yves Desaubies[1]

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The four-year Mersea Project, funded since 2004 by the European Commission to develop Ocean and Marine Applications for GMES, is now nearing its conclusion. As the final reports are being prepared it is timely to take stock of its achievements and legacy.

The stated objective of Mersea was to develop an integrated European operational system for global monitoring and forecasting of the ocean and a coordinated network of regional systems for European waters. To reach that objective, the project has undertaken a wide range of activities, including basic research, system engineering and information technology, development of merged data products, upgrades of the systems, special focus experiments, demonstration of user-oriented applications, training and outreach.

This multipronged approach has proven quite successful in engaging a large multidisciplinary European community of scientists and engineers to tackle the diverse challenges set forth in the proposal. While some of the research conducted in the project is prospective and will not yield practical implementation in the short range, several important developments have been directly transferred into the systems, with great positive impact on their performance. The list is long, and only a few examples are selected here: the results on high resolution physical modelling (partial steps, advection schemes); downscaling and nesting; process representation and data assimilation in ecosystem models; sea-ice data assimilation; improved retrievals, production of merged data sets, and re-analysis in remote sensed data (altimeter, SST, surface fluxes, and ocean colour).

We have long advocated how critical it is for operational ocean systems to maintain in situ observations. Although the project could not support a large observational programme, it did have several actions on multidisciplinary time series stations, contributions to Argo (in particular at high latitudes), and glider demonstrations (and the set up of a European user group, EGO). The global synthesis of in situ data is an important advance in the use of such data for resolving seasonal and inter-annual variability. Efforts to promote systematic observations from research vessels have had more modest results.

Data assimilation into the circulation models is one of the most significant achievement of the project; in particular, the global 1/12° was a formidable challenge, that has been suc cessfully met. Most of the models now assimilate altimeter, sea surface temperature, in situ profiles, and / or sea-ice; the positive impact of assimilation has been convincingly demonstrated. Nesting of the different models into one-another has been attempted, but with mixed results, in part for lack of time to assess fully the impact and to resolve some of the inevitable bugs. This issue will have to be tackled in the future.

Major upgrades and improvements have been implemented into all the systems, in terms of resolution (spatial, vertical, and time), assimilation schemes, inclusion of bio-geochemical variables (and ice in some cases). Several of the systems have adopted the NEMO code, the TOPAZ system has been transferred into the operational suite at met.no.

The integration of the different components, comprising the Monitoring and Forecasting Centres and the Thematic Data Centres is effected through a concerted approach developed as the Mersea Information Management system, which is one of the key stones of this whole system of systems. Participants have adhered –and implemented, to common standards which allow efficient access to the data and products (discovery, visualisation, download), with the maintenance of catalogues, inventories, servers, and standard format.

Similarly, the validation and assessment of MFC outputs has followed a common method and set of principles, which have been adopted in the context of the Global Data Assimilation Experiment.

Two Special Focus experiments have investigated the modelling and forecasting of ecosystems in the Mediterranean and on the North West European shelves, and the potential impact of the Mersea high resolution analysis for improved seasonal forecasting. The ecosystem models have been incorporated into the operational suites, but still warrant further evaluation and validation. The seasonal forecasting developments are somewhat less conclusive at this point; however, studies conducted at Météo France suggest that improved hurricane predictions can be achieved by incorporation of high resolution upper ocean temperature information from the global system.

Specific user oriented applications for oil-spill drift forecast, ship routing, and support to the off-shore industry in the Gulf of Mexico, have been considered, with tantalizingly promising results. The drift forecasts have made the most interesting progress, with field exercises, and a fruitful cooperation with the Interisk project, and several key users and stakeholders (Met agencies, emergency response teams). Nonetheless, accurate forecasting of ocean currents at very high resolution is a real challenge, which has become apparent in the stringent requirements set forth by the offshore industry. Thus one must be realistic in matching capability with expectations, but a positive dialogue has been initiated with intermediate users.

Two key words in GMES must be underscored: **G**lobal and **E**nvironment. MERSEA has addressed both aspects. Particular emphasis has been put on environmental monitoring. We have initiated a positive dialogue with the European Environmental Agency, and participated in its EMMA initiative (European Marine Monitoring and Assessment). While it is recognized that the MERSEA system can deliver only a subset of the Core Set of Indicators required by the State of the Environment reports, or by the Conventions (OSPAR, HELCOM, UNEP/MAP), they are key ones, underpinning climate change, large marine ecosystems and the understanding of trans-boundary transports. For historical reasons, several processes have developed independently: the Conventions, national mandates, the EEA (with its Expert Topic Centres), the Shared Environment Information System, ICES, and now the emerging Marine Strategy Directive, European Marine Observations and Data System (EMODNET, associated with the Maritime Policy), all of which require marine observations, data and information systems. There is a clear need for convergence and streamlining. The Marine Core Service will play an essential role in this context.

In the course of the project, the concept of the European Marine Core Service has emerged, that provides an integrated service to intermediate users and policy makers in support of safe and efficient off-shore activities, environmental management, security and sustainable use of marine resources. In its present configuration, the Mersea system delivers a set of basic, generic information products based upon common-denominator physical and bio-geochemical state variables. Although it is developed primarily to fulfil the reporting, monitoring and forecasting requirements of European agencies and stakeholders, they do have a global scope.

Several of the concepts, principles and techniques developed in Mersea are being extended in the coastal realm in the course of the ECOOP project. They are also to a large extent at the basis of the MyOcean vision –although the objectives and emphasis are different: while Mersea developed the system, MyOcean will stress the services and the overall framework in which the Marine Core Service will operate.

The main achievement and legacy of Mersea is perhaps its contribution to the emergence and establishment of Marine Core Service in Europe.

Aknowledgements

The Mersea project has been partially supported by the European Commission, under contract AIP3-CT-2003-502885 of the FP6.

The Mercator Ocean global 1/12° operational system: Demonstration phase in the MERSEA context

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Introduction

In the context of MERSEA project, Mercator-Ocean is developing a new ocean forecasting system (PSY4V1) which consists of a global ocean and sea ice model (at the resolution of 1/12°), based on the NEMO OGCM coupled to the SAM 2V1 data assimilation scheme based on the SEEK filter. The Mercator demonstration phase consists of a short near real time experiment (two weeks forecast on April 2008) using this new ocean forecasting system. To assess the quality of the global ocean and sea ice model and to build the background error for the assimilation scheme, an interannual simulation without data assimilation has been realized. A 5-month hindcast experiment has been also performed in order to check the feasibility of the data assimilation proposal but also to provide the initial oceanic condition for the Mercator demonstration phase.

The PSY4V1 forecasting system

The PSY4V1 ocean model component is built from the OGCM NEMO 1.09 [Madec, 2008]. It consists of an eddy resolving global ocean model coupled to the sea ice model LIM2 [Fichefet & Gaspar*,* 1988]. The grid is a global quasi isotropic ORCA-type grid with a resolution of 1/12° with 4322X3059 points. T he vertical resolution based on 50 levels with layer thickness ranging from 1m at the surface to 450 at the bottom. The vertical coordinate is z-level with partial steps [Barnier, *& al.*, 2006]. TVD advection scheme [Lévy, *& al.*, 2001] and an energy and enstrophy conserving scheme [Arakawa & Lamb, 1980] are used. A free surface filtering the high frequency gravity waves [Roullet & Madec*,* 2000] is used for the surface boundary condition. The model is initialized with the Levitus 2005 temperature and salinity climatology. Two restoring zones toward climatological temperature and salinity are prescribed, one at Gibraltar strait and the other in the Bab el Mandeb strait. A monthly climatological runoff is applied. The closure of the turbulent equation is a turbulent kinetic energy mixing parameterization. An isopycnal laplacian operator is used for the lateral diffusion on the tracers and a horizontal bilaplacian operator is used for the lateral diffusion on momentum. The global bathymetry is processed from ETOPO2V2 bathymetry. The model is forced by daily mean analyses provided by ECMWF using the CLIO bulk formulae [Goosse, *& al.*, 2001]. The PSY4V1 assimilation system is based on the SAM2v1 tool which is a multivariate assimilation algorithm derived from the Singular Extended Evolutive Kalman (SEEK) filter analysis method [Pham et al., 1998]. It is a sequential method where the innovation is calculated during the model integration by using the First Guess at Appropriate Time (FGAT) approximation. The error statistics are represented in a subspace of small dimension where the background error covariances are modelled by an ensemble of 3D anomalies. The formulation of the assimilation algorithm relies on a low-rank error covariance matrix, which makes the calculations tractable even with state vectors of very large dimension. The extrapolation of the data from observed to non-observed variables is performed along the directions represented by these error modes which connect all dynamical variables and grid points of the numerical domain. Weekly dependant multivariate 3D anomalies (HBAR, TEM, SAL, U, V)[1], computed from the interannual simulation without data assimilation, have been used to estimate the background error. The analysis provides a 3D oceanic correction (TEM, SAL, U, V), which is applied progressively during the model integration by using the IAU method (Incremental Analysis Update). Unlike the original SEEK filter, SAM2V1 doesn't evolve the error statistics according to the model dynamics. However, some form of evolutivity of the background error is taken into account by adapting the error variance at each analysis cycle. Numerically, the analysis step of the conventional Kalman Filter is reformulated to take advantage of the low-rank approximation, leading to a more efficient inversion in the reduced space than in the observation space [Testut et al., 2003]. To minimise the computational requirements, the analysis kernel in SAM2V1 is massively parallelized and integrated in the operational platform hosting both the SAM2 kernel families via the PALM software [Piacentini et al., 2003].

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[1] HBAR: Barotropic Height
TEMP: Temperature
SAL: Salinity
U: Zonal Velocity component
V: Meridional Velocity component

Assessment of the PSY4V1 system

A 8 years simulation has been performed with the free model configuration from 1999 to 2006 to validate the general circulation, the meso-scale representation and the seasonal and interannual variability. All these points are crucial to build the statistic data base which will be used to describe the background error in the assimilation scheme. To illustrate the quality of the free model, the Figure 1 shows the Root Mean Square of sea surface height over the period 2004 to 2006. The mean general circulation is in good agreement compare to the altimetry observation and the main variability patterns observed in the ocean are well reproduced. The main ocean currents have the good intensity in term of mean and variability and the western boundaries currents pathways are correct: the Gulf Stream separation, the North Atlantic current penetration, the Kuroshio extension, the North Brazil or the Agulhas currents are realistic. The level of variability in the tropical region and in the circumpolar current is also in good agreement with altimetry observation. A description of regional features and their influence on the larger scale would be realised with such simulation like for example the study in Caribbean Sea, Gulf of Mexico or China Sea, currents around Australia or circulation in the Mozambic channel. All these results are clearly better compared to previous version of global ocean simulation realised with the NEMO ocean model thank to the physical parameterisation in the model and of course thank to the high horizontal resolution of this model.

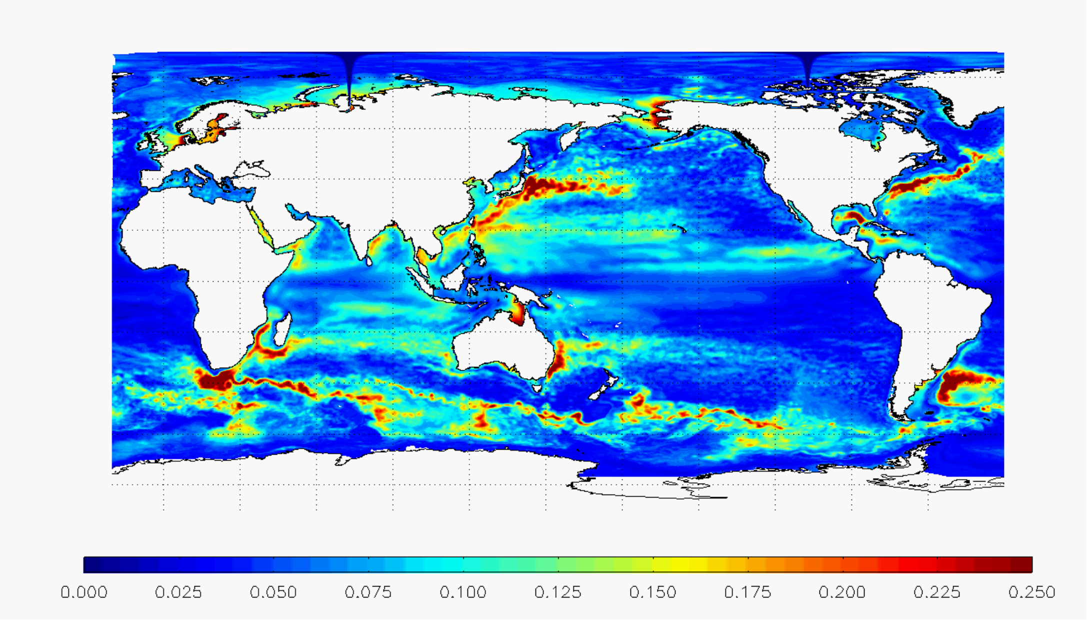

Figure 1

2004-2006 Sea Surface Height variability (m) simulated with the Mercator Océan high resolution global configuration ORCA12.

To evaluate the ability to monitor the circulation in term of realistic mean oceanic structures and variability, a 5-month hindcast experiment, from November 2007 to March 2008, using the fully PSY4V1 system has been performed. This system has been deployed on the computer of Mercator-ocean (SGI altix) using 158 processors for a total memory of 800 Gigabytes. This simulation uses a 7-day assimilation cycle. Operational dataset has been assimilated: Sea Surface Temperature (SST), in-situ profiles of temperature and salinity and Sea Level Anomalies (SLA). A mean dynamic topography [Rio and Hernandez, 2004] is also used as a reference level for the Sea Surface Height (SSH). This simulation shows a significant convergence in terms of innovation statistic. In addition to internal diagnostics as misfits to assimilated data, validations by independent in-situ measurements demonstrate the benefit gained from the assimilation (see figure 2). This hindcast experiment is also characterised by a good stability without diverging trajectory. This feature is an important guarantee for the robustness of the PSY4V1 forecasting system considering that this simulation provides the spin up phase of the near real time demonstration.

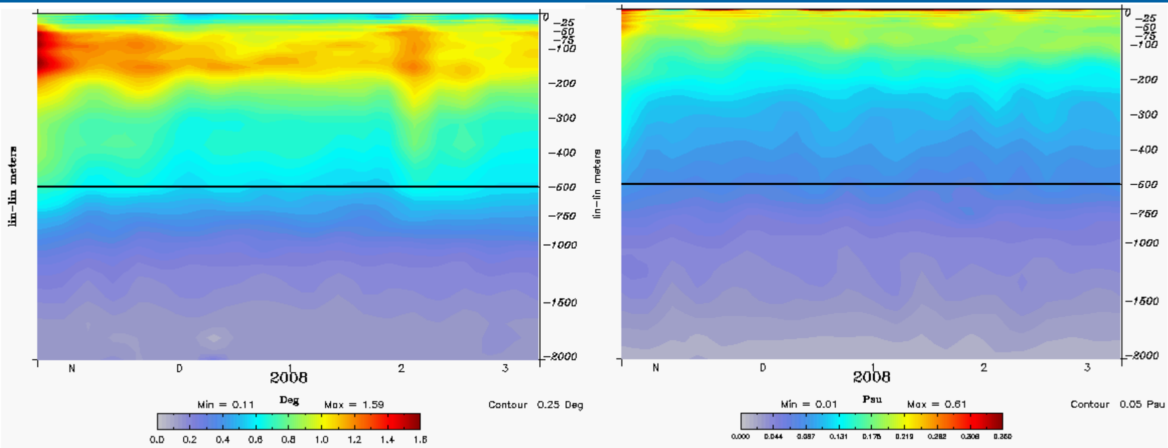

Figure 2

RMS of innovation Temperature (left) and Salinity (right) until 2000 meter depth during the first 5 months (from November 2007 to March 2008) for global ocean. These vertical profiles of Temperature and Salinity (ARGO floats, XBT/CTDs, moorings or buoys) are assimilated.

A near real time demonstration using the PSY4V1 forecasting system

A near real time demonstration using the PSY4V1 forecasting system has been performed for two weeks on April 2008. This ocean forecasting experiment previously initialized from the 5 months hindcast experiment simulate an operational sequence consisting in a nowcast step followed by two weeks forecast. This experiment has been produced on the French Meteorological Office (Météo-France) super computer (NEC SX8-R). It enables to assess the PSY4V1 system ability to be deployed in near real time on this operational computer. This system has been performed on 8 nodes (128 Gigabytes) of 8 processors for a total memory of 600 Gigabytes and four hours and thirty minutes (real time) have been necessary. To illustrate this first step, the two weeks forecast in the Indonesian region of the sea surface salinity is shown in figure 3. This demonstration phase has been well achieved and very encouraging results have been produced. This system demonstrates clearly its great potentiality in terms of performance (mesoscale variability) and application (regional systems among others topics) offering then, new perspectives to monitor global ocean circulation at high resolution.

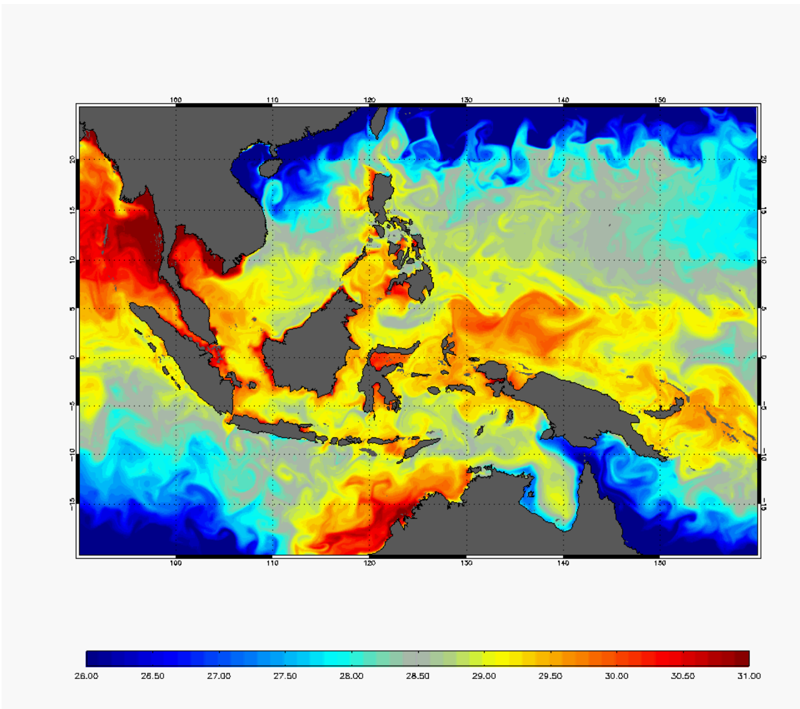

Figure 3

Forecast for the 21 April, performed the 9 April, of the sea surface salinity in the Indonesian region.

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Ocean circulation and water properties in 2007 described by the MERSEA/Mercator Ocean V2 global ocean analysis and forecasting system

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During the MERSEA project final meeting in Paris, the very first results of a global ocean forecasting system at eddy resolving resolution (1/12°) have been displayed, illustrating the final achievement of the project, and the beginning of the MyOcean operational oceanography era. Mercator Ocean has been designing and operating a hierarchy of ocean analysis and forecasting systems since 2001. The MERSEA V2 system is the state-of-the-art system. It demonstrates that the coupling of NEMO and SAM2 (Système d'Assimilation Mercator V2) can produce high quality real time analyses and forecast of the ocean at the global scale, and up to the "eddy resolving" resolution. The V2 system comprises a global ocean configuration at ¼° horizontal resolution and a North Atlantic and Mediterranean zoom at 1/12°. It is operated in real time since April 2008, after a comprehensive validation over the year 2007. In a first section, the ocean and sea ice models as well as the data assimilation system are shortly described. In a second section, some results of the validation over the year 2007 are commented. In a final section, the strong points and weaknesses of the system are discussed.

Description of the analysis and forecasting system: methods and data

Ocean and sea ice modelling

The target MERSEA V2 forecasting system uses the NEMO 1.09 (Nucleus for European Models of the Ocean) modelling system (Madec, 2008) which includes the version 9 of OPA, coupled to the thermodynamic-dynamic sea ice model LIM2 (Louvain sea Ice Model 2, Fichefet and Morales Maqueda (1997), Goosse and Fichefet (1999), as described in Drévillon et al. (2007, 2008). The global ¼° configuration was built within the framework of the DRAKKAR (www.ifremer.fr/lpo/drakkar) working group. The zoom at a 1/12° horizontal resolution covers the North Atlantic from 20°S to 70°N and the Mediterranean Sea.

As shown by Barnier (2006) the combination of an energy-enstrophy conserving scheme for momentum advection with a partial steps representation of the bottom topography significantly improves the mean circulation and the representation of western boundary currents. Moreover, the ¼° horizontal resolution model solution is often comparable to solutions obtained at 1/6° or 1/10° resolution on some aspects concerning the mean flow patterns and the distribution of eddy kinetic energy.

In order to better resolve the upper layers, the vertical grid (now 50 levels) has been refined. The layers from the surface to 20 m have a thickness of 1 m. Below it progressively increases and reaches 500m at the bottom. This new vertical grid has been designed to improve the circulation near coastal shelves and to represent more adequately the impact of the atmospheric diurnal cycle, which is planned to be explicitly modelled in the near future.

The atmospheric forcing fields are calculated from atmospheric analyses of the ECMWF using the so-called CLIO empirical bulk parameterisation described by Goosse *et al*. (2001). In the global ¼°, a systematic bias in the precipitations is removed thanks to GPCP observations when available. For the recent analyses and forecast the bias is removed thanks to a predictor computed from these observations.

The sea ice is fully comprehensive with the implementation of the LIM2 model. With sea ice concentration, sea ice/snow thickness, sea ice drift and sea ice thermal content prognosed by this multi-layer model based on the Semtner 3-layers and the Hibler visco-plastic formulations, forecast handle most of the processes linked to the sea ice lifecycle.

Data assimilation

Assimilation procedure

The V2 system is operated each week (on Wednesdays 0H00) and performs two weeks of hindcast. We produce a "best estimate" of the ocean 7 days back in time each week, which is constrained with all available observations.

The global ¼° and North Atlantic and Mediterranean Sea at 1/12° are currently operated independently.

Assimilation Method

The assimilation software SAM2 (Système d'Assimilation Mercator version 2) is coupled to NEMO thanks to the software PALM_MP (Tranchant et al., 2008).

The data assimilation technique is a multi-data and multivariate assimilation algorithm consisting of a Singular Extended Evolutive Kalman (SEEK) filter analysis method. The SEEK filter is a reduced-order Kalman filter introduced by Pham (1998) in the context of mesoscale ocean models. This method assimilates satellite Sea Level Anomalies SLA, Sea-Surface-Temperature SST, and *in situ* profiles of temperature and salinity. The error statistics are represented in a sub-space spanned by a reduced number of dominant 3D error directions.

The control variables are three-dimensional temperature T; salinity S; zonal U and meridional V velocities; as well as the two-dimensional barotropic component of the Sea-Surface-Height SSH, hereafter called HBAR.

About 300 seasonally varying high frequency anomalies of the control vector (model states from a numerical experiment without data assimilation) are used to compute the background error covariance matrix for each analysis.

Assimilated data

The assimilated data are *in situ* profiles of T and S provided by the CORIOLIS center (Ifremer), the Real-Time Global SST (RTG_SST product from the NCEP National Center for Environmental Prediction, Thiébaux (2003)) at ½° ho rizontal resolution, and altimeter tracks coming from the SSALTO/DUACS data centre (from JASON, ENVISAT and GFO).

For each type of data, innovations (observation – model) are computed at the geographical location and at the time of the data (First Guess at Appropriate Time, FGAT).

Only SST data of the day before the analysis (once a week) are currently assimilated.

Special treatments

In order to constrain the model SSH with altimetry, the mean dynamic topography RIO-05 (Rio et al., 2004) is used to compute sea level anomalies SLA from daily averages of the modelled SSH. High frequency barotropic fluctuations are filtered from the model to compute the "model equivalent" of the observations. Finally, HBAR is partly constrained with "pseudo observations" (the modelled HBAR itself) with a geographically varying observation error, in order to avoid spurious barotropic height corrections which were observed in the previous systems.

The system is not yet assimilating velocity measurements. The baroclinic velocity corrections are deduced from T and S corrections via geostrophy. Barotropic velocity corrections are computed statistically as well as the other corrections, from the multivariate analysis of U, V, T, S and HBAR.

Validation of the analysis and forecasting system on the year 2007

The V2 system has been run in reanalysis mode for more than one year, starting from T and S climatological initial conditions (Levitus, 1998 and MEDATLAS in the Mediterranean Sea) in October 2006, and from climatological sea ice conditions of October derived from a NEMO ¼° experiment.

Two numerical experiments have been validated over the year 2007: the global ¼° system experiment here after referred to as GLO, and the zoom at 1/12° experiment hereafter referred to as ATL.

Water masses characteristics

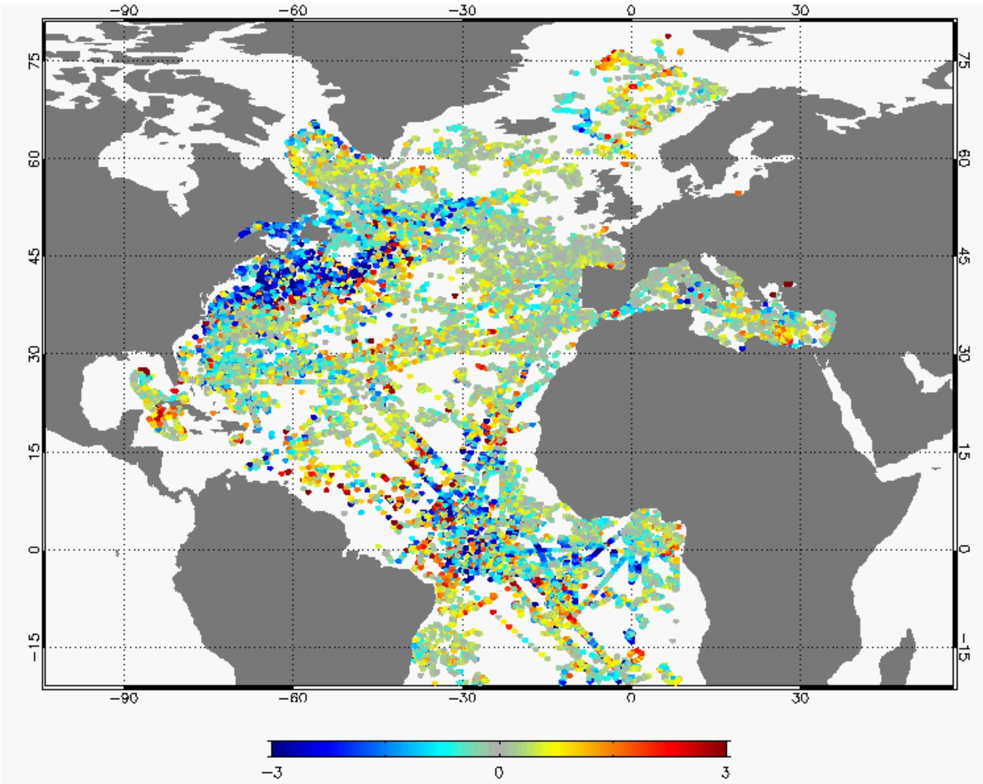

Figure 1

ATL averaged temperature (℃) innovations or misfit (assimilated observations – model forecast) at 100 m in 2007. NB: the color key is the same for figures 1, 2 and 3

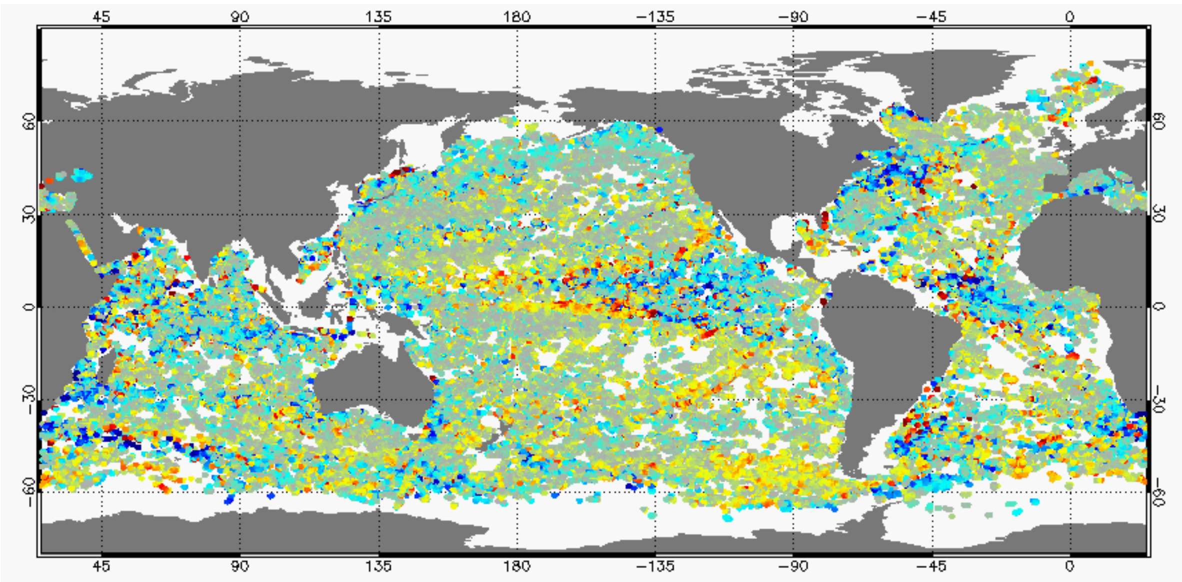

Figure 2

GLO averaged temperature (℃) innovations or misfit (assimilated observations – model forecast) at 100 m in 2007. NB: the color key is the same for figures 1, 2 and 3

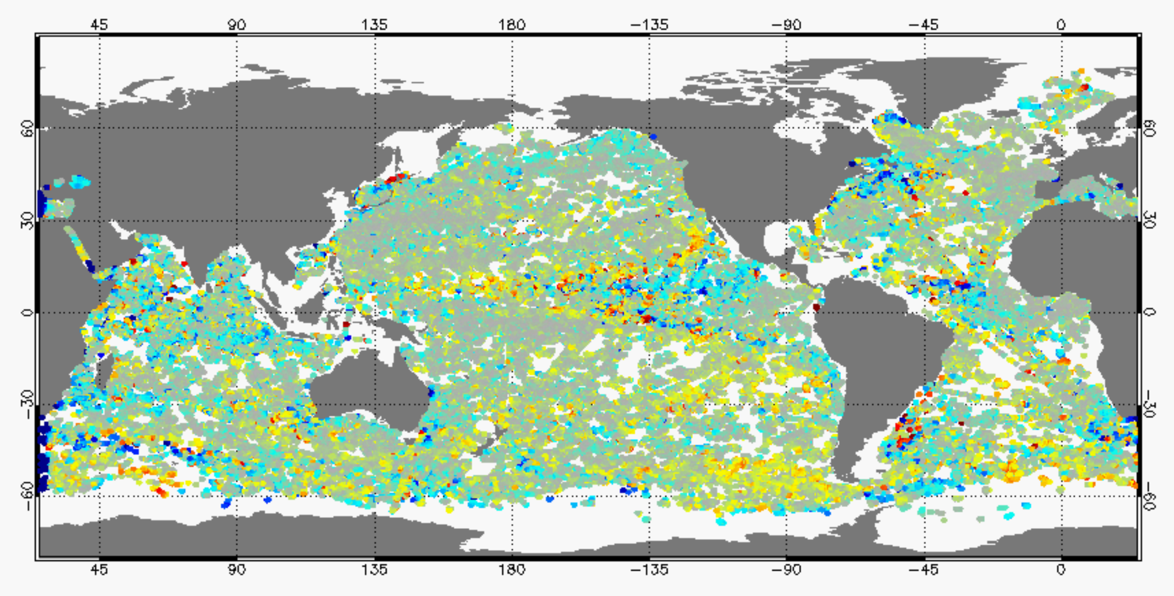

Figure 3

GLO averaged temperature (℃) residuals (assimilated observations – analysis) at 100 m in 2007. NB: the color key is the same for figures 1, 2 and 3

On Figure 1 and 2, the same spatial patterns of averaged temperature innovations appear in the Atlantic and Mediterranean region of ATL and GLO. The innovation is small and centred, showing that the model is close to the observed data, except in the strong mesoscale activity regions like the Gulf Stream region as well as the circumpolar current, Aghulas and Zapiola regions for the GLO experiment. Strong differences appear in the tropical band, reflecting the strong gradients of the thermocline. Most of this information is assimilated by the system, as the residuals are small on average, as shown on Figure 3 for GLO. The residuals reach their maximum values in regions of high variability or in regions of systematic biases, like the Labrador Current region, where the system always tends to inject the same correction.

This satisfactory behaviour of the system can be seen in both GLO and ATL experiments at most levels, for T and S. Nevertheless one can note that if T residuals are generally weak, S residuals are stronger especially at depth, as there are not enough T and especially S corrections at deep levels (not shown). The most significant bias appears in the Antarctic with fresher waters around 1000m and saltier waters near 100m (GLO, not shown).

On the whole as the innovations are small, the density field and thus water masses characteristics seem realistic in most places.

Water masses as shown with T-S diagrams on Figure 4 compare well with *in situ* observations from the CORIOLIS data base. There are still some minor flaws. The vertical structure is better reproduced in the Gulf of Guinea than east of Australia. In the latter region, the GLO experiment results miss the halocline minimum (the model is fresher by 0.2 psu). Central and intermediate waters are too salty in the model (0.05 psu to 0.1 psu above the observations).

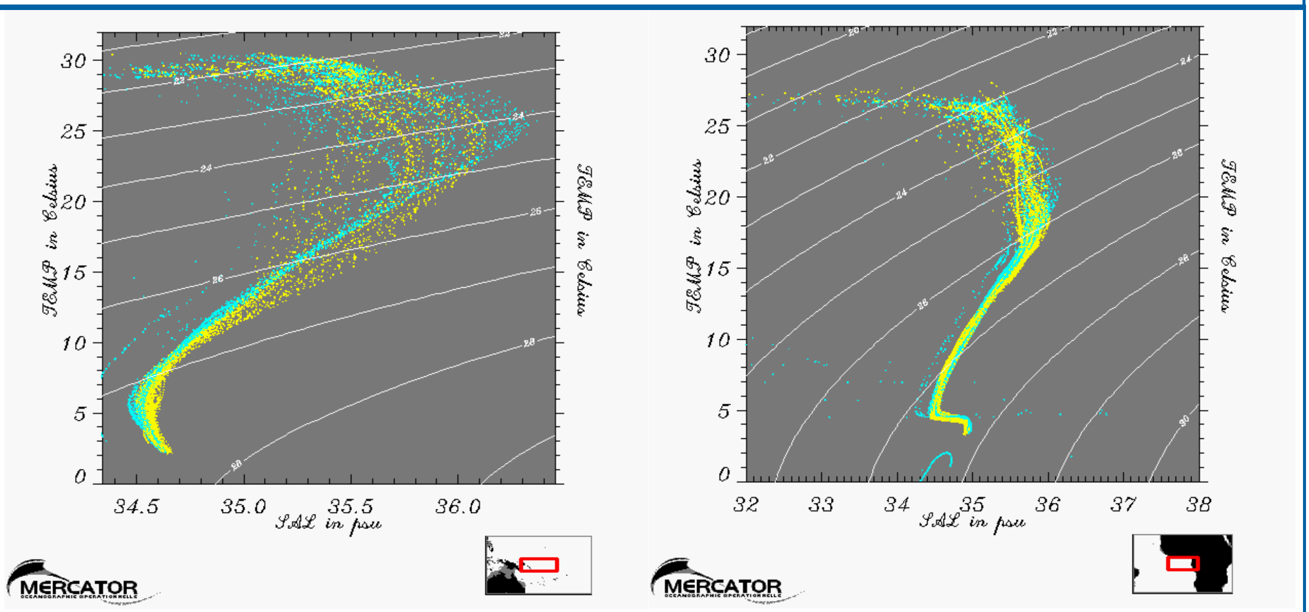

Figure 4

Temperature versus salinity scatter plots (T-S diagrams) of GLO experiment results (yellow dots) together with CORIOLIS in situ data (blue dots), in the New Caledonia region (left panel) and Gulf of Guinea region (right panel).

Sea Surface Temperature

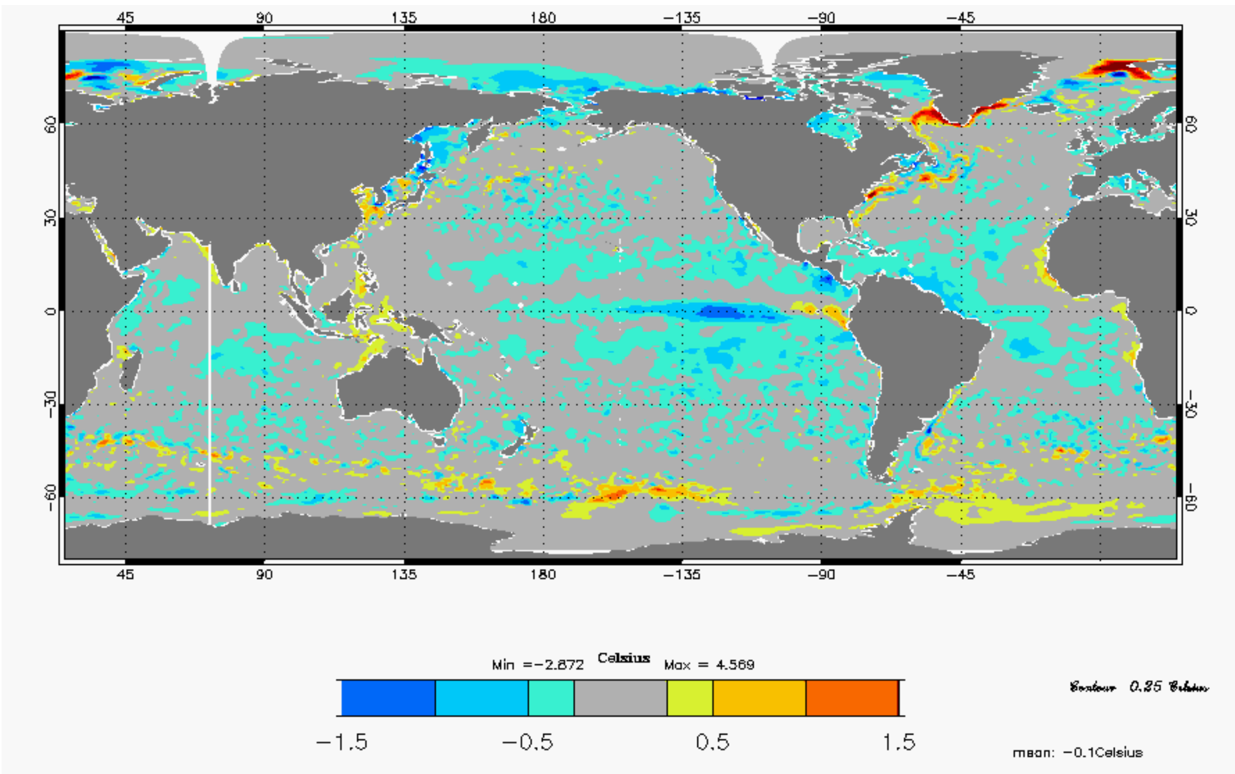

Figure 5

SST differences between the model forecast (before the analyses) and RTG-SST averaged on 2007 (℃) for the GLO experiment.

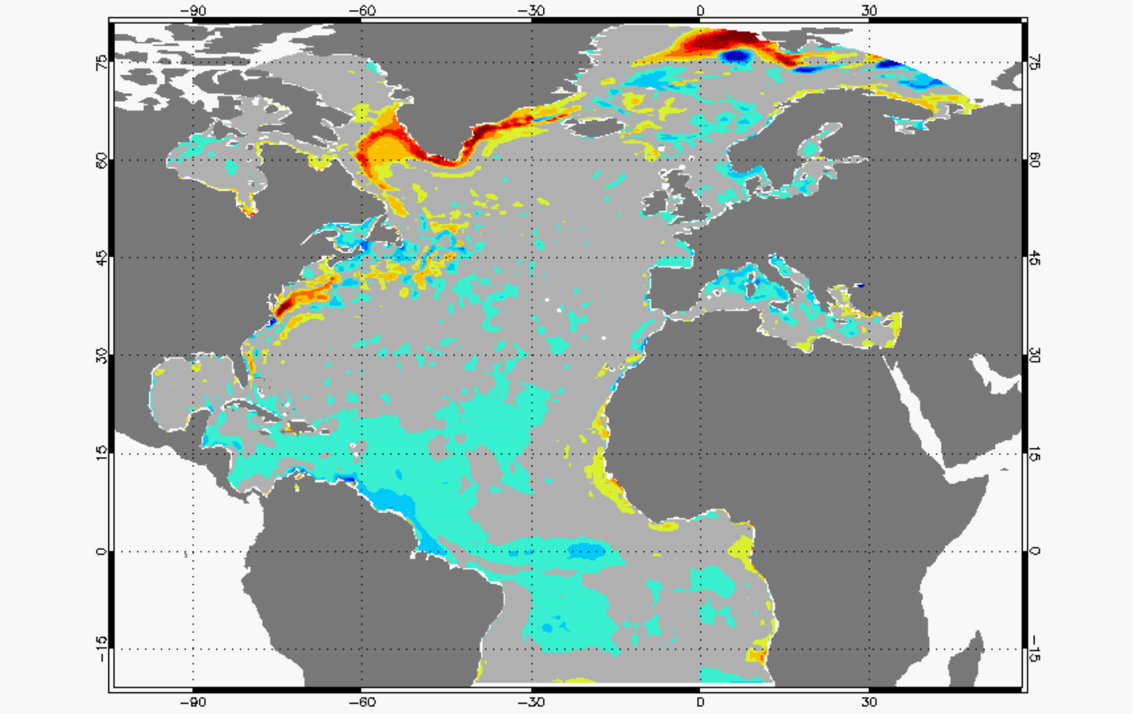

Figure 6

Same as Fig 5 for ATL experiment

As can be seen on Figure 5, a too marked cold tongue can be diagnosed in the Tropical Pacific from the time averaged SST differences between GLO and RTG-SST observations. This tropical bias is the most striking feature of the differences, together with several warm biases of large amplitude near the sea ice limit.

The spatial patterns of SST differences are again very similar in ATL and GLO over the Atlantic and Mediterranean (Figure 5 and 6). SST cold biases appear mostly in tropical regions. On the contrary, the Labrador Current and the limits of the subpolar gyre are warmer than the observations.

Biases appear as well near sea ice near Svalbard and in the Southern Ocean (in GLO, Figure 5).

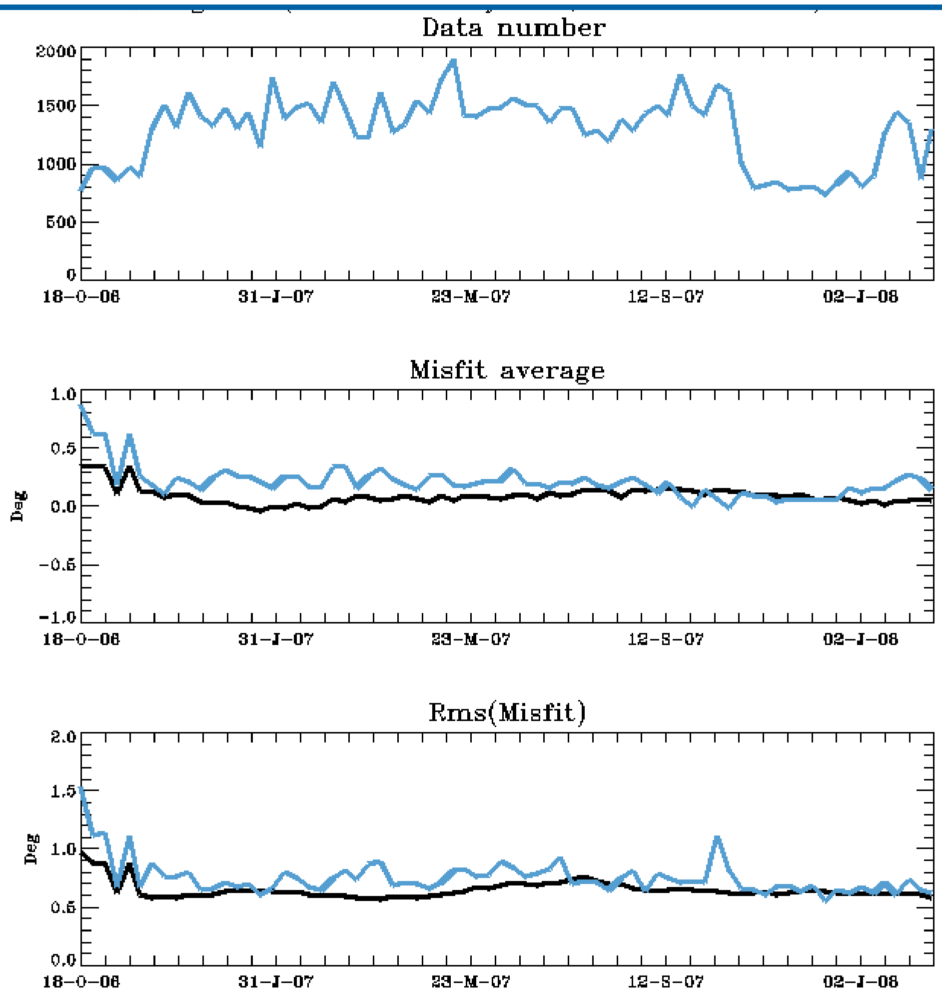

Figure 7

Mean SST innovation or misfit (assimilated SST_RTG data – model forecast), globally averaged and evolving in time from October 2006 to February 2008. The blue curves correspond to *in situ* SST data, and the black curves correspond to RTG-SST data. The number of RTG-SST data is constant in time and is of the order of 160000 data per analysis.

In situ and satellite (RTG-SST products) data of SST agree on average (Figure 7) but local discrepancies can appear (not shown). Over the year 2007 the RMS error is close to the observational error (0.6 °C).

Again, the results are satisfactory, except for the systematic biases that seem to affect all variables in the tropical band, the Labrador Current and the Antarctic Circumpolar Current. It has been diagnosed that the ATL "model equivalent" (which is compared with the observation to give the innovation) has to be smoothed in order to ensure consistency with the observed data resolution (1/2°).

Sea Level Anomalies and currents

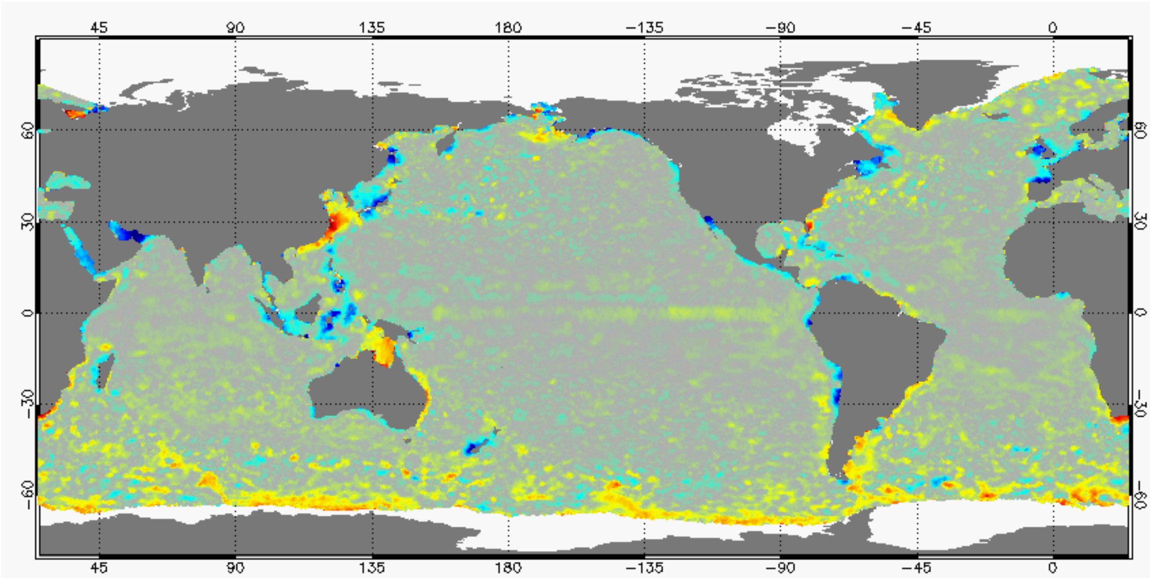

Figure 8

Mean SLA (m) innovation or misfit (assimilated observations – model forecast) over the year 2007 for the GLO experiment. NB: the color key is the same for fig 7 and 8.

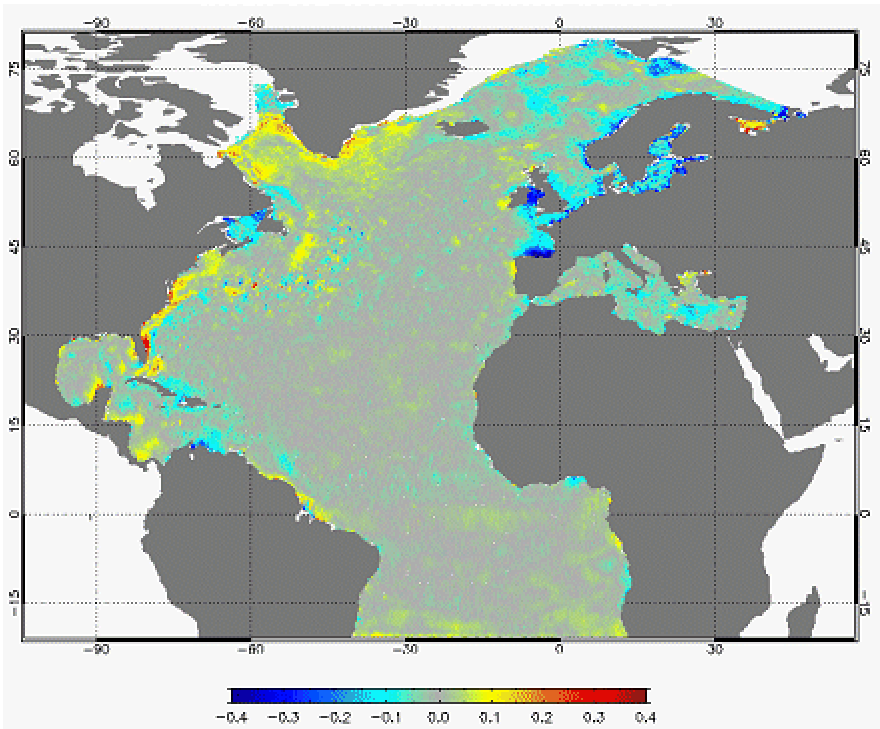

Figure 9

Mean SLA (m) innovation or misfit (assimilated observations – model forecast) over the year 2007 for the ATL experiment. NB: the color key is the same for fig 7 and 8.

Aside from the coastal regions where the observational error is large (thus the innovation information will not be used by the system) the innovation is generally small. Two main biases arise in the GLO experiment (Figure 8). First, the tropical band is lower than the observations on average in 2007, which corresponds to the cold bias already diagnosed in the previous sections. Second, the model is systematically lower than the observations in the Antarctic circumpolar current and near the sea ice limit.

In the ATL experiment, the model seems to be systematically higher than the observations in the Norway Sea as can be seen on Figure 9. This bias is not present in the GLO experiment on Figure 8.

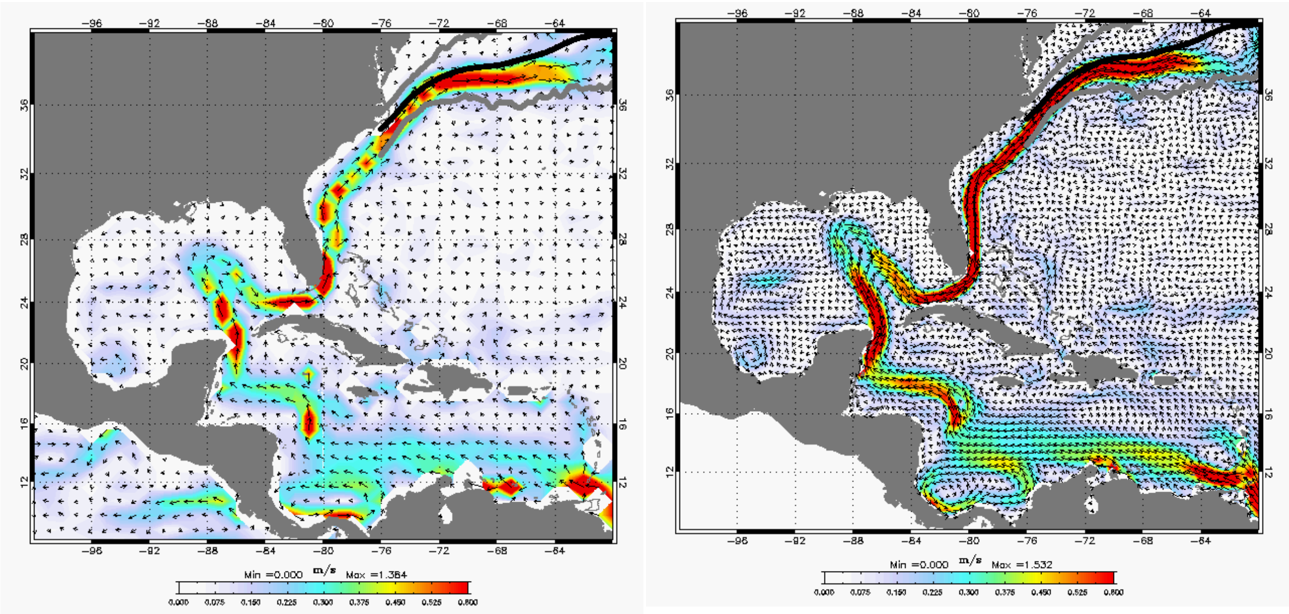

Figure 10

Loop Current and Gulf Stream mean intensity in 2007, in the GLO experiment (left panel) and in the ATL experiment (right panel). For both experiments the mean location and extreme positions of the Gulf Stream are superimposed.

The mean position and intensity of strong currents are well reproduced by the system, for instance the Loop Current and the Gulf Stream path are very similar in GLO and ATL as illustrated on Figure 10, with a better accuracy and more intensity due to the high resolution in ATL. Nevertheless comparisons with independent velocity data from drifting buoys show that surface currents (currents are compared at a depth of 15 m) are underestimated by the system over all the domain. This problem is currently under investigation and is partly linked with model parameterizations.

Seasonal and High Frequency variability

The high frequency temporal evolution of the subsurface (0-500m) temperature and salinity is generally in remarkable agreement with the observations from the TAO/TRITON array of moorings. These data among other *in situ* data of the CORIOLIS base are assimilated every 7 days, but as can be seen on Figure 11 even the daily fluctuations of the mass field are realistic. This good subsurface behaviour is found through the entire TAO/TRITON array, and also through the PIRATA array in the tropical Atlantic for both GLO and ATL experiments (not shown).

For unexplained reasons so far, unobserved high frequency fluctuations can also be detected in GLO and ATL, like spurious high frequency baroclinic waves and large peaks in the SSH (not shown). These phenomena are under investigation with model studies.

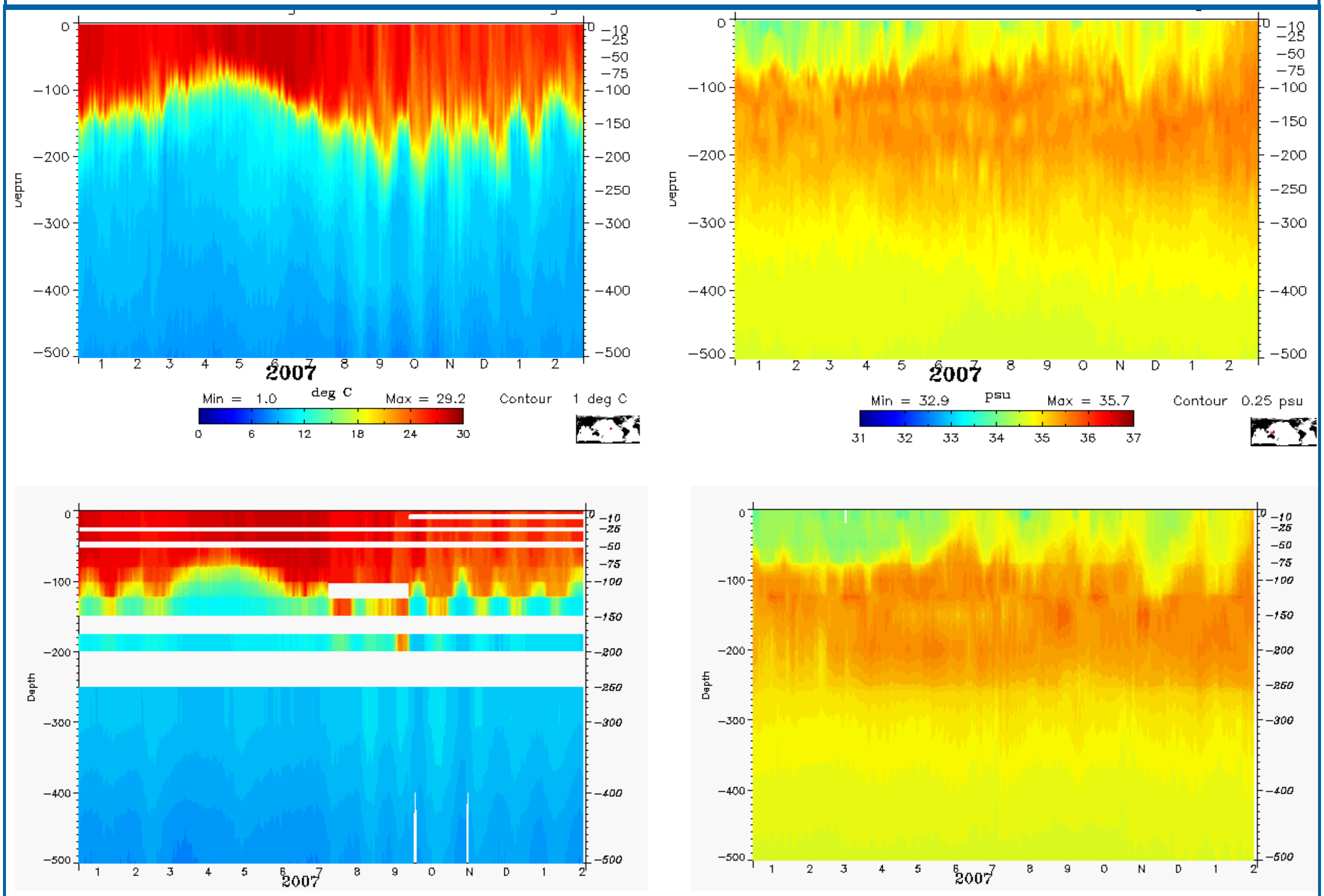

Figure 11

On the left column, temporal evolution of local subsurface 0-500m temperature (°C) at 140°W and 5°N from the GLO experiment results (upper panel) and from the corresponding TAO/TRITON mooring (lower panel). On the right column, temporal evolution of local subsurface 0-500m salinity (psu) at 147°E and 0°N from the GLO experiment results (upper panel) and from the corresponding TAO/TRITON mooring (lower panel). GLO high frequency (6 hours) outputs have been smoothed for consistency with the daily TAO data.

Sea Ice

Data assimilation is switched off in the vicinity of sea ice. The LIM2 model behaves in GLO and ATL nearly as it would have behaved in a NEMO experiment without data assimilation. The Arctic sea ice cover is realistic in boreal winter but not during summer (Fig. 12), as the model does not melt the ice pack sufficiently. This problem is mainly due to the shutdown of ocean-sea-ice dynamical interactions in GLO and ATL experiments, because it was not adapted to high vertical resolution.

Recent developments show that the summer Arctic ice cover is realistic in LIM2 experiments including EVP (Elasto Visco Plastic) rheology of the ice, as well as a fully coupled dynamical interface between the sea ice and the ocean (Garric et al., 2008).

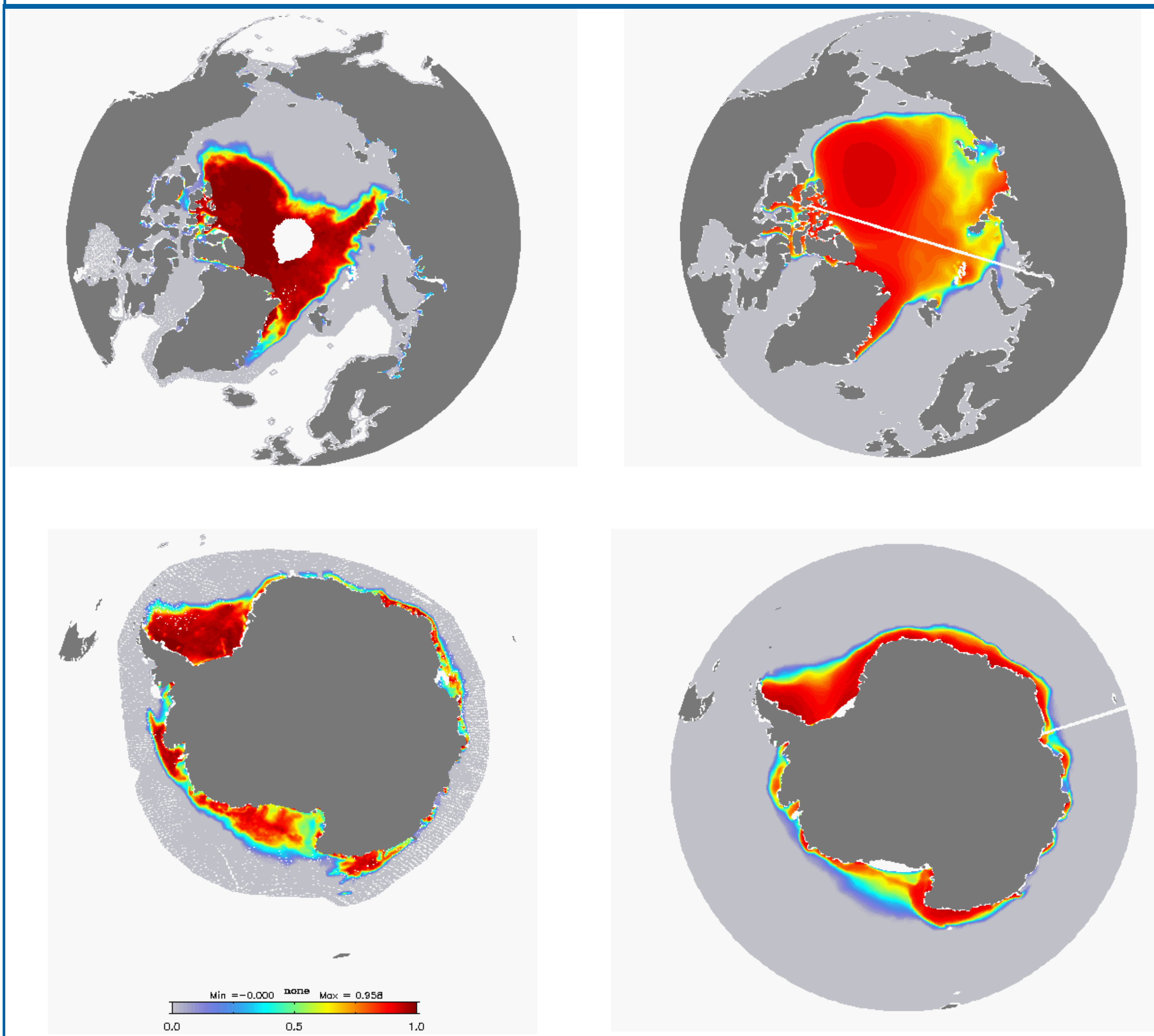

Figure 12

September 2007 sea ice fraction in the Arctic (top panels), and March 2007 sea ice fraction in the Antarctic (bottom panels) from CERSAT observations (left panels) and from the GLO experiment (right panels). NB: the color key is the same for all the panels.

Volume transports

Inline computations of volume transports have been implemented in GLO and ATL. The volume transports of 2007 have been validated against various observations and model estimates (not shown). The results of both experiments are generally of the expected order of magnitude except for the buffer zones of ATL where a relaxation towards Levitus (1998) climatology takes place. GLO volume transports estimates are larger than ATL estimates, as can be seen for instance in the Gulf of Mexico (Figure 13). In this region, ATL estimations are more realistic with respect to the literature. The higher resolution is not the only factor explaining this difference, as a bug in the error covariances has been affecting the GLO experiment during 3 months (from July to October 2007), which has particularly impacted the ocean circulation in the region of the Gulf of Mexico.

ATL estimates of volume transport can also be compared with previous estimates from an older version of the high resolution Atlantic and Mediterranean Sea forecasting system (PSY2V2). As can be seen on Figure 14 the ATL and PSY2V2 estimates of the transport through the Florida-Bahamas section are better correlated with the cable measurements than the GLO estimates. PSY2V2 give the best amplitude estimate in this case. Nevertheless the windward passage transport may be better represented in ATL and GLO with respect to previous systems including PSY2V2. Estimates made from observations indicate that the transport should be southward on average, and of the order of 7 Sv even if there is a strong variability in this region (Johns et al, 2002). It is actually northward in ATL and GLO but has significantly lower values (0.7 and 1.95 Sv) than in PSY2V2 where it was of the order of 5 to 10 Sv northward.

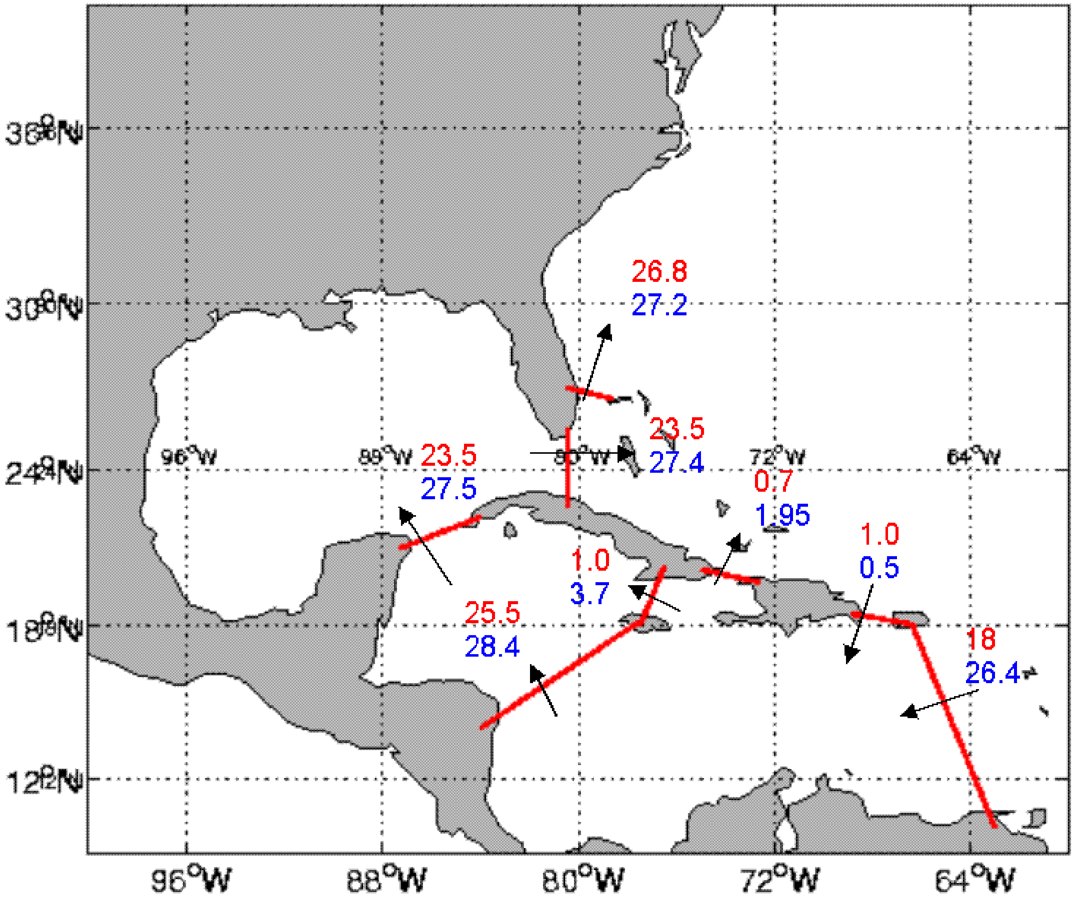

Figure 13

Volume transports (Sv) in the Gulf of Mexico computed during the GLO experiment (in blue) and the ATL experiment (in red).

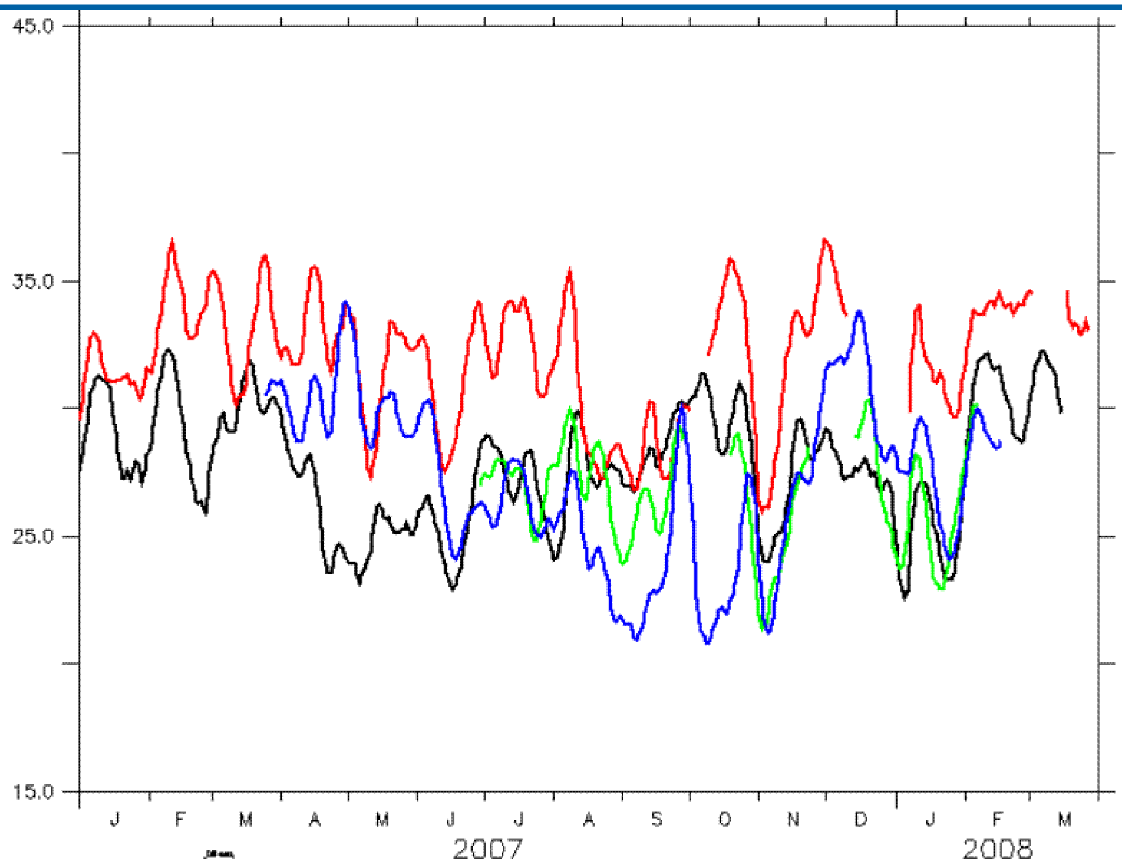

Figure 14

Volume transport (Sv) across the Florida-Bahamas section, as measured by the Florida-Bahamas cable (in red), as computed by the old version *(PSY2V2)* of ATL (in black), and by GLO (in blue) and ATL (in green).

Discussion and future work

The GLO and ATL experiments results compare well on average over 2007. They show an overall good physical and statistical behaviour of the system. Excluding the systematic underestimation of surface currents strength, the system stays relatively close to all available observations, and provides a realistic description of the ocean physics, of the water masses, and heat transports.

Yet several weaknesses have been diagnosed. The SAM2 software has to be amended as increments (especially salinity corrections) should be stronger at depth. This should be solved with a modification of SAM2 anomalies computation at depth in order to make them smoother, and to allow the system to capture more information on interannual and intraseasonal variability.

Several points will need further investigation on the model parameterizations. Surface currents should be stronger. Tropical Instability Waves (TIWs) are not phased with the observations and some high frequency baroclinic waves and SSH peaks can appear (which source is unidentified so far). The ice model has to be upgraded to include EVP rheology and a bug free sea-ice-ocean interactions scheme at high resolution.

Furthermore, a bug has impacted 3 months of the GLO experiment, producing biases in the water masses and currents. Some work is also needed to improve the observation operator, for instance the SST model equivalent has to be smoothed (ATL).

These factors all together made biases develop in the Antarctic (GLO), in the subpolar gyre, in the tropical band and other regions where complex interactions take place between the different flaws of the system.

In conclusion, these results show that scientific improvements are necessary before producing a reanalysis with the global ¼° configuration. Nevertheless on average this new system gives a far better real time estimation of the ocean 3-dimensional state than the previous systems. In addition, a lot of work has been done to homogenize the systems, and to make them evolutive on a scientific and technical point of view. The validation protocol (in real time and in delayed mode) has also been improved.

Aknowledgements

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MERSEA multi-sensor satellite SST products

By Hervé Roquet[1], Jean-François Piolle[2] with a large contribution from other MERSEA partners

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Introduction

In the MERSEA project, an important activity was dedicated to remote sensing, to provide the MERSEA ocean modelling and assimilation centres with the needed altimeter, Sea Surface Temperature (SST), Ocean Colour and Sea Ice Products. A previous paper released in 2006 in the Newsletter Mercator (H. Roquet et al, 2006) gave an overview of the different satellite SST data sources available, and of the international cooperation context within GODAE for satellite SST. The present paper is focussing on the multi-sensor level 3 and level 4 SST products, which are now produced and made available in near real-time in the framework of the MERSEA project and of the forthcoming MyOcean project.

Level 3 satellite SST products

As part of the MERSEA satellite SST activities, IFREMER and M-F/CMS have developed and implemented a common methodology for the processing of satellite L2P SST products, defined and made available in NRT in the framework of the GODAE High Resolution SST Pilot Project (GHRSST-PP, see http://www.ghrsst-pp.org/), to produce high resolution SST analyses (level 4 products).

The main steps of this methodology are (see Figure 1):

- for each data source, the individual L2P products (most of which are swath products in satellite projection) are "collated" into a single file, corresponding to a pre-defined time window and a pre-defined area on a regular latitude/longitude grid. Among all the individual observations found in the pre-defined time window for a given mesh of the pre-defined grid, the "best" observation is selected, according to a suite of quality criteria, but the exact location of the observation, as well as the information on the observation bias and error standard deviation are preserved in the "collated" file.

- for each data source, an adjusted SST is then computed, using the ENVISAT/AATSR sea surface temperature as a reference. The choice of AATSR as a reference is justified by the fact that AATSR is currently providing the highest accuracy SST measurements from space, thanks to its high quality on board calibration system, and to its particular design (dual look). The adjustment method, developed in the framework of MERSEA, and applied to each data source, relies on a large scale analysis of the observed SST departures from AATSR, computed on a moving 10-day time window. The adjusted SSTs, as well as the new error standard deviation estimates, taking into account the errors due to the adjustment procedure, are then appended to each "collated" file.

- a single "merged" file is then produced, combining all the "collated" files from all available data source. For each mesh of the pre-defined grid, the selection of the "best" SST observation among the various data sources is done according to a pre-defined priority order among existing data sources, and taking also into account the confidence in the SST adjustment, without any average of observations from different data sources. This priority order is based on an a priori knowledge of the accuracy of each sensor, and on its horizontal resolution. Currently, ENVISAT/AATSR has the highest priority, and TRMM/TMI the lowest. The "merged" product contains also a variable identifying the origin of each selected observation, as well as its error standard deviation. The "merged" file is then used as the input for the SST objective analysis, but is also made available as such for other applications, like assimilation into an ocean modelling system.

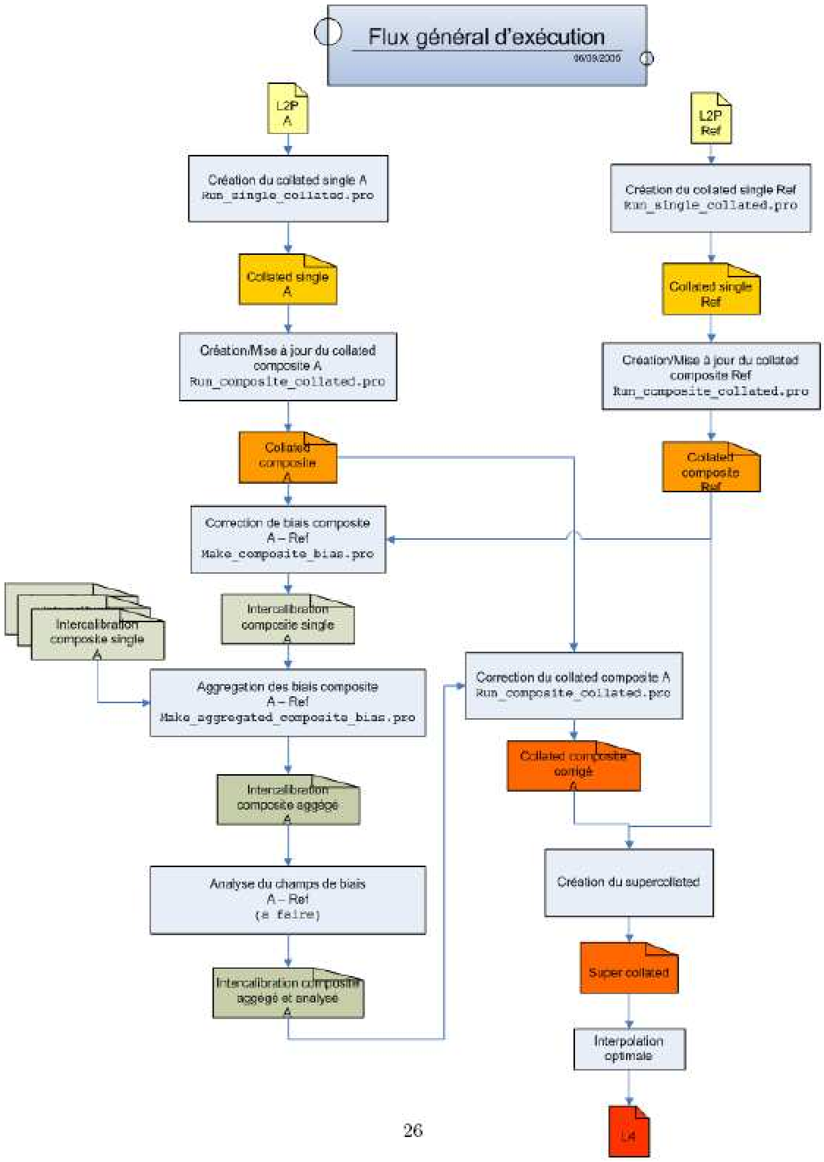


Figure 1

General overview of the level 3 and 4 satellite SST processing scheme developed by M-F/CMS and IFREMER in the framework of the MERSEA project.

In the framework of the MERSEA project, IFREMER is producing currently in near real-time daily global "collated" and "merged" SST products at 0.1° horizontal resolution, as part of its ODYSSEA system (see http://www.mersea.eu.org/Satellite/sst_validation.html for detailed information and product access). The time window defined for these global products is currently ± 3 days around the product time.

Similarly, M-F/CMS is producing currently daily in near real-time daily regional "collated" and "merged" SST products at 0.05° horizontal resolution over the Atlantic Ocean. The time window defined for these products is currently 24 hours. An example of "merged" product is given in Figure 2, together with the origin of the selected observation at each grid mesh. In the context of MyOcean, this production will evolve towards higher resolution products (0.02°), covering the North Eastern part of the Atlantic Ocean and the European Seas (40 W – 55 E – 20 N – 70 N).

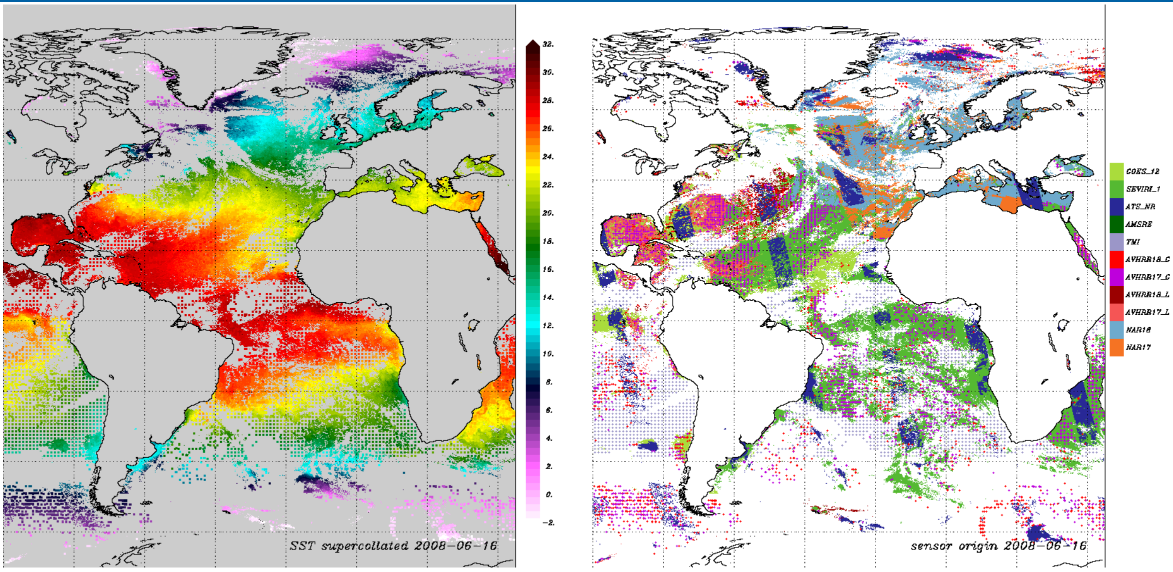


Figure 2

Example of regional "merged" level 3 satellite SST product, adjusted to ENVISAT/AATSR SSTs, and processed at M-F/CMS in the framework of MERSEA, with the origin of the selected observation at each grid mesh.

Level 4 satellite SST products (SST analyses)

In the framework of MERSEA, IFREMER and M-F/CMS are also processing in near real-time daily global and regional SST analyses, based on the "merged" level 3 SST products which have been described before.

The global SST ODYSSEA daily analysis, processed at IFREMER, is at 0.1° horizontal resolution, and is using as first guess the mean SST field of the day derived from K. Casey's global 5 km climatology (which has been derived from the AVHRR pathfinder V5 dataset). The data sources which are currently used actively in the ODYSSEA analysis system are listed in Table 1.

Data source	**Provider**
ENVISAT/AATSR products	ESA
NOAA-17 and NOAA-18/AVHRR GAC and LAC products	NAVOCEANO
NOAA-17 and NOAA-18/AVHRR NAR products	EUMETSAT Ocean and Sea Ice SAF
MSG/SEVIRI	EUMETSAT Ocean and Sea Ice SAF
AQUA/AMSR-E products	REMSS (Remote Sensing System)
TRMM/TMI products	REMSS (Remote Sensing System)

Table 1

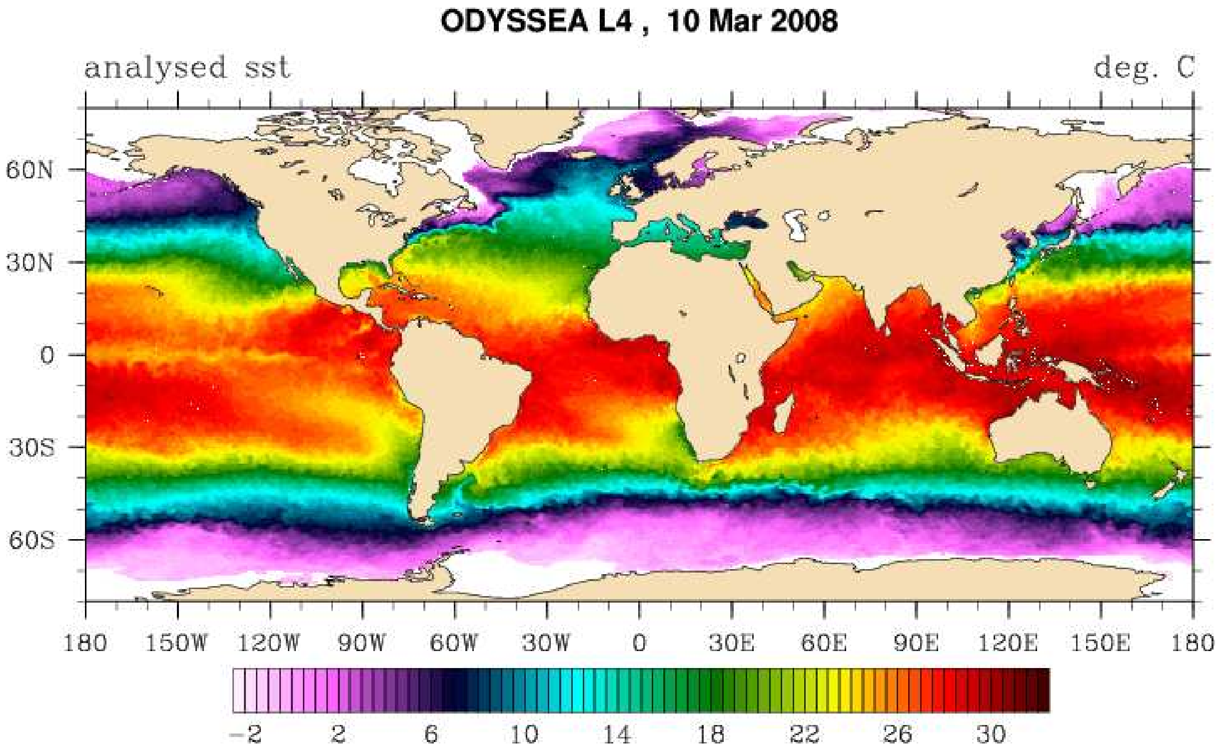
Data sources which are currently used actively in the ODYSSEA analysis system

Furthermore, the ODYSSEA system is currently assessing in passive mode the new global METOP/AVHRR products (*EUMETSAT Ocean and Sea Ice SAF*).

It is worth to notice that the ODYSSEA system does not use in-situ SST observations at the analysis step.

An example of ODYSSEA global SST analysis, with associated analysis error variance, is given in Figure 3.

a)



b)

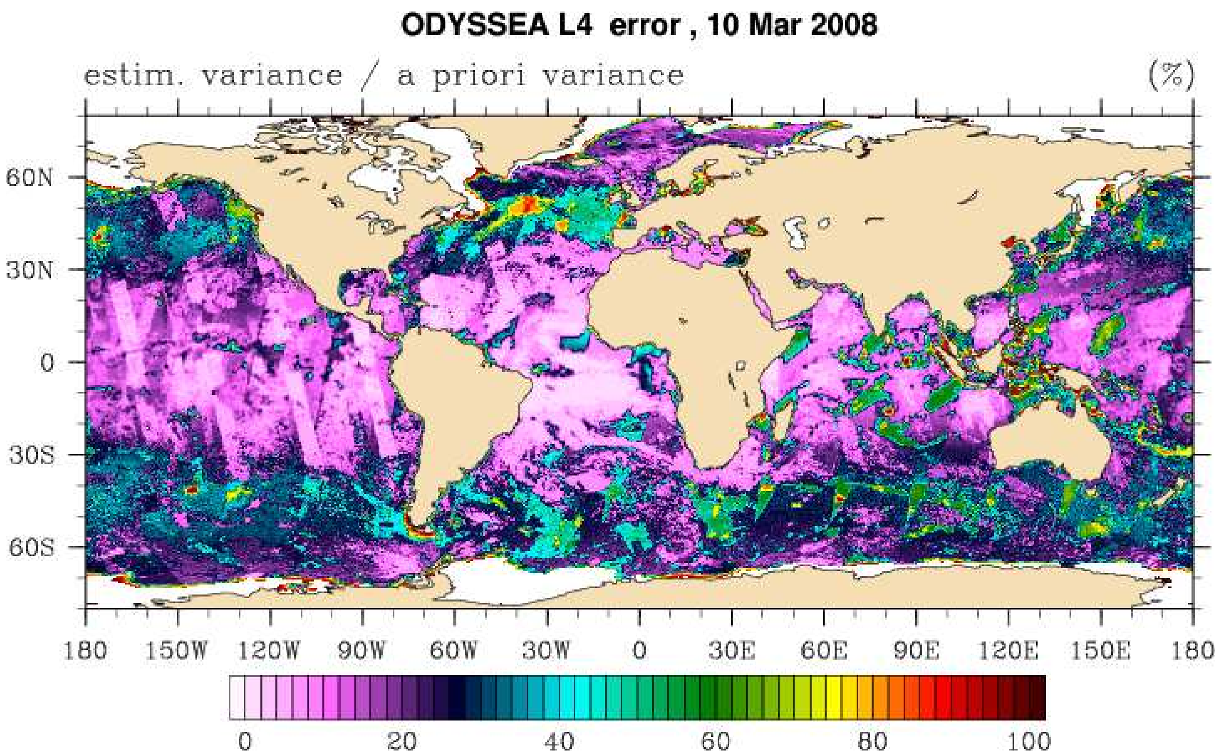


Figure 3

Example of a) analysed SST (K) from the global ODYSSEA SST analysis system, and b) ratio (%) of analysis error variance over first guess (climatology) error variance

In the framework of GHRSST-PP, the Met Office is producing an operational daily global SST analysis at 0.05° horizontal resolution, called OSTIA (J. Stark et al., 2007). The OSTIA and the ODYSSEA global analysis systems are using many common SST data sources, with a few differences: OSTIA is not using the NOAA-17 and 18/AVHRR NAR products, but is using in addition to satellite data in-situ SST measurements from ships, moored and drifting buoys. OSTIA uses also ENVISAT/AATSR as a reference for bias correction through a daily large scale analysis of each sensor bias. A major difference lies in the choice of the first guess field : OSTIA uses as first guess a linear combination of the analysis of the previous day and of the climatology.

The differences between the ODYSSEA and the OSTIA SST analyses are monitored daily on the MERSEA www site at http://www.mersea.eu.org/Satellite/sst_validation_l4_glob_oi.html . This page presents also differences between the ODYSSEA and the RTG-HR SST analyses.

The differences between ODYSSEA and OSTIA are usually small from a overall statistical point of view, but in the current versions, the OSTIA analyses are clearly much smoother than the ODYSSEA analyses, as illustrated by Figure 4, showing the SST gradients derived from both analyses on 10 March 2008 in the Gulf Stream region.

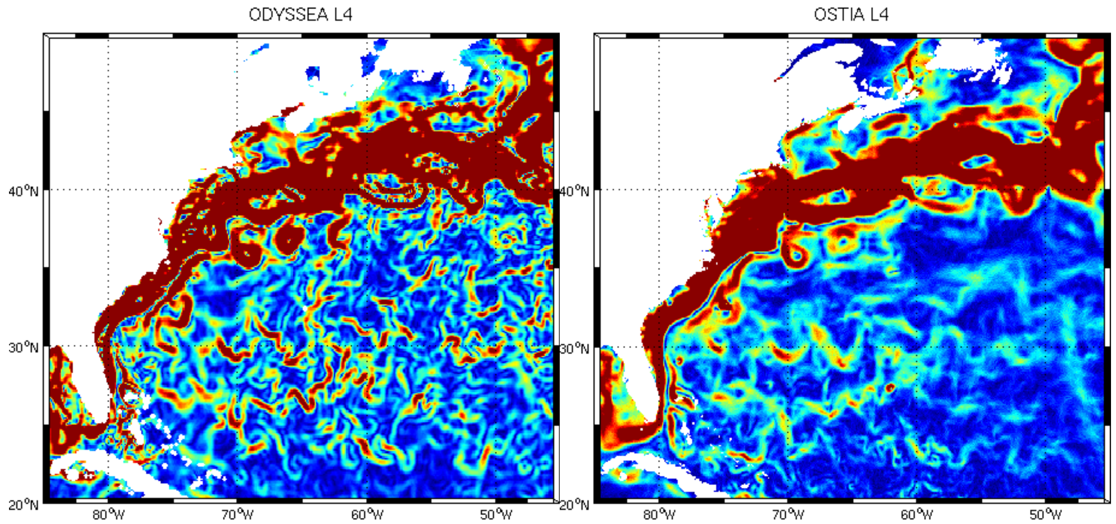


Figure 4

Example of SST gradients in the Gulf Stream region on 10 March 2008 derived from the ODYSSEA (left) and the OSTIA (right) SST analysis.

These differences are probably due for some part to the different error covariance models used in both analyses, but more largely to the large observations sub-sampling which is done in the pre-processing step of the OSTIA analysis, to decrease its computational cost.

Conclusion and perspectives

The R&D activities performed on satellite SST in the framework of the MERSEA project have demonstrated the great benefit of the GHRSST-PP project, which has resulted in the near real-time availability of high quality L2P satellite SST products with a standard format and content. This benefit is clearly illustrated in the MERSEA multi-sensor level 3 and level 4 SST products which have been developed, and which will be maintained and improved in the framework of MyOcean, in which a lot of efforts will be devoted to the operational reliability and continuous quality monitoring and validation of the products.

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Oil spill fate forecasting in the MERSEA Integrated Project

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In the MERSEA Integrated Project, oil spill fate forecasting is identified as a first-rank application for operational oceanography: "Oil pollution from catastrophic accidents and illicit dumping continues to be a major threat to European coastlines and ecosystems. Despite efforts to reduce the incidence of spills, there is still a need for improved predictions of oil spill fate. Forecasts are necessary in support of recovery efforts, preparedness, and mitigation measures. To fulfil their national and international responsibilities, operational agencies developed oil spill drift prediction systems. The capability to incorporate accurate estimates of currents in these systems still needs to be improved. MERSEA will provide in real time the required high resolution current fields."

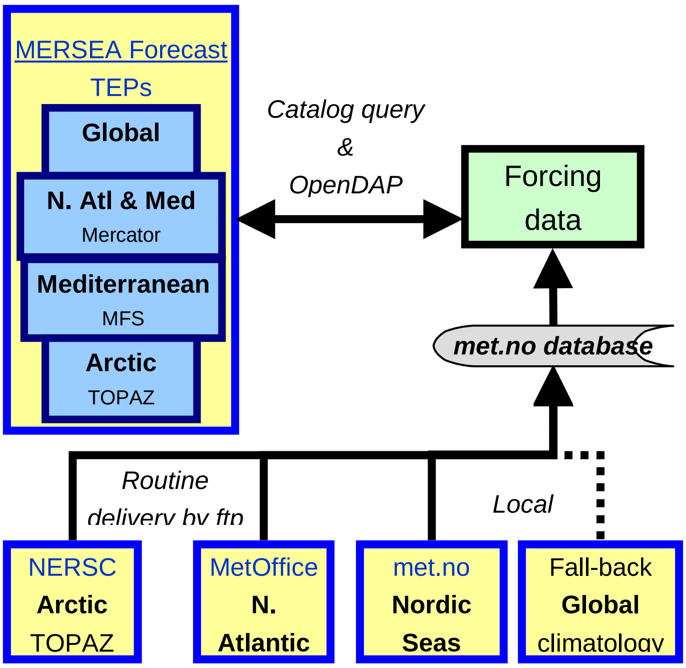


Figure 1

Schematic of forcing data pre-processor for met.no oil spill fate forecast model OD3D. At bottom are ocean model data sets that are updated routinely (daily, weekly) and delivered to a special database for use in OD3D.This database contains the current forecast and analyses for the last 7 days ; it may be very large. At upper left are OPeNDAP servers; they are accessed on demand. The preprocessor also contains semi-automatic procedures for selection, subsetting, conversion and reformatting.

Task 12.3 under WP12 of MERSEA addresses oil spill fate prediction. Its objective is to interface MERSEA global and regional current forecasts with existing oil spill modelling systems, and evaluate improved forecast skill and accuracy. Task 12.3 has three partners: the Norwegian Meteorological Institute (met.no, lead partner), Météo-France (MF) and the Oceanography Centre, University of Cyprus (OC-UCY).

The three partners of MERSEA TASK 12.3 brought existing, state-of-the-art oil spill fate prediction models to the project: OD3D at met.no, MOTHY at MF and MEDSLIK at OC-UCY. While all three models use a similar representation of the oil slick (particle) and it chemical evolution, there are significant differences in how the geophysical forcing data are applied. At the one extreme, MOTHY only uses ocean model data from a single depth – typically 100 m – in the place of a climatological background current, and calculates the main drift component from the wind data. At the other extreme, OD3D is formulated to heavily weight the ocean model data for determining the oil drift velocity, relying on the ocean model to account for most of the wind-driven current component. In addition, OD3D requires vertical profile data for velocity, and for the case of a release of oil at some depth temperature and salinity is needed for calculating the buoyant rise of oil. MEDSLIK is similar to MOTHY in its use of ocean current data from a single depth. Thus, the requirements on the MERSEA ocean data provision and, consequently, the suitability of those data, vary according to the oil drift model system.

In addition, the MERSEA ocean data may be utilised in an oil spill forecast system in two ways: either applied directly to the oil spill model, or applied as boundary forcing to a local, fine-scale ocean model (nesting) that, in turn, supplies forcing data to the oil spill model. With respect to the existing oil spill fate services, this means using MERSEA ocean data either as a replacement for the existing ocean data, or as a replacement for existing boundary conditions for a local model. Both methods have been applied by met.no and OC-UCY, while MF has only used MERSEA data as direct forcing.

All three systems have all undergone significant developments during the project in order to utilise ocean forcing data from the MERSEA Forecast Thematic Portals (TEPs). The most important developments deal with accessing the various ocean data sets available in the MERSEA Core services in an operational routine. Two methods of access have been implemented: 1) regular delivery of agreed data products, typically by ftp, and 2) on-demand access to standardized data products served by OPeNDAP at the Forecast TEPs. Each method has its relative merits. Routine delivery, which has been used by all three partners, is generally more robust and allows nesting of local ocean models, but requires transfer and local storage of large amounts of data, most of which are never used. On-demand access has the advantage of only delivering what is required, when it is required; met.no has also implemented this method of access. Figure 1 shows schematically an example of how the data access has been implemented, in this case at met.no. These developments are documented in the MERSEA deliverable reports D12.3.2 and D12.3.4.

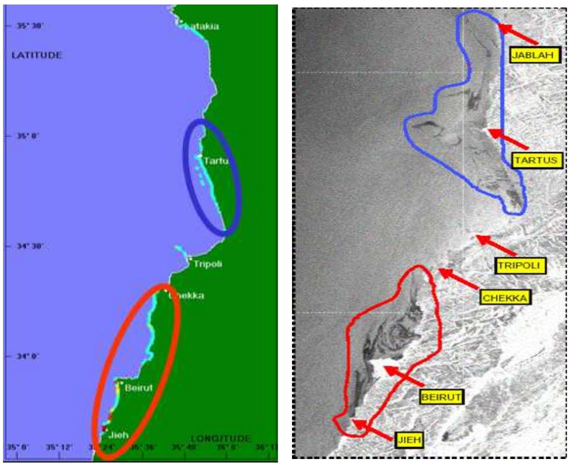


Figure 2

Oil spill incident Lebanon, July 2006. Left: Forecast stranding from MEDSLIK. Right: Oil slicks observed by SAR (courtesy EMSA).

An unplanned opportunity to test the new developments was afforded by the oil spill incident at the Jieh power station in Lebanon during the hostilities in July, 2006. In response to requests by the EU, REMPEC[2] and Cypriot authorities, OC-UCY carried out a number of oil spill forecasts. These proved to be quite accurate in predicting the drift direction and areas of stranding (Figure 2). In these simulations, MEDSLIK was forced by ocean forecast data from the CYCOFOS local model nested in MFS basin-scale data.

In order to further evaluate the benefits of the MERSEA forcing data for oil spill fate forecasting in a variety of ocean regimes, the models have been applied in four demonstration exercises in various ocean areas, including two in the Mediterranean Sea, one in the North Sea and one in the Indian Ocean. A plan document for the demonstrations was established in the spring of 2007 and the demonstrations were carried out in the fall of 2007 and the winter of 2008. In order to exchange and publish the results from the oil spill fate models, an interactive Task web site for the demonstrations has been established at http://mersea-oil-spill.wiki.met.no. An important feature of this web site is the publication of the model results in KML format for easy viewing in Google Earth. The formatting procedures are documented in the MERSEA deliverable report D12.3.5.

In the fall of 2007, validation demonstration experiments were carried out in two areas of the Mediterranean Sea. Oil-emulating surface drifters were deployed first southwest of Cyprus by OC-UCY and later off the southern coast of France by Cèdre. An overview of the drifter trajectories is shown in Figure 3.

[2] REMPEC: Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea

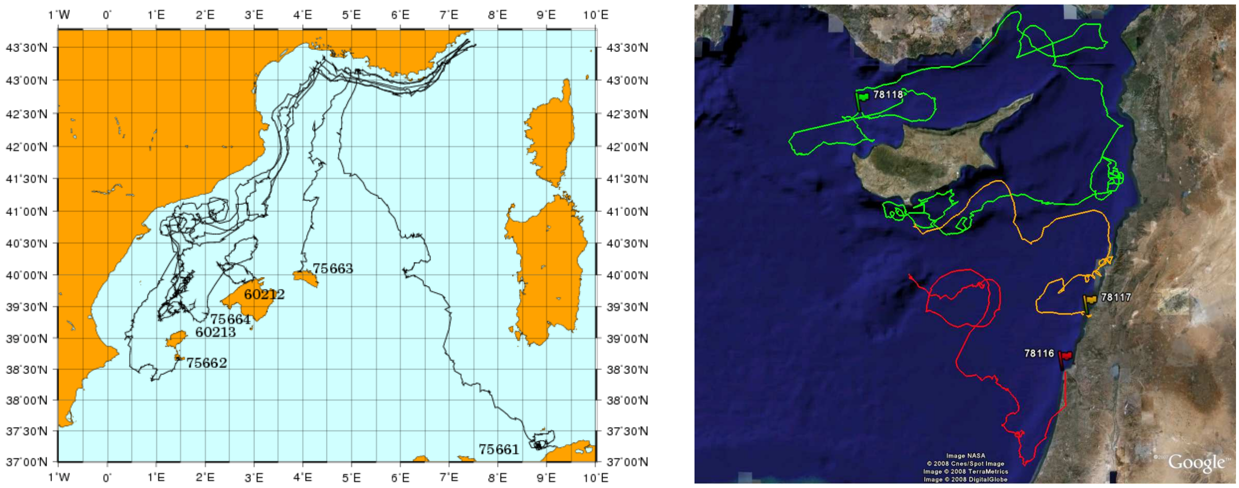
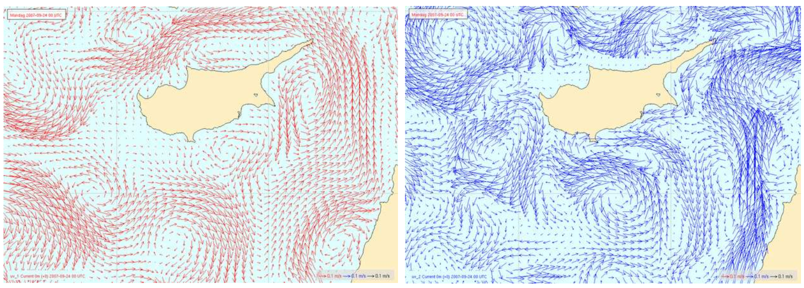


Figure 3

The tracks of the drifters released in the Eastern Mediterranean by OC-UCY (right) and in the Western Mediterranean by Cèdre (left), Fall 2007. Both deployments were supported by funding from Mersea.

The partners' oil spill forecast services were applied to these "oil spills" facilitating an assessment of model-model forecast comparison and model-data validation. Furthermore, the models were forced by several alternative ocean data sets, including MERSEA operational products from Mercator and MFS. The results of the Mediterranean demonstrations are documented in the MERSEA deliverable report D12.2.7 (MERSEA-WP12-OCUCY-STR-001).



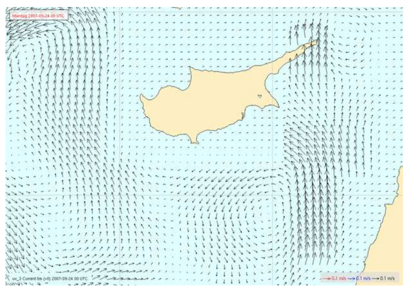


Figure 4

Surface currents predicted by MFS (upper left), Mercator Med (upper right) and Mercator Global (lower right). All are daily means for 2007-09-24 00 UTC, plotted with same scaling. Note differences in eddy structures.

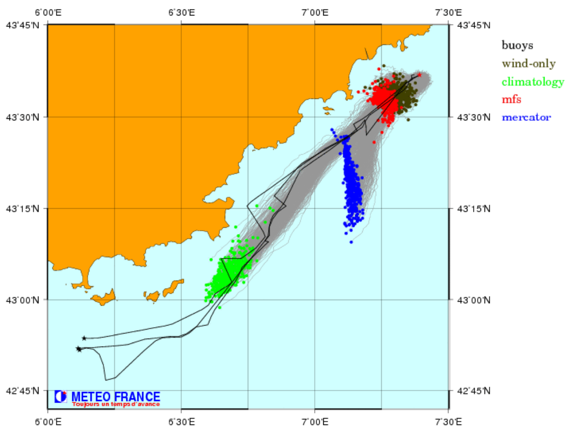
The most important findings from the Mediterranean drifter experiments are:

- Simulations in the eastern Mediterranean using MEDSLIK indicate that the most accurate results are obtained when applying currents from a local, fine-scale ocean model (CYCOFOS) nested in MFS basin-scale data. The results are generally better than using MFS current data directly in MEDSLIK.
- In the eastern Mediterranean, the three ocean data sets used – MFS, Mercator Mediterranean and Mercator Global – showed large differences in the predicted current fields (see Figure 4). MFS and Mercator Med are both considered eddy-resolving and assimilated the same data, yet the eddy fields they produced south of Cyprus differ considerably.

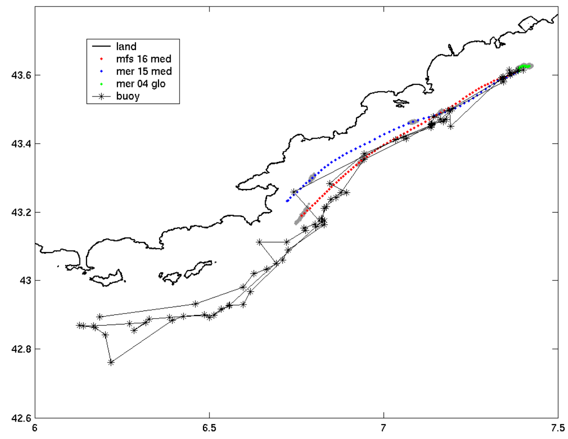
Mercator Global produced much smoother and weaker currents simply because the Mercator Global system used in this experiment is not designed for the Mediterranean Basin because of its too low resolution (1/4°). Furthermore no-assimilation was done in this region for this system. The resulting oil drift trajectories vary considerably and often agree poorly with the drifters. This is most evident in the simulations using OD3D, since that model relies heavily on the ocean model currents to calculate the drift.

- In the western Mediterranean, the drifters were deployed off Nice in the coastal current, which is a strong, persistent feature of the current field. Looking at the overall results the MOTHY and the OD3D models were more accurate for predicting the pathways of the drifters in this region. This is especially true for the coastal current regime, while the predictions are less accurate in the open ocean eddy field of the Balearic Sea and the interior of the western Mediterranean.

The western Mediterranean experiment also demonstrates the importance of how the forcing data – currents, wind and waves – are applied in different oil spill models. For instance, Figure 5 displays a 72 h forecast for the MOTHY and OD3D models using a number of forcing scenarios (the drifter trajectories for 72 h are also displayed for easy comparison). The simulations using OD3D with Mercator and MFS direct forcing agreed reasonable well with observations, the model predictions are in correct direction but too slow (Figure 5). It should be noted that the OD3D with Mercator forcing run on land after 55 hours due to bad representation of the coastline so the Mercator is truly moving much faster than with MFS forcing in this case, nevertheless even the energetic Mercator forcing gave too weak velocities. For the MOTHY model, the drift is much too slow for both Mercator and MFS forcing. These observations seem to be general for the western Mediterranean experiment: The advection is generally too weak in all models and the MOTHY has somewhat slower velocities than the OD3D model. As a final note we note that MFS give slightly stronger currents than the Mercator model for the main part of the experiments. Figure 5 also shows that the four MOTHY simulations show strikingly different excursions, depending on the current data used. In this case, wind forcing – on which MOTHY relies – was weak and the current field was dominated by the density-driven coastal current. Consequently, the "wind-only" simulation (black dots) shows very little movement of the predicted slick, while the simulations with current data move in the right direction. The amount of movement reflects the relative current strength at 100m depth in the MFS and Mercator data. In contrast, OD3D uses the surface currents from the ocean models, which gives better results. MF has since rerun this case with current data from different depths and from an upgraded Mercator Med model; the results agree much better with the observed drifter trajectories.



MF MOTHY



met.no OD3D

Figure 5

Comparisons of oil drift simulations (colored lines and dots) against three drifters (black lines) in the Western Mediterranean demonstration experiment, October 2007. Colors indicate the ocean data used: red = MFS; blue = Mercator Med; green = climatology (MOTHY); black = wind only (MOTHY)

- A common result from both experiments is that the drifter trajectories are better reproduced in coastal areas than in the open ocean (not shown here but is clear when comparing model runs with drifters trajectories using all drifter data). This is directly attributable to the ocean current forcing data used. The often large discrepancies between the predicted currents in the open ocean reflects the fact that the current field is dominated by unstable mesoscale dynamics (eddies, meanders); these processes are difficult to predict. Nearer the coast, the presence of land and the continental slope tends to align the currents along the isobaths, a process which is much better replicated in numerical ocean models.

The demonstrations in the North Sea and Indian Ocean were carried out in the winter of 2007-2008, with participation from met.no and MF. The results of these two demonstrations are documented in the MERSEA deliverable report D12.2.6 (MERSEA-WP12-METNO-STR-002).

In the first case, a real oil spill accident in the North Sea was targeted. On 12 December 2007, about 4400 tons of oil was spilled at the Statfjord field west of Norway. met.no and MF provided real-time and post mortem simulations of the spill using MERSEA ocean forcing data (Figure 6). This supplemented the national service forecasts issued by met.no, which did not utilise MERSEA forcing data (it is based on a MIPOM model with 4 km resolution called Nordic4), and thereby afford a comparison of standard practise with MERSEA-driven predictions. Persistent, strong southerly winds led to an initially northerly drift and rapid degradation of the oil slick. Further observations are unfortunately conflicting. The met.no national service gave an easterly drift prediction [which was subsequently found to be based on erroneous forcing data]. All the other predictions – OD3D and MOTHY, forced by MERSEA data – showed a more northerly drift, which is believed to be more correct. One of these used data from a different met.no operational ocean model that is nested in MERSEA data; it appears to be the closest to the real slick trajectory. This supports the proposition that MERSEA data are best applied through local nested models (cf. CYCOFOS–MFS in the eastern Mediterranean). Forecasters at met.no's Marine Forecasting Centre found the access to alternative drift predictions valuable in giving advice to the response teams in the field.

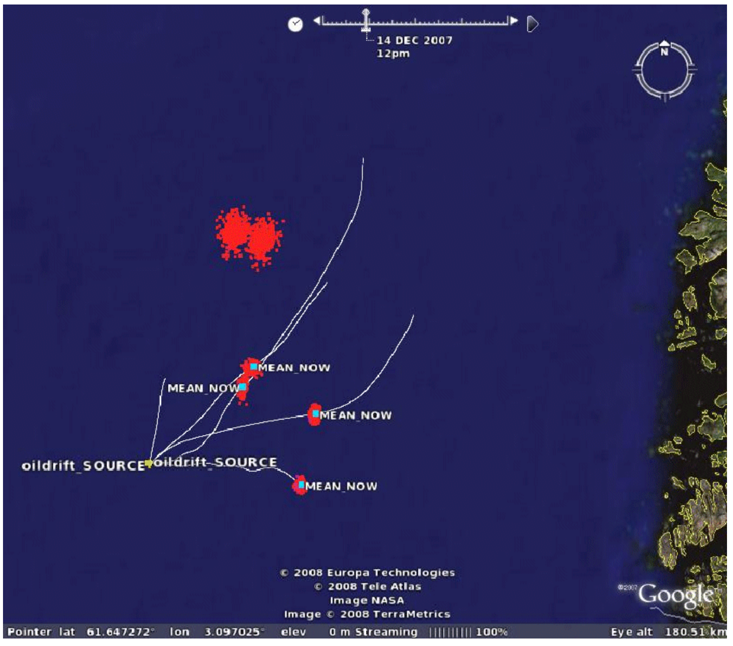


Figure 6

Simulations of Statfjord oil spill, December 2007: 4 by OD3D and 2 by MOTHY. Southernmost is national service (no MERSEA data used).

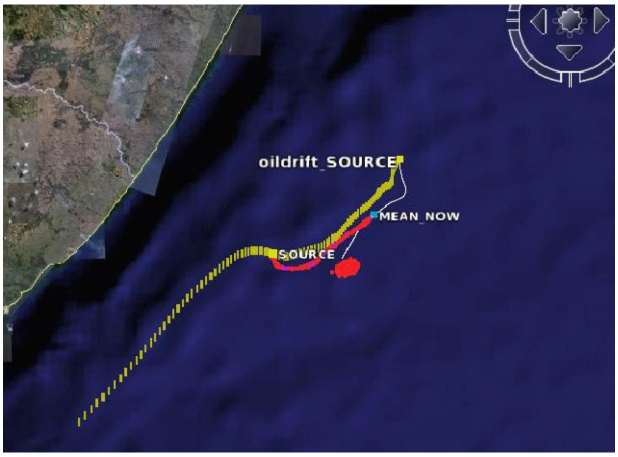


Figure 7

Indian Ocean demonstration displaying results 66 h into a 111 h forecast. Snapshot of oil spill forecasts from OD3D (the red line represent positions

The Indian Ocean demonstration was a scenario exercise, i.e., no real drifters or oil, in which a tanker is damaged southeast of South Africa and leaks oil. Optionally, the tanker comes adrift while leaking oil, similar to the "Prestige" accident (Figure 7). The aim of this scenario is to demonstrate the global capability made possible through access to MERSEA data sets. Specifically, the ocean forcing data used by met.no and MF are all obtained from Mercator Global. An important issue here is the method of access. Since the full global data sets are very large, it is generally not feasible to download and store them routinely for possible use in an oil spill simulation somewhere in the world ocean. For met.no, on-demand OPeNDAP access with subsetting is the method of choice. MF has a unique solution inasmuch as the Mercator data are available on the same computing facility as the oil spill modelling system. In addition, one aimed to demonstrate extending the scope of maritime emergency forecasting services by including a ship drift model coupled to an oil drift model in order to simulate the oil spill from a drifting tanker. Both MF and met.no ran sample simulations and posted the results on the Task web-site (http://mersea-oil-spill.wiki.met.no/doku.php). In addition, met.no provided access to its online ordering and viewing service so that selected users could do their own simulations in the Indian Ocean or anywhere else.

Beyond assessing the improvement to forecast accuracy, Task 12.3 also looked into other possible enhancements to existing oil spill fate forecasting services that might be expected from the availability of MERSEA ocean data sets. Specifically, MERSEA data facilitate extension of the services temporally (longer forecast horizon) and geographically, as well as offering several alternative ocean forcing fields. User feedback from the demonstrations was particularly sought for these issues. On the topic of forecast length, users report that extension to 10-14 days can be beneficial for incidents that are large or well offshore. Near the coast – where most incidents (90%) occur – short-range forecasts are sufficient. Extending geographical reach to whole regions and the global ocean is seen to be primarily of interest to international and intergovernmental bodies (e.g., EMSA). Local end-users are more interested in higher-resolution coastal capabilities (e.g., estuaries, fjords and skerries). One interesting suggestion is the use of global services on the web as an "export product" to developing nations, shiping companies, etc. Finally, users found the possibility of alternative predictions or mini-ensemble forecasts to be a potentially valuable source of useful uncertainty information. However, they need to be delivered properly to users. For example, response teams in the field want *one* best estimate of the oil spill drift, provided after expert deliberation. Met service duty forecasters, on the other hand, are familiar with "second opinions" and ensemble forecast products, and they are able to utilize them in preparing forecast advice.

In summary, the MERSEA ocean data have been found to represent the state-of-the-art in ocean prediction, and its current level of forecast accuracy. Use of these data in modern oil spill fate forecasting services has led to some improvements in accuracy, but also highlighted areas where the ocean modeling systems are imperfect. The MERSEA data taken directly are perhaps most useful at the global level, allowing oil spill services to be applied quickly anywhere in the world ocean. For most users, however, MERSEA data will be most beneficial when applied as boundary data sets for local, nested hydrodynamic models that in turn supply fine-scale current fields to the oil spill fate models. There is, still, potential for contributing valuable "second opinions" and providing members to mini-ensemble forecasts for expert middle users.

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Mersea Developments at the Met Office

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The development of a North-East Atlantic tidal NEMO system

Presently the UK Met Office run a suite of models simulating shelf seas regions in both the North-East Atlantic and elsewhere using the Proudman Oceanographic Coastal Ocean Modelling System (POLCOMS). Detailed descriptions of POLCOMS are given in Holt and James (2001) and Holt et al. (2005). It is a 3D baroclinic finite difference model which uses an Arakawa-B grid (Arakawa, 1972) in the horizontal and sigma coordinates in the vertical. This choice of grid, the decision not to model explicitly the horizontal diffusion and the use of a sophisticated horizontal advection scheme (the Piecewise Parabolic Method (James, 1996)) combine to give the model good front-conserving properties. Hence the model is ideally formulated for high resolution shelf-seas work, where gradients in both topography and scalar properties can be large. The POLCOMS model is coupled with a complex ecosystem model developed originally for the North Sea region. ERSEM (Baretta et al., 1995) was conceived as a generic model, and is one of the most complex lower trophic-level marine ecosystem models currently in use. Its philosophy is to include all those processes which significantly influence ecosystem dynamics, and to resolve the ecosystem into sufficient functional groups so that those processes can be sensibly defined. A description of the operational coupled POLCOMS-ERSEM system is described in Siddorn et al. (2006).

POLCOMS has been shown to successfully simulate the region of interest; descriptions of the POLCOMS modelling system as applied within the North-East Atlantic region can be found in the literature (Proctor and James, 1996; Holt and James, 1999a/b; Holt et al., 2001; Holt and James, 2001). A review of ecosystem models of the North Sea (Moll and Radach, 2003) show that the coupling of POLCOMS with ERSEM is extremely effective.

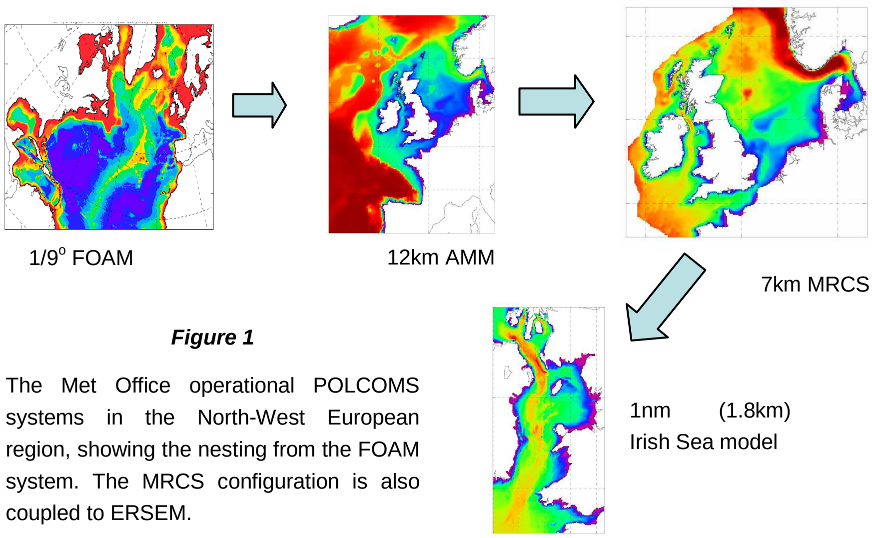


Figure 1

The Met Office operational POLCOMS systems in the North-West European region, showing the nesting from the FOAM system. The MRCS configuration is also coupled to ERSEM.

In figure 1 the operational configurations presently allowing tidal simulations of the North-East Atlantic are shown. The 12 km Atlantic Margin Model is nested into the 1/9° Forecasting Ocean Assimilation Model (a non-tidal model), nesting through to the Medium Resolution Continental Shelf model and the high resolution Irish Sea model. Ecosystem modelling of the North-West European continental shelf is undertaken within the MRCS.

Strategically, it has been decided that the modelling system for the tidal regions within the Met Office should come into line with other ocean modelling being done at the Met Office and more widely. The main objective relating to the North-East Atlantic system within Mersea has therefore been to develop a NEMO shelf seas configuration that is directly comparable to an existing POLCOMS configuration, and to use this for a comprehensive assessment of the quality of the NEMO shelf seas configuration in comparison to POLCOMS. This is a challenging objective, especially given the amount of effort that has been spent in preparing the POLCOMS system for effective simulations in the North-East Atlantic and the lack shelf-type components in the NEMO system, which was designed exclusively as a an open ocean modelling system.

A work plan was established that comprised two stages: firstly, development of a tidal simulation with comparison to equivalent tide-only runs of POLCOMS; and secondly development and assessment of the full 3D baroclinic system. This article will focus on the progress made to simulate the tidal properties of the system within Mersea.

The development of NEMO for use in the shelf seas has focussed on an Atlantic Margin configuration equivalent to the existing operational POLCOMS Atlantic Margin Model (AMM). Initial work has aimed to set up a basic barotropic tidal simulation to test the various new developments required for shelf seas modelling, implemented by partners in the MERSEA IP project. These developments have included the split-explicit free surface (Bessières, 2003), unstructured open boundary conditions (Chanut, 2005), re-activation of the s-coordinate code and new pressure gradient algorithms (An and Beckmann, 2006) and the non-linear free surface (variable volume code) (Levier et al, 2006). Validation of both the tidal and surge components has been conducted and will be detailed below.

The NEMO-AMM configuration has been set up using a similar bathymetry and horizontal grid to that used in POLCOMS-AMM, although it should be noted that as NEMO is a Arakawa C-grid model and POLCOMS on a B-grid. The NEMO AMM replacement grid therefore has had some remapping of the coastline to take into account these differences. The vertical grid for the initial experiments in NEMO uses pure sigma levels since the Song and Haidvogal S-levels are not fully coded yet in NEMO.

For the purpose of comparison between the NEMO and POLCOMS AMM configurations, the two systems have been configured to be as similar as possible. However, the ability to do this is limited by the availability of common schemes in the two models, and hence a number of differences remain.

Testing of the barotropic code

Barotropic testing has been undertaken using 1-year tides-only experiments forcing with 15 tidal components at lateral boundaries. These have been validated against tide gauge and buoy data. Each model has been run with the native TKE scheme and also with a k-ε model (Canuto et al., 2001) within the GOTM (General Ocean Turbulence Model) framework. These runs have mainly been undertaken by POL using NEMO on a linux cluster. There have also been modifications made to the code to allow GOTM to be run in vector environments such as on the NEC at the Met Office. This work allows some functionality of the GOTM system to be used within NEMO on vector machines, but significant effort is required if GOTM is to become generically available for the NEMO system.

The figure 2 above show the cotidal chart for the M2 constituent for the NEMO and POLCOMS configurations. This shows that the NEMO system is now producing similar results to the POLCOMS system and broadly reproduces the key features of the barotropic system in the North-West European continental shelf.

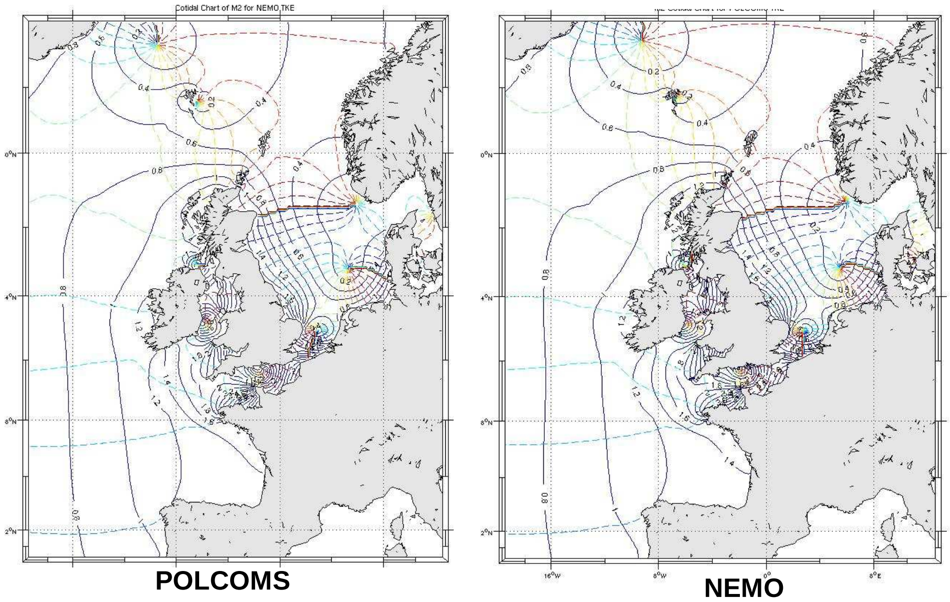


Figure 2

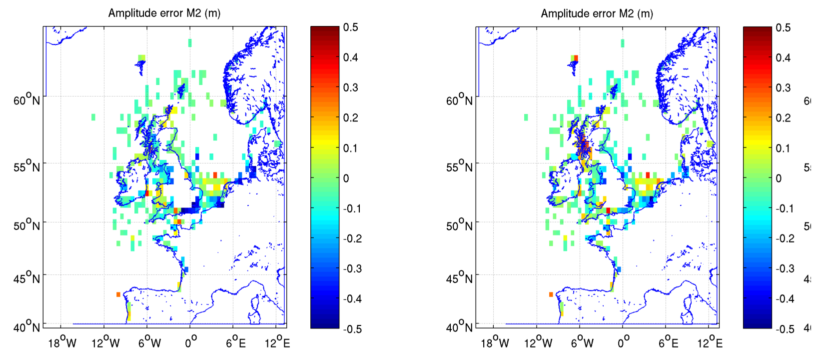
M2 cotidal chart from an annual run of AMM using POLCOMS (left) and NEMO (right) using the standard TKE scheme for each model.

A new data set of approximately 2200 tidal analyses are used to validate the 15 tidal constituents in each run. The accuracy is very similar in the POLCOMS and NEMO simulations (see table 2), NEMO shows a marginal improvement probably because the C-grid gives a better representation of the coast-line and NEMO has higher formal accuracy. The differences seen when using different turbulence models are unlikely to be significant. Together this suggests the tidal accuracy is primarily determined by the bathymetry and the open boundary conditions. The errors seen in this comparison with a new data set are similar to those found in other comparisons with POLCOMS (e.g. Holt et al 2001, Holt et al 2005), and other tidal models (e.g. Kwong et al 1997). This confirms the utility of NEMO for tidal simulations on a shelf wide scale.

	NEMO TKE	**NEMO k-ε**	**POLCOMS TKE**	**POLCOMS k-ε**
Q1	1.07	1.04	1.03	0.98
O1	2.54	2.62	2.23	2.48
P1	1.33	1.28	0.80	0.73
S1	1.04	1.04	1.07	1.07
K1	3.84	3.74	1.70	1.79
2N2	2.73	2.71	2.61	2.63
MU2	3.81	3.93	6.52	6.24
N2	3.86	3.89	4.40	4.39
NU2	0.94	0.96	1.06	1.18
M2	15.93	16.82	17.74	20.55
L2	3.88	3.85	4.15	4.16
T2	0.59	0.59	0.67	0.61
S2	6.70	6.71	7.06	6.47
K2	1.78	1.85	1.98	2.22
M4	6.11	6.24	5.47	5.71
Total	69.67	68.13	75.60	75.45

Table 1

Root Mean Squared errors (cm) for tidal amplitudes using the same data as used in Figures 2 and 3 showing the overall reduction in RMS errors when going from POLCOMS to NEMO and furthermore in the use of the k-ε scheme over the TKE scheme.



POLCOMS-GOTM AMPLITUDE ERRORS (TOP) and SCATTER PLOT (BELOW)

NEMO-GOTM AMPLITUDE ERRORS (TOP) and SCATTER PLOT (BELOW)

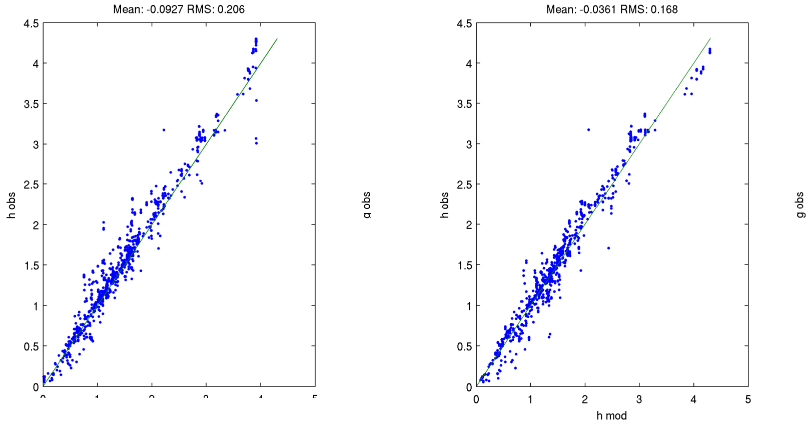


Figure 3

Errors in the M2 tidal amplitude (m) (top) and a scatter plot of model against observed M2 amplitudes (bottom) for the AMM using POLCOMS (left) and NEMO (right). Both use the k-ε turbulence scheme.

Comparisons of the phase (not shown) and amplitude (Figure 3) of the M2 tide indicate the NEMO code outperforms POLCOMS in both the RMS error and mean error for amplitude, but broadly matches POLCOMS for the phase RMS error with POLCOMS significantly better in the mean phase error.

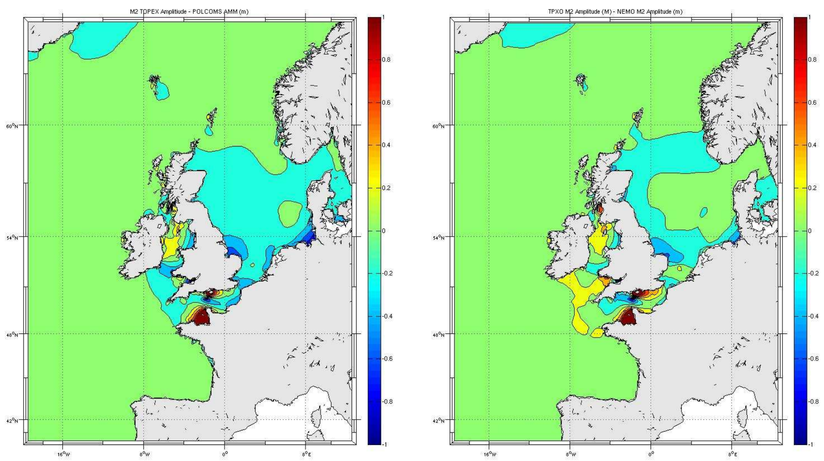


Figure 4

Differences between TOPEX derived M2 amplitude and the modelled M2 amplitude (m) for the AMM using POLCOMS (left) and NEMO (right). Both use their native TKE turbulence scheme

A comparison of the TOPEX derived M2 amplitudes and the model based M2 amplitudes is given above in Figure 4. Both models appear to overestimate the tidal amplitudes in the North Sea. In the North Sea the NEMO system appears to fare better, with errors in the central area of less than 20 cm. In the Western Approaches and Irish Seas NEMO again seems to be slightly better, although the picture is slightly more confused. There are also significant errors for the Breton coastline although in such areas (as discussed below) the reliability of the TOPEX product is likely to be poor.

The TOPEX derived tidal amplitudes are based on Oregon State Universities TPXO inverse model, Egbert and Erofeeva (2002). TPXO best-fits, in a least-squares sense, the Laplace Tidal Equations and along track averaged data from TOPEX/Poseidon and Jason. TPXO assimilates both satellite altimeter data and in situ data. It is accurate to within one cm in the open ocean, but is not accurate near the coast, particularly in areas with large tidal amplitude, e.g. the Bristol Channel and along the Breton coast. It's accuracy away from the coasts, where in situ observations are not readily available is its main advantage for spatial comparisons against model data. See Egbert and Erofeeva (2002) for more information on the TPXO accuracy. The tides are provided as complex amplitudes of earth-relative sea-surface elevation. TOPEX derived data is provided for the North Atlantic at 1/12 of a degree resolution. For further information see: http://www.coas.oregonstate.edu/research/po/research/tide/global.html

Testing of atmospheric pressure gradient forcing

An atmospheric pressure gradient forcing has been included within NEMO to allow the inclusion of the effect of atmospheric pressure systems upon the sea surface height. This code was then used to simulate a surge event to check both the effectiveness of the implementation and the ability of the NEMO system to model storm surges.

In November 2007 a particularly large storm surge propagated down the east coast of Britain (and on to mainland Europe). Astronomical tide and residual (i.e. surge) data was obtained from the National Tidal and Sea Level facility hosted at BODC (British Oceanographic Data Center) to allow comparisons with the period of this storm surge. The model was started on the 7th November from static conditions using forcing from archived ~12km Met Office North Atlantic European NWP atmospheric pressure and wind forcing and using tidal harmonics at the lateral boundaries. The results are shown in Figure 5. As can be seen the model quickly spins up and produces a short period of negative surge before responding to the low pressure system moving through and producing a peak at around the same time and amplitude and timing as the observed peak. Errors in this peak are likely to be due to the lack of a significant spin-up of the model as well as any model errors. The second peak (the larger, and in fact the largest surge observed in half a century) came through in the early hours of the morning of the 9th November. The modelled surge arrives at the right time and with a good replication of the shape and amplitude of the surge passing by Lowestoft. The model underestimates the amplitude of the surge, although this is to be expected as the measurements are taken at stations in relatively shallow waters and with a resolution of 12km the AMM could not be expected to pick up the amplification of the surge that would occur so close to the shore. This model was run in barotropic mode and any baroclinic (density) affects upon the propagation of the surge are not included. This test case will be re-run in full baroclinic mode to test the impact that non-linear interactions between the barotropic and baroclinic systems.

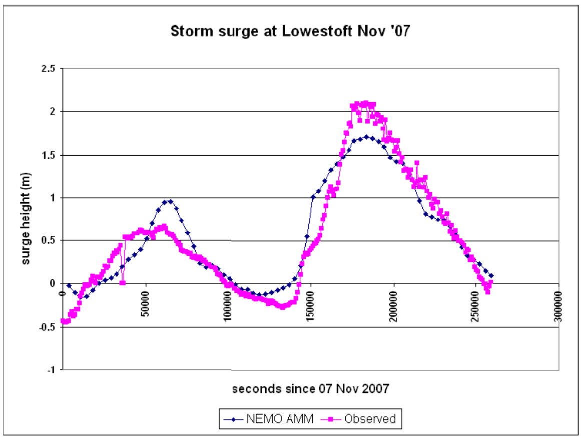


Figure 5

Storm surge data for Lowestoft provided by BODC for a three day period starting on the 7th November compared with the NEMO-AMM model surge predictions. Modelled surge is in blue and observed in pink. The model uses the native TKE scheme.

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