Chapter 14

MERCATOR OCEAN GLOBAL TO REGIONAL OCEAN MONITORING AND FORECASTING

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Abstract : The MERCATOR OCEAN monitoring and forecasting system has been routinely operated in Toulouse in near-real-time since early 2001. MERCATOR OCEAN service is aiming at providing estimates of the ocean circulation and thermodynamics at high resolution at the global scale. Products are already used by more than 150 referenced users from various communities: public bodies such as met services and agencies dealing with the ocean and its environment, as well as private bodies that are directly linked with the customers operating in the marine environment.

The system is based on high resolution ocean general circulation models (OGCM), real-time processing of remotely sensed and in situ observations, and data assimilation techniques. Its has been regularly upgraded, expanding the geographical coverage from regional to global ocean, improving models and assimilation schemes, adding new data and building new products. Three prototypes of the MERCATOR system are currently running: one global coarse resolution (2°) configuration, one in the north and equatorial Atlantic at medium resolution (1/3°), and one with high resolution (1/15°) in the north Atlantic and Mediterranean. The goal is to build a high resolution O(1/12°) global unique system by the end of 2008. This service is one component of GODAE in Europe, and is one of the key components of the GMES/MERSEA European integrated project. A brief overview of MERCATOR OCEAN, the project and the systems, some recent upgrades and some examples of application using MERCATOR inputs are presented.

Keywords : MERCATOR, operational oceanography, ocean monitoring and forecasting, data assimilation, scientific assessment, ocean services.

1. MERCATOR OCEAN, an assimilation center for ocean monitoring and forecasting

MERCATOR is the French ocean monitoring and forecasting center. Objectives are to:

- simulate the global ocean with a primitive-equation high resolution model, assimilating satellite and in situ data, to provide hindcasts and near-real time nowcasts and forecasts of the global ocean circulation,
- be operated on an operational mode (ie routine and near-real-time) to provide continuous and well-assessed global/regional ocean monitoring and forecasting information
- through a new ocean service, serving (1) Institutional Operational applications; (2) Research; (3) Private sector Operational Recreational and Commercial applications and (4) Environment Policy Makers end-user needs,

The project was launched in 1995 by the six major French agencies involved in oceanography (namely: Centre National d'Etudes Spatiales (CNES), Centre National de Recherche Scientifique (CNRS), Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Institut de Recherche pour le Développement (IRD), Météo-France, Service Hydrographique et Océanographique de la Marine (SHOM), with involvement of their subsidiaries CLS and CERFACS). The project is lead today by the MERCATOR OCEAN public company, created in 2002 to develop this joint operational capacity for global high resolution ocean monitoring and forecasting, with commitments to prepare transition to an operational centre.

The MERCATOR OCEAN monitoring and forecasting center is in Ramonville St Agne near Toulouse (France), with a team of around 50 people gathering the R&D, Integration, Assessment, Operation & Services requested skills.

Since 2001, the team has been providing weekly ocean bulletins without any service interruption to a wide range of users, and went through 3 major releases of the forecasting system. Real-time outputs, as well as validation reports, are available at http://www.MERCATOR.eu.org.

MERCATOR is a key partner of the international Global Ocean Data Assimilation Experiment "GODAE" and the European MERSEA project for operational oceanography.

2. The MERCATOR OCEAN monitoring and forecasting system

The MERCATOR system provides a full 3D depiction of the ocean dynamics and thermohaline circulation (T, S, currents, mixed layer depth,), with a priority given to high resolution (eddy resolving) scales. Information is available on a near-real-time and routine basis, by providing weekly Near-Real-Time Analysis and 2-week Forecasts; and on a Reanalysis mode, with data assimilation.

Three prototypes of the MERCATOR system are currently running: one global low resolution (2°) configuration, one in the north and equatorial Atlantic at medium resolution (1/3°) and one with high resolution (1/15°) in the north Atlantic and Mediterranean. An upgrade in the resolution will soon be achieved for the global configuration from 2 to 1/4°

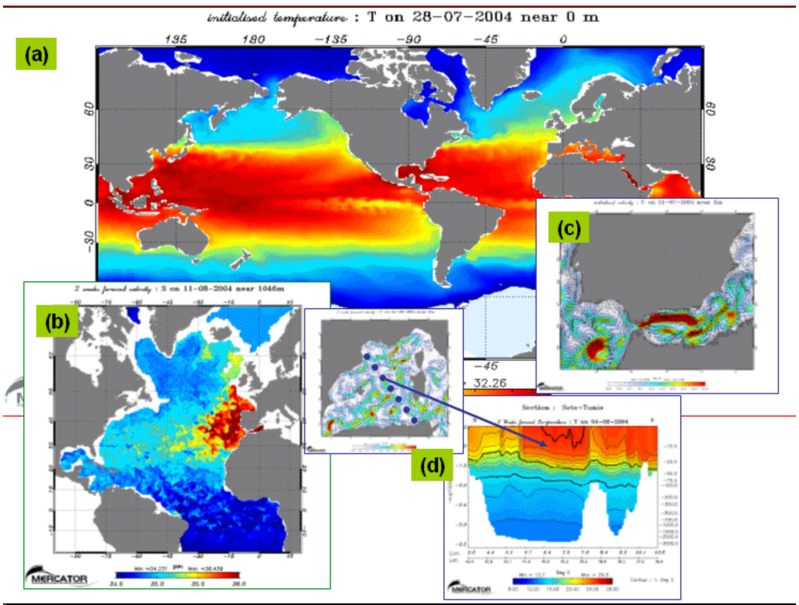

Figure 1. Examples of MERCATOR OCEAN system outputs. (a) Global Ocean (2° model) Sea Surface Temperature field, Real-Time Analysis 28 July 2004 computed 28 July 2004; (b) North & Tropical Atlantic (1/3° model) 1000 m depth Salinity, 2-week forecast 11 August 2004 computed 28 July 2004 ;(c) Gibraltar straight (5-7 km model, ~1/16°) surface currents; Real-Time Analysis 21 July 2004 computed 21 July 2004 ; (d) Mediterranean sea(5-7 km model, 1/16°) Temperature vertical section between Sète and Tunis (and surface current map) 2-week forecast 4 August 2004 computed 21 July 2004.

2.1 Input data

MERCATOR relies on existing data assembly centres to collect, process and validates its input real time and delayed data mode. Input data for MERCATOR include several in situ observations and remote sensing ones. Data are used for several applications: forcing, assimilation and model validation. The

Table 1 lists the current datasets used.

DATA	CENTER	RETRIEVAL FREQUENCY	FORCING	ASSIMILATION	VALIDATION
***In situ* data** : high resolution XBT and CTD, low resolution TESAC and BATHY, ARGO profiling floats, moorings (TAO/PIRATA/TRITON/), drifters, ...	**Coriolis Data Center**	weekly		x	x
Altimetry : Jason-1, GFO, Envisat, Topex-Poseidon	**SSALTO / DUACS**	weekly		x	
Reynolds **Sea Surface Temperature**	**NOAA**	weekly	x	x	
High Resolution SAF Ocean&Ice Atlantic **Sea Surface Temperature** (10 km, daily product)	**Eumetsat / Météo-France**	daily			x
Climatologic **Sea Surface Salinity**	*Reynaud & al. (1998)*		x	x	
6-hour analyses and predictions of winds, heat fluxes, Evaporation-Precipitation, cloudiness, air surface temperature, air surface humidity, surface wind	**ECMWF for operational forcing**	weekly	x		
Monthly Climatologic **Runoffs**	**Unesco database** *J. D. Milliman and R. H. Meade, 1983* *G. L. Russell and J. R. Miller, 1990* *F. Van D Leeden & al*		x		
Real-time scatterometry **winds**	**Cersat**				x
Mean Sea Surface Height combining gravity/ *in situ* data	*M.H. Rio & al. (2004)*	Regularly upgraded		x	
High resolution daily **sea ice concentration** (12 km) and **drift** (60 km). Real-time.	**Cersat** *R. Ezraty and J.-F. Piollé (2004)* *R. Ezraty & al. (2004)*				x

Table 1. Input MERCATOR data used for assimilation, forcing and model assessment.

2.2 Model

MERCATOR uses the OPA-NEMO primitive equation ocean code developed at LODyC, Paris [*Madec et al.*, 1998]. The four MERCATOR configurations have a lot of common points like using the rigid lid assumption, a vertical z-coordinates and a turbulent kinetic energy mixing parameterisation (1.5 closure scheme). The bathymetry is processed from the Smith et Sandwell, data base completed in the Antarctic region, the initialisation temperature and salinity fields come from Levitus Climatology [*Levitus and Boyer*, 1994] completed with the Reynaud Climatology [*Reynaud et al.*, 1998] in the Atlantic and the Medatlas climatology [*MEDAR/MEDATLAS*, 2002] in the Mediterranean Sea. At this time the surface forcing function uses daily stress of wind, evaporation, precipitation, net heat and solar fluxes provided by the European Center for Medium-range Weather Forecast (ECMWF) analyses and forecast. The surface forcing includes a retroaction term in the net heat flux, based on the difference between the model SST and the weekly Reynolds Sea Surface Temperature [Reynolds], with the constant value of $40 W/m^2$ [*Barnier et al.*, 1995]. A relaxation term to the Sea Surface Salinity from climatological data is also added to the E-P flux with the constant value of 5.10^{-6} $m.s^{-1}$. The next version of all the configurations will using Bulk Formulae which allow a better coherence between ocean surface and atmospheric fields and also is the good way to forced the sea ice model. The main rivers are represented by an input of fresh water at the river mouth given by the climatological monthly data base from UNESCO [*UNESCO*, 1996]. A fresh water flux is also added along Antarctica to simulate the melting of the continental ice.

Two configurations are MERCATOR target configurations for the GODAE intensive phase, so that to cover global ocean with an eddy-permitting resolution, and North Atlantic and Mediterranean Sea basins with an eddy-resolving resolution:

- A high resolution basin configuration (5 to 7 km horizontal resolution, 43 vertical levels from 6 m at the surface to respectively 200 m and 300 m at the bottom of the Mediterranean Sea and the Atlantic) covering North Atlantic from 9°N to 70°N and Mediterranean sea [*Siefridt et al.*, 2002]; this configuration focuses on mesoscale processes [*Drillet et al.*, 2004] and links with coastal modelling in European seas. The first version of this configuration used a bilaplacien operator for the horizontal viscosity and diffusivity, a free slip lateral boundary condition and climatological buffer zone at the south and north boundaries of the domain. Several improvements will be soon used in the operational version of this model like laplacien isopycnal diffusivity, a partial slip lateral boundary condition, a bottom boundary layer and a south open boundary allowing a coupling between global and regional configuration. The next version of the high resolution Atlantic model will design the future global high resolution model (1/12°) with a free surface, a partial step vertical coordinate, the atmospheric bulk formulae and a sea ice model.

- A middle resolution global configuration (1/4° horizontal resolution, 46 vertical levels from 6 m at the surface to 250 m at the bottom) covering global ocean; this configuration aims at providing the best ocean state estimates for global ocean analysis and boundary conditions for regional models worldwide. This configuration use the same parameterisation and physics than the high resolution model describe upper and the improvements (free surface, partial step vertical coordinate, atmospheric bulk formulae and sea ice model) will be implemented .

Two lighter configurations are also implemented in real-time by MERCATOR for demonstration and testing of new algorithms:

- A middle resolution basin configuration developed during the clipper project [*Treguier et al.*, 2001] (1/3° horizontal resolution, 43 vertical levels from 12 m at the surface to 200 m at the bottom) covering North and Tropical Atlantic.
- A low resolution global configuration (2° horizontal resolution, 30 vertical levels) covering global ocean [*Madec and Imbard*, 1996].

In September 2004, the two basin configurations (middle and high resolution) as well as the low resolution global ocean one are operational; the ¼° global ocean model is under development and will integrate the operational chain in the coming months.

2.3 Assimilation method

An ocean monitoring and forecasting system is based on two integrated components: the remotely sensed (e.g. SST, altimetric data) and in situ (e.g. temperature and salinity profiles) observations and the thermodynamical ocean model that are combined to give the best possible description of the real ocean. The way to optimally combine the information given by each system component is called “data assimilation”. This optimal combination (i.e. data assimilation) is achieved by taking advantage both from the information contained in the observations of the real ocean and from the constraints imposed by the ocean model physics. Data assimilation allows for instance eddy permitting ocean models to have meso-scale structures that are in phase with what can be observed and to provide a description of the ocean closer to the reality.

MERCATOR assimilation deals with altimeter sea level anomaly, sea surface temperature and temperature and salinity in situ profiles data into its basin and global scale models. Assimilation is considered for routine near-real-time nowcasts and forecasts issues, but also long term reanalysis products.

MERCATOR is developing a suite of assimilation tools (called "SAM" for MERCATOR Assimilation System) of increasing complexity, from sequential to variational method: the first release, SAM-1, is based on optimal interpolation ; the second release, SAM-2, will consider a Singular Extended Evolutive Kalman (SEEK) filtering analysis method ; and the third one, SAM-3, will consider advanced methods such as 4D variational method.

The SAM suite uses the PALM coupler [Lagarde et al., 2001] which performs explicit communications between different heterogeneous units such as between model and assimilation operator units, and simplifies or makes easier the transition from one SAM version to the other.

In September 2004, SAM1 is used on operational real time basis since early days of year 2001, SAM2 is under development and will be integrated in the operational chain, and SAM3 is studied on a research mode.

2.3.1 SAM-1

The SAM-1 is based on a Reduced Order Optimal Interpolation method (De Mey and Benkiran, 2002). Two different assimilation versions of this system are used in the MERCATOR prototypes: the SAM1v1 and SAM1v2 techniques.

- Version 1 (SAM1v1) is based on the Cooper and Haines (1996) lifting-lowering of isopycnal approach and allows assimilating SLA data only. The SAM1v1 algorithm starts by calculating a global sea level anomaly increment from innovations (i.e. model-data differences) of along tracks sea level anomaly. It is the reduced order optimal interpolation tool which calculates this increment $\delta\eta$. Based on the statistics for the 3 last months of the ocean model simulation, $\delta\eta$ is partitioned into a baroclinic and a barotropic contribution. The baroclinic part is used to build the temperature increment and the salinity increment by vertically shifting the isopycnals for each water column of the model. Geostrophic velocities are diagnostically adjusted to the new mass field. The barotropic contribution to sea level is used to build a barotropic current stream function increment from which one can deduce a barotropic velocity increment. More details can be found in Ferry et al. (2005).
- Version 2 (SAM1v2) is MERCATOR's first multivariate assimilation method that allows assimilating simultaneously temperature and salinity profiles, SST and SLA data. This system uses fully multivariate 1D Empirical Orthogonal Functions (EOFs of T(z), S(z) and the barotropic stream function) to perform a ROOI (Benkiran et al., 2005). This assimilation system works as follows: first, the differences between the observed and forecast SLA, SST data and in situ measurements are computed over a one week model integration. These differences are then analyzed using a fully multivariate Optimal Interpolation (OI). It is worth noting that the SST product assimilated is the daily Reynolds SST at the analysis time (note that it is already used to correct the flux through a

restoring term). The model equivalent to this SST is the temperature at the first level of the model (6m for the 1/3° North Atlantic system). The Reynolds product is used with a non-Gaussian error so as not to damp the model's meso-scale features but rather to correct locally the model's large drifts. As a consequence, only innovations larger than 2σ (σ~0.6°C r.m.s) are taken into account in the analysis. The model state is updated by the sum of the contribution of each selected EOF to the gain multiplied by the innovation. This scheme is fully multivariate, since the covariances between the errors of different variables are taken into account in the EOFs calculation. The effect is that the assimilation of a single observation has an impact on all the variables in the state vector through the multivariate statistics.

2.3.2 SAM-2

The next generation of multivariate assimilation system, referred as SAM-2, is being developed from Reduced Order Kalman Filters using 3D multivariate modal decomposition of the forecast error covariance (See Brasseur [2005] for a complete description of these methods). The use of 3D modal representation for the error statistics is intended to overcome some of the limitations of SAM1v2 in highly inhomogeneous, anisotropic, and non separable regions of the world ocean such as shallow areas, as well as in the surface layer. SAM-2 includes two versions differing by the formulation of the analysis kernel. The final scheme derived from the SEEK (Singular Evolutive Extended Kalman) algorithm [Pham et al., 1998] (LEGI, Grenoble) has an inversion in the modal space, whereas the intermediate kernel has an inversion in the observation space.

2.3.3 SAM-3

Advanced data assimilation techniques, such as the variational approach, are also investigated in MERCATOR. The variational approach is based on the minimization of the model-observation square misfit over a time period with their given a priori errors. The solution given is the closest trajectory to the observations dynamically consistent with the model equations in a least square mean sense. At given time, the solution is constrained by past and future observations available on the assimilation window. This technique will be used first with the coarse resolution (~2°) global ocean configuration, ORCA2, to assimilate both in-situ and altimetric data.

2.4 Products dissemination

Dissemination of MERCATOR products is made through www and FTP automated tools, both for real-time and archived products. Dissemination tools guaranty access to multi-year reference simulations (and reanalysis to come) with different extraction tools on one hand and real-time ocean bulletins and numerical fields (recent hindcasts, real-time nowcats and 2-week forecasts) on the other hand. For this purpose, a Live Access Server (LAS) tool is implemented and has been defined to be the standard interface for the GODAE community, and the MERSEA group in Europe.

MERCATOR outputs are freely available for Research and Educational applications; a user identification procedure (login/password) enables a precise knowledge of our user community and two-way dialogue with it.

A User Bureau is taking care of any request and can be contacted at mailto://products@mercator-ocean.fr.

3. System assessment

For operational activities, system assessment is a critical issue to guaranty high-level products to the system end-users; MERCATOR OCEAN organized four assessment loops with different scopes, time scales and team involved to ensure a perfect validation of any output of the system.

Each assessment result is widely communicated (see MERCATOR website) in a quaterly newsletter, so that interested users can access to this information. So far, 13 newsletters have been published: they give a good overview of the MERCATOR system products validation activity.

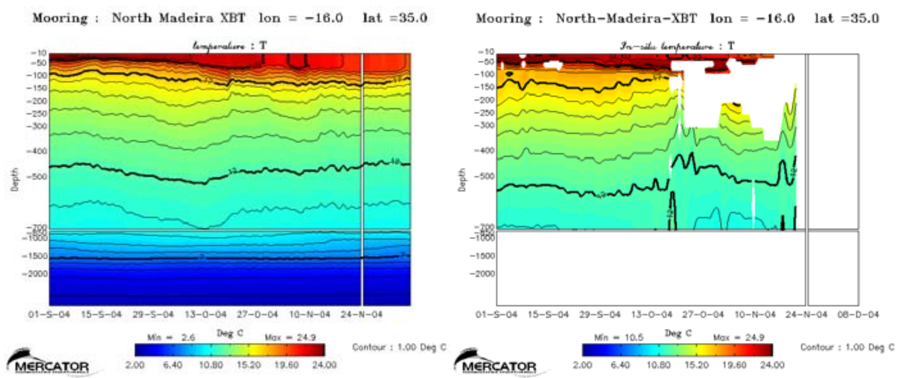

Figure 2. Temperature time series at North Madeira XBT mooring for model (left) and interpolated in situ data (right). See the MERCATOR Newsletter n°6 for details (*http://www.mercator-ocean.fr/html/lettre/presentation_lettre_en.html*).

3.1 Short loop

The first loop of validation is under the responsibility of MERCATOR OCEAN forecasters and considers real-time validation associated to the weekly bulletin. Before allowing any new Ocean Bulletin diffusion, Ocean Forecasters validate the new information processed during Tuesday/Wednesday night. Input data entering the system are first assessed through the Armor tool (data 3D optimal interpolation tool for global ocean) to detect any strong anomalies in the data sets (combination and cross-correlation). Model outputs are compared to independent in situ data set where available, and simple scores (e.g. Analysis / Forecast comparison) are computed. The systematic comparisons with in situ observations, as illustrated on *Figure 2*, are weekly computed and are available on the MERCATOR Web site, as well as internal diagnostics of assimilation.

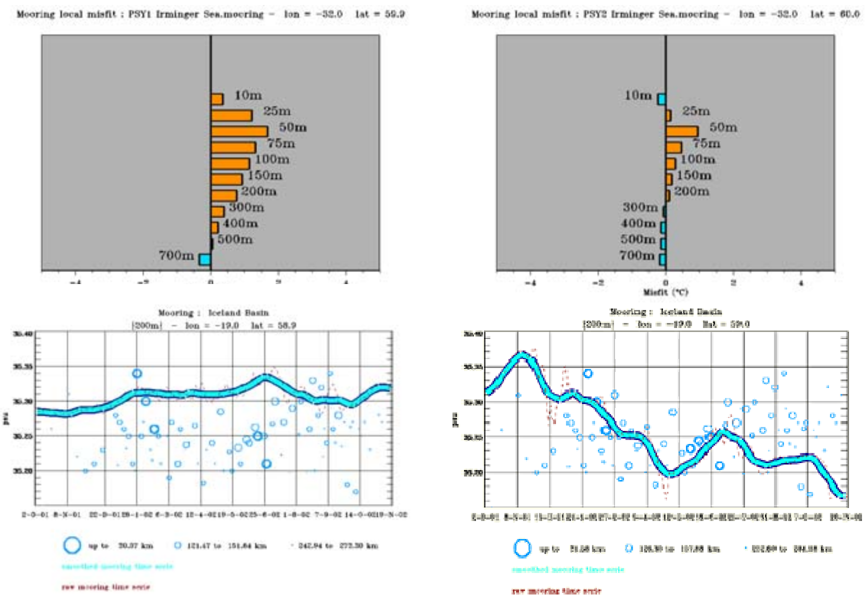

Figure 3. Performance comparison between middle and high resolution operational models (PSY1v1 and PSY2v1). In situ observations (Coriolis database – Ifremer) are used to measure the improvement between the two systems. The upper graphs show the temperature differences between PSY1v1 (left) and PSY2v1 (right) and interpolated observations for several depths and for the Irminger Sea mooring (32W-60N). A positive value indicates a colder model than observations. The lower curves represent the salinity PSY1v1 (left) and PSY2v1 (right) time series at 200 meters depth and for the Iceland mooring (19W-58.9N). The blue lines are 30-days-smoothed time series. Circles represent in situ observations located around the mooring point. The bigger the circle is, the nearer the observation is from the model mooring point. Both analyses show a significant improvement from PSY1v1 to PSY2v1.

3.2 R&D loop

The second loop involves the R&D teams inside MERCATOR and its main objective is to assess precisely impacts of any R&D improvements in the operational system. Change in the model parameterization, upgrades of the assimilation systems, integration of a new data set in the assimilation system could have minor or major impact and could have positive or negative impact. But in any case, this impact has to be perfectly known to measure the progress made to give to the user all the information needed to appreciate the impact for its own application. This loop also permits to analyse more precisely the model performances and diagnoses the model ability to represent physical processes. As examples of such analysis, the Figure 3 illustrates the quality jump realised at the time of the transition from middle (PSY1v1) to high (PSY2v1) resolution model.

3.3 Internal metrics and intercomparison plans

This third loop entered recently ocean operational centres assessment activity thanks to the effort undergone in the GMES/EC MERSEA Strand 1 project and the GODAE experiment at international level.

An open collaboration with FOAM (UK), MFS (Italy), TOPAZ (Norway) and HYCOM-Miami (US) teams enabled to define standard "metrics" adopted for the North Atlantic and Mediterranean Seas and to be extended to the global ocean (see the chapter by L. Crosnier in this volume and http://www.mersea.eu.org/html/strand1/intercomparison.html#metrics). This is now a core component of the assessment activity of the MERCATOR OCEAN centre. Systematic intercomparison has already allowed clear improvements in the different systems.

3.4 Scientific and user feedback

The fourth loop considers the feedback of the user community, with a clear focus on the scientific community using MERCATOR outputs in its own research activity. The MERCATOR Science Working Team is composed of around 100 researchers, directly associated to this scientific assessment activity and improvements of MERCATOR algorithms. Coupling with ecosystem models, with coastal models, statistical analysis, etc., any research initiative conducted with MERCATOR outputs conveys direct opportunities to assess quality of the MERCATOR system.

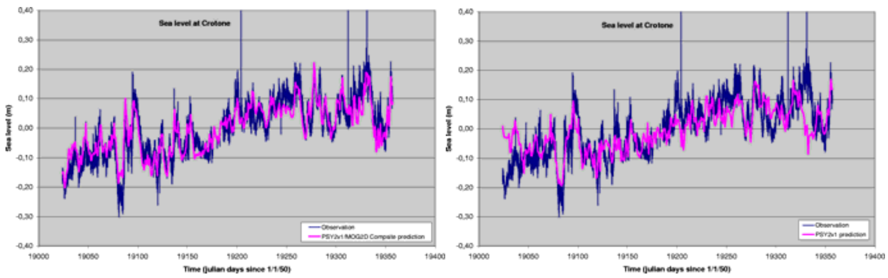

Figure 4: Crotone tide gauge: observed sea level versus MERCATOR (left), versus composite (Mog2D plus low-pass filtered MERCATOR) sea level (right). Series start February the first 2002 (by Florent Lyard and Laurent Roblou, July 2003 – MERCATOR Newsletter 10).

Extension to a wide user community is clearly considered and first feedbacks are already collected. To illustrate this last point, we show in Figure 4 a result of a combination of two dynamical models. The first one, MERCATOR PSY2v1, is designed to solve the ocean circulation and the second one, Mog2D, is designed to solve the tide and storm surge processes. In the figure, the MERCATOR alone solution and the composite solution are compared with tide gauge measurements (for details, see F. Lyard and L. Roblou, july 2003 –MERCATOR Newsletter n°10).

4. Serving ocean services

Developing this new generation of ocean service, able to provide a fruitful operational, 4D space & time consistent and accurate “general ocean information” to specialized ocean services, is the key objective of MERCATOR operational oceanography.

After more than 3 years of continuous operations, ie more than 180 ocean bulletins for ocean forecasters, and more than 150 referenced users in continuous interaction, the MERCATOR team has been studying user feedbacks in a wide range of application sectors where MERCATOR OCEAN inputs were.

Four categories are considered: (1) institutional operational applications; (2) research; (3) private sector operational recreational and commercial applications and (4) environment policy makers.

Under category 1, MERCATOR has been involved in various experiments concerning: Oil Spill drifts experiments (Météo-France, Met.No, CEDRE), Navy operations (SHOM), Ocean inputs for Seasonal Forecasting system (Météo-France) and Education (schools, user training sessions, individual requests, ...). Under category 2, MERCATOR has been requested to provide boundary conditions to coastal models, ocean inputs for biogeochemical models and seasonal forecasting systems, and involved in various Research Sea campaign (IRD, Ifremer, CNRS, IFM Kiel, ...). MERCATOR has been serving under category 3 commercial activities (offshore and fisheries) and many recreational marine activities (sailing races, rowing races,...), and a growing range of activities enter today category 4 amongst with: assessment on observation network (satellite & in situ) for decision makers, monitoring and expertise on extreme ocean climate events (2003 hot summer event, Bay of Biscay ocean synthesis bulletin) or new indicators for ocean pollution risk.

Figure 5 is an illustration of MERCATOR role in serving institutional operational applications: here oil spill fate activity conducted by Météo-France. The impact of MERCATOR OCEAN currents in Météo-France’s pollution dispersion model (called MOTHY) in assessing the consequences of the Prestige shipwreck were studied with great attention. As a preliminary test case to assess MERCATOR impact on his operational oilspill model, P.Daniel (Météo-France) used MERCATOR 103 meters depth currents to force his model with large-scale time/space information and showed the usefulness of such ocean currents forcings for long simulations.

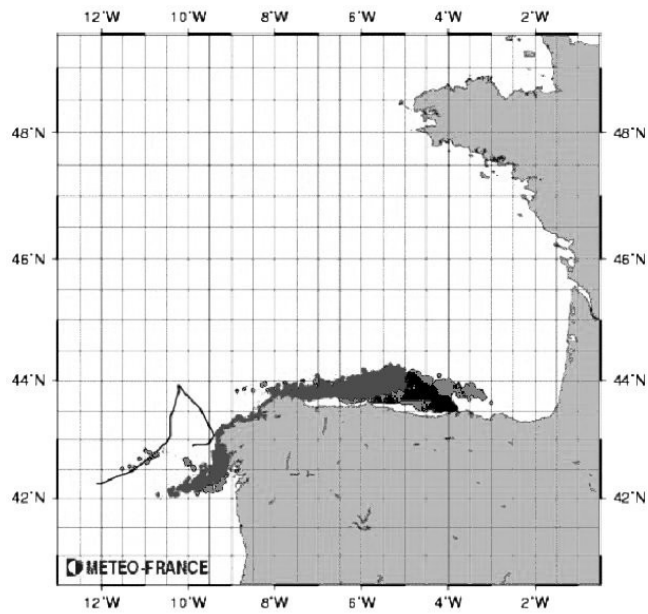

Figure 5. Impact of MERCATOR currents inputs on operational oil drift forecast. Courtesy P.Daniel (Météo-France). Oil spill position (05/12/2002 analysis) forecasted by Météo-France Mothy model alone (dark grey),with MERCATOR inputs (light grey) compared to observations (black).

5. Conclusion

The MERCATOR OCEAN assimilation centre has been running in Toulouse a pre-operational ocean monitoring and forecasting activity for more than 3 years, covering today European basins at 5-7 km, global ocean at 2° and coming to global ¼°; the team developed a strong experience in this matter, and is one of the core team of European GMES program actions to build an Integrated capacity at European level for global ocean monitoring and forecasting.

The MERCATOR OCEAN forecasters team has progressively developed an ocean service for services capacity, serving today more than 150 referenced users, from different application sectors (institutional to private sectors, operational to research, ocean maps to assessment), and bring to them ocean expertise and assimilation capacity.

This ocean monitoring and forecasting is now mature enough to consider the challenge of high resolution and global ocean coverage raised by strong user demands and the transition to a strong operational activity.

But this activity is also fully dependant on real-time, continuous and accurate ocean observation networks, and associated actions for in situ (Argo, ...) and satellite (satellite altimetry, ...) sustained network are critically required.

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