MERCATOR, the Mission

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Abstract. Mercator, a project initiated by the oceanographic community in France, is described. The objective is to develop an eddy resolving data assimilation system for the ocean.

1 Introduction

The Mercator project whose aim is the development of an eddy resolving global data assimilation system is a proposal elaborated by the scientific oceanographic community and endorsed by the French institutes interested in operational oceanography, Centre National d'Etudes Spatiales (CNES), Centre National de la Recherche Scientifique / Institut National des Sciences de l'Univers (CNRS/INSU), Institut Français de Recherche pour l'Exploitation de la MER (IFREMER), Météo-France, Office de la Recherche Scientifique et Technique Outre Mer (ORSTOM) and Service Hydrographique et Océanographique de la Marine (SHOM).

Two workshops took place in 1995 in order to draw the general lines of the project while CLS-Argos (Collecte, Localisation par Satellite) was in charge of the synthesis and as such of the phase 0. 1996 was the year where the project was set-up by Jean-François Minster (CNRS / INSU) and the phase A of feasibility was decided (and funded) by the above institutes February 3rd, 1997. CERFACS (Centre Européen de Recherche et Formation Avancés en Calcul Scientifique) is the focal point for Mercator and Jean-Claude André has been appointed as executive secretary in order, among other things, to ensure an efficient feedback between the project and the institutes.

Mercator is a contribution to the Global Ocean Data Assimilation Experiment (GODAE) planned for the years 2003--2005.

The following section describes the rationale of the project and the mission objectives. Some perspectives relevant for operational oceanography are then outlined in conclusion.

2 Mercator Project Rationale and Mission Objectives

The goal of Mercator is the operational implementation within five to seven years of a system which simulates the global ocean with a primitive equation high-resolution model and which assimilates satellite and in situ data. In the longer term the system has to contribute to the development of a climatic prediction system relying on a

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coupled ocean atmosphere model. In addition the system has to be useful for the military and commercial applications of oceanography.

Three users of Mercator have been clearly identified during the set-up of the project:

Seasonal Prediction. The meteorological community is considering the operational implementation of seasonal prediction systems. The predictions rely on the integration of a coupled ocean atmosphere model. Initial conditions are required both for the atmosphere and the ocean over the whole globe. Mercator will provide the initial conditions for the ocean whereas the atmospheric data assimilation systems used for numerical weather forecasts will provide the initial conditions for the atmosphere.

At this stage, it is not envisaged to operate coupled ocean atmosphere data assimilation systems. A fundamental difficulty would be the difference of time scale of the two fluids, which for the ocean goes beyond the deterministic predictability limit of the atmosphere. This issue will be reconsidered in the future if unstable coupled modes are identified which would then need to be properly controlled during the assimilation process.

The European Centre for Medium-Range Weather Forecasts (ECMWF) is presently operating a seasonal prediction system in experimental mode. It is foreseen the Mercator will be developed in collaboration with ECMWF. The main short-term priority is the availability of a global system with the emphasis being put on the tropical oceans.

Marine Applications. The French Navy is presently operating an experimental data assimilation system for the Eastern Atlantic. High spatial resolution, better than a tenth of a degree, is deemed necessary. The primary area of interest is the Eastern Atlantic with also a high priority for the Mediterranean Sea. The prediction range should be of 4 to 6 weeks ahead. Error bars will have to be provided which imply that ensemble prediction may have to be considered at some stage.

Coastal applications are not part stricto sensu of the Mercator project. Nevertheless Mercator has to be able to provide lateral boundary conditions for coastal models.

The UK Meteorological Office (UKMO) expressed interest in developing collaboration with the Mercator project.

Scientific Applications. Besides the operational implementation, which produces oceanic fields made available to the scientific community, Mercator will be used as a research tool for producing level 3 (gridded) fields at the occasion of measurement campaigns. Consequently flexibility has to be part of the overall design in order to be able to accommodate specific requirements like being able to concentrate on a given area.

2.1 Mercator Main Components

The Mercator system consists of three main components: firstly, an ocean general circulation model, secondly a data assimilation algorithm and lastly a data stream (observations, forcing fields, initialisation fields, validation data ...).

The Ocean General Circulation Model. The ocean general circulation model of Mercator is a primitive equation model based on OPA, which has been developed at Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC). It is recognised that the OGCM will be in constant evolution. At the time of GODAE the model will have been validated at the global scale and with a typical horizontal resolution of 1/12°.

In order to achieve this goal, two lines of development will be followed in parallel:

Global, low resolution. The main priority here is to concentrate on the global aspect of the problem, and in particular on the validation in coupled ocean-atmosphere mode. Mercator will benefit from and rely on the effort made by the French research community in the field of climate simulations and co-ordinated under the " groupe GASTON ". Two atmospheric models are being used, the code developed by Laboratoire de M\'et\'eorologie Dynamique (LMD) and the code whose kernel has been jointly developed by M\'et\'eo-France and ECMWF under the framework of the Arpege-IFS collaboration. The coupling module is OASIS developed by CERFACS.

Furthermore, OPA has been implemented at ECMWF and the sensitivity of seasonal predictions to the OGCM used will be assessed by comparisons with the present experimental seasonal prediction system of ECMWF which makes use of the OGCM HOPE developed by the Max Planck Institute, Hamburg.

Basin, high resolution.

The CLIPPER project which involves scientists from LPO (Brest), LEGI (Grenoble), LEGOS (Toulouse) and LODYC (Paris) aims at simulating the Atlantic ocean circulation at a resolution of a sixth of a degree. Several scientific issues particularly relevant for Mercator are being addressed.

The following step is to build on the experience acquired during CLIPPER and to operate in 1999 a prototype system based on OPA, which will simulate the North Atlantic and Mediterranean circulations at a resolution of a twelfth of a degree, and with TBD vertical levels. Temperature, salinity and horizontal velocity are prognostic variables. The rigid lid hypothesis is made. A mixing layer based on a TKE closure is used

Data Assimilation. Data assimilation methods are currently in quick evolution, particularly under the impulse of the oceanographic community. It is therefore necessary to allow for flexibility in the algorithms, which can be accommodated as well as to offer various possibilities for future evolution. On the other hand, (pre-) operational requirements imply to be rather conservative in the choice for initial implementation. ECMWF has implemented for the seasonal prediction project an existing bidimensional Optimal Interpolation scheme that is not in the position, at the present stage of development, to use altimeter data. The basin, high resolution, initial implementation of Mercator will rely on the already validated code SOFA that uses empirical orthogonal functions of the vertical covariance matrix to decouple the vertical and horizontal directions. SOFA does not assimilate yet in-situ observations, this is a short-term development scheduled for 1998.

Data assimilation attempts at combining various information sources (observations, dynamic's of evolution, ...) and as such is a statistical estimation problem. The methods, which may be used within Mercator, will rely on a specification of the statistics of error (either static or adaptive) in order to be able to improve the system by a careful study of the innovation vector. Besides the theoretical motivation, this choice is motivated by the lesson drawn from the meteorological operational experience that the only Centres still at the cutting edge of weather forecasts have followed this path.

Mercator has to offer the possibility to accommodate the main "modern" data assimilation methods, Optimal Interpolation since it is the initial implementation, variational approach (3D and 4D) in the direct and dual formulation (representers), simplified Kalman filters and adaptive filtering. In order to save computational time, space reduction techniques have to be accounted for in the design. A plausible implementation for the GODAE era would be an adaptive filtering which evaluates key aspects of the statistics of estimation error while the analysis is solved on a limited time window with a variational approach formulated in a reduced space.

It can be shown that all the above methods use more or less the same operators (observation operator, model, projector on the reduced space, covariance matrices of the various errors, gain, ...) or solver (minimisation, eigen values), which are in limited number, but with a very different calling sequence. In order to accommodate the above flexibility requirement, the algebraic component of the data assimilation methods and the scientific content of the operators will be made independent. A generalised coupler, PALM, will solve the algebraic part; it builds on the technical experience acquired with OASIS. The scientific content of the operators will depend on the experience acquired during the experimental phases of the basin, high resolution and global, low-resolution implementations, and on the results obtained by the research community.

While the initial experimental implementation may rely on a univariate formulation, a multivariate formulation in order to be able to accommodate several different data types will be implemented quickly afterward.

In the initial experimental phase, the computer resources used for a week of assimilation should be less than twice the cost of a week of the assimilating model integration. At the time of GODAE, the cost of a week of assimilation should not exceed five time the cost of the assimilating model integration.

Data Stream

Ocean observations, space segment. The requirement of Mercator for oceanic space based data consists of sea surface temperature and altimetry. In the longer term, ocean colour information may be used in coupled physical biological assimilation system, but this is not foreseen as an operational requirement for Mercator at the time of GODAE. Nevertheless this will most likely become soon a research requirement, and as such be thought of within Mercator. There is a requirement of Mercator for global salinity observations, therefore the space agencies are invited to develop, if feasible, the required technologies.

Sea surface temperature fields may be produced using observations from various instruments. The main operational source is the visible/infrared imager AVHRR (Advanced Very High Resolution Radiometer) on board the National Oceanic and Atmospheric Administration (NOAA) operational satellites. AVHRR is also part of the METOP/EPS payload as approved by the Eumetsat Council in June 1996.

Altimetric data are necessary for Mercator. Beyond Topex-Poseïdon, the Jason collaborative NASA/CNES programme will provide high precision observations. In parallel, observations of lower precision like onboard the ERS-1 and ERS-2 satellites (and ENVISAT for the near future) of the European Space Agency provide a significant complement, which with its improved sampling is essential for mesoscale applications. It has to be pointed out that no altimetric operational programmes have been decided yet, it is one of the goal of Mercator to demonstrate the operational need. A fast delivery product (a very few days) is necessary for some of the Mercator operational applications, but high quality products remain necessary for scientific applications.

Oceanic in-situ observations. Electromagnetic waves do not penetrate beyond a few meters in the ocean it is therefore necessary for Mercator to assimilate in-situ observations, which provide access to the vertical structure of the ocean. Temperature, currents and salinity are the parameters to be assimilated. Eulerian observations are useful in that under some sort of stationarity hypothesis, they allow to identify model biases. Nevertheless there is no difficulty for assimilating Lagrangian observations.

Tomography may provide access to the mean thermal structure of the ocean with access to a few degrees of freedom in the vertical. In a project like Mercator, the meteorological experience shows that once the physical interpretation of remote-sensed data is mature enough at the research level, it is still necessary to have one or two persons dedicated to the implementation in the assimilation suite. Therefore assimilation of tomographic data is not considered as a first short-term priority for Mercator. The issue will have to be reconsidered a couple of years before GODAE, resources permitting.

Forcings. Reanalysis as performed at the ECMWF are essential for providing consistent thermodynamical and momentum forcings for Mercator. It only covers the period 1979 to 1993 and has not used as surface wind speed observations the passive microwave radiometer SSM/I from the DMSP satellite, neither the scatterrometer wind observations (with their 180° directional ambiguity) from the satellites ERS-1 and ERS-2. A reanalysis of the "Scatt years" at higher resolution (T213) would be extremely useful, a bonus would be to cover the whole of the "Topex years", such an effort is taking place at ECMWF within the ERA-40 reanalysis project, nominally at a T106 resolution, possibly at T213, resources permitting. At T213, the smallest half wavelength resolved is 95 km and the shortest scales are heavily dissipated, a significant variability of the wind field is then not resolved. Mercator will benefit from the effort to produce as representative as possible wind forcings, conducted in the research community.

The latent heat fluxes at the surface of the ocean can be estimated from satellite data with some accuracy, at least under the Semaphore conditions. This is not the case for the sensible heat flux, which is significantly smaller. Precipitations are largely unknown. Radiation fluxes are heavily dependent upon clouds whose representation is not the strongest feature of the atmospheric models. It is not a priori obvious that an improvement of the latent heat fluxes of the reanalysis by using satellite data but without the possibility of improving the other fluxes will result in an improved oceanic circulation since the overall consistency will have been lost. Mercator will have to assess its requirements in view of the results obtained during the experimental phases.

Real time. Real time is a key aspect of the various data streams for the operational applications of oceanography. The requirement is of the order of 3 days, and in that respect Jason will be a significant improvement upon Topex-Poseïdon.

2.2 Mercator Technical Requirements

Considering the computer resources involved in running in a high resolution global oceanic model, the assimilation suite will be have to run on the most powerful computers available on the market. In the coming few years, it can be expected that such platforms will rely on moderately high (O100) to high (O1000) parallelism and on distributed memory.

The observational data flow as well as the oceanic fields data flow require a significant amount of Input/Output and of archiving capabilities, while the bandwidth remain limited. Mercator will build on the experience acquired by the ECMWF reanalysis team for the development of the assimilation suite.

A secured data flow has to be designed for sensitive data.

2.3 Some Steps toward Operational Oceanography, Context of Mercator

France has significantly contributed to the emergence of operational oceanography through an investment in the international observing research programmes. As an illustration, France has been the main contributor to the ERS-1/2 programmes, and

beyond the ERS altimetric mission is the partner of NASA in Topex/Poseïdon and in the forthcoming Jason. France will also be the main contributor of the space segment of Metop. Concerning in situ data, the involvement in the observing phase of WOCE has also been significant.
In order to valorise this already significant investment, France has to be present in the three aspects of operational oceanography as foreseen in GODAE.

Space Segment. Assuming the Metop programme decided, a long-term commitment of Europe for the measurement of sea surface temperature and the surface momentum fluxes will have been achieved. Operational oceanography further requires a long-term commitment for high precision altimetry and therefore a follow-on of Jason. As of today, altimetry has been funded by development agencies like CNES, NASA or ESA. Following the example of scatterometry and the transfer of the mission responsibility from the development agency ESA to the user agency Eumetsat, the emergence of operational oceanography will probably imply a similar transfer.

In Situ Observations. At the international level, the ARGO proposal of the deployment of an in situ network of Lagrangian profiler will allow Mercator to be fed with the necessary observations. The contribution of France to the in situ part of GODAE is currently being discussed in the Coriolis working group chaired by Ifremer. It could be along 4 actions, which build on already existing or planned systems. First an effort similar as during WOCE, typically 5000 per year, should be performed for maintaining the XBT measurements. Second, Lagrangian profilers of the class of the US Palace or the French Provor has to be deployed on a large-scale basis, research and development is necessary for the measurement of salinity. Third, Eulerian profilers need to be developed and deployed, with a typical number similar to the Lagrangian profilers. The cost of a profile has to be less than 1000FF for providing a viable long term observing system. Lastly moored and drifting buoys have to be maintained and/or systematically instrumented for oceanographic measurements. The Pomme experiment will be a significant milestone.

Modelling and Assimilation. The Mercator project is currently conducting the research and development effort in this area. In order to implement operationally the data assimilation suite to be developed by Mercator, two additional elements are required besides the Mercator team. First, high performance computing facilities and the corresponding archiving system are mandatory. This corresponds to resources comparable to a significant fraction of operational numerical weather prediction requirements. Second a team needs to be in place whose responsibility is to manage and scientifically monitor the incoming data flow (observations, forcings...) and the outcoming data flow (products). In other words, an Operational Oceanographic Centre (CO^2) is required.