Advanced altimeter data assimilation for the development of operational oceanography

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Advanced data assimilation methods are being developed for operational ocean monitoring and prediction systems, with a view to assimilating satellite observations such as altimetry, sea-surface temperature and ocean color into high-resolution models of the ocean circulations and marine ecosystems.
The prototype of an operational North Atlantic forecasting system is currently in development.
This paper provides an overview of the most recent results obtained with the TOPEX/POSEIDON Science Working Team, and further develops our plans for the Jason-1 mission.

Objectives

Satellite observations provide a unique opportunity to monitor the ocean evolution in real time, accurately, at the global scale, and with high resolution. As only the properties of the sea-surface can be observed from space, data assimilation systems are needed to improve the consistency between satellite data and model simulations, to dynamically extrapolate and interpolate measurements scattered in space/time, and to better exploit the results of observation programs like Jason-1. The general objective of this project is to implement and validate innovative methodologies for the assimilation of the Jason-1 altimeter data into ocean and ecosystem models in order to contribute to the development of operational oceanography for programs such as MERCATOR and GODAE and related components (CLIVAR, GOOS, GCOS, etc.). Altimeter data from the Jason-1 satellite will be the primary source of observations in conjunction with TOPEX/POSEIDON and ERS satellites, but particular attention will also be paid to other data types, including in-situ observations from ARGO and their complementarity with satellite altimetry.

The scientific workplan is based on a two-track approach: (i) the development of advanced methodologies for data assimilation, and (ii) their application within pre-operational systems.

Methodologies

A variety of advanced data assimilation and numerical methods are being developed by this project, including:

• Sequential filters: Two non-linear methods, both derived from the sequential estimation theory, are currently being developed and tested in a pre-operational environment: the SEEK (Singular Evolutive Extended Kalman) filter and the EnKF (Ensemble Kalman Filter). The SEEK filter is a reduced-order Kalman filter, in which the error statistics are expressed in terms of a three-dimensional, multivariate sub-space [Pham et al., 1998]. Most often, the reduced space is initialized from an EOF (Empirical Orthogonal Function) analysis of the free model variability.
The dynamical propagation of the error covariance from one analysis step to the next is performed according to the KF equations [Ballabrera-Poy et al., 2001].
In addition, adaptive mechanisms are used to compensate for the lack of representativeness of the original EOF sub-space [Brasseur et al., 1999]. The EnKF is essentially a Monte Carlo method where an ensemble of ocean states is integrated forward in time to evaluate the forecast error covariance [Evensen 1994].

• Variational data assimilation: in order to reduce the dimension of the control vector (i.e., typically the model state vector at the initial time) and the associated cost of the minimization in a 4DVAR formulation, the concept of order reduction developed for sequential filters is further explored by approximating the control space with suitable vector bases of small dimension. The pertinence of candidate sub-spaces built on EOFs, Lyapunov vectors, singular vectors or breeding vectors is currently being examined within a simplified shallow-water model.

• Parameter optimization: a number of intrinsic processes are represented in ocean circulation and biochemical models, requiring the specification of poorly known parameters which hopefully can be estimated from observations using adjoint techniques. Considering the lack of robustness in the model parameterizations, studies are being conducted to explore (i) the necessity

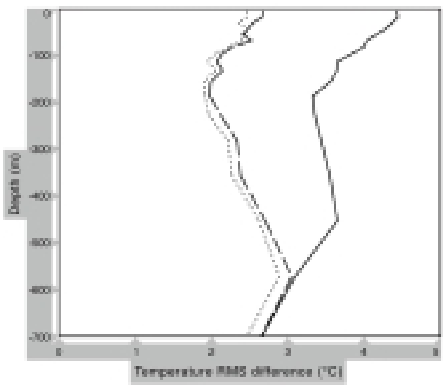

Figure 1: RMS difference (in °C) on the upper water column between validation XBT data and the 1993-1996 hindcast experiment of the DIADEM system (solid line is the free model run; dotted line is the analysis, and dashed line is the 10-day forecast).

of a thorough model error analysis in the optimization process [Fennel et al., 2001], and (ii) the ability to fit the scalar parameters to regional characteristics.

Applications

The validation of these methodologies in a realistic context is achieved using different primitive equation models and ocean configurations, namely: a coupled ocean circulation and marine ecosystem model of the North Atlantic and Nordic Seas (DIADEM and TOPAZ projects of the EU); an eddy-permitting model of the North Atlantic ocean circulation (French MERCATOR project); and, a basin-scale model of the Tropical Pacific ocean circulation.

The SST (sea-surface temperature) and SSH (sea-surface height) observations assimilated in these prototypes consist of 1/4° composite maps of NASA Pathfinder SST data, combined TOPEX/POSEIDON-ERS altimeter data, and SeaWIFS ocean color data. Typical illustrations of three specific applications are given below.

• Within the *DIADEM project*, hindcast experiments have been conducted during the 1990s to reconstruct the variability in the Atlantic Ocean from synoptic to seasonal scales, using the isopycnic MYCOM model and ECMWF atmospheric data. These experiments are validated objectively by comparison with independent XBT data. A positive impact of the assimilation on temperature is demonstrated in the top 600 metres of the water column (figure 1). In addition, a real-time demonstration of the DIADEM system started in October 2000 (figure 2), delivering ocean predictions for the North Atlantic every week. This activity will be pursued using the hybrid-coordinate HYCOM code and Jason-1 data within the framework of the TOPAZ project. Alongside these activities, we are also investigating the sequential assimilation of ocean color data into the FDM marine ecosystem model coupled to MICOM on the North Atlantic. Twin experiments have been conducted initially to investigate the feasibility of the approach [Camillet et al., 2000] and to calibrate the parameters of the SEEK filter for the biological assimilation problem. Further, hindcast experiments covering the spring bloom of 1998 (from April to June) have been performed using SeaWiFS measurements (http://meol715.hmg.inpg.fr/Web/Projets/DIADEM).

• In association with the *MERCATOR project*, a prototype assimilation system based on the SEEK filter, the SESAM assimilation software and a 1/3° resolution OPA model of the North Atlantic is operating between 20°S and 70°N [Testut 2000]. A series of hindcast experiments have been performed, assimilating SST and SSH data between October 1992 and December 1993 using ECMWF atmospheric forcings. Figure 3 illustrates the impact of the assimilation on the mean currents at 50 metres. The Gulf Stream separation at Cape Hatteras, its northward extension and the associated mesoscale activity are significantly improved in the run with assimilation (NATL3/ASS) compared to the free model simulation (NATL3).

• With a focus on *seasonal forecasting*, the SEEK filter has been coupled to the Gent & Cane [Verron et al. 1999] model, and to an OPA model of the Tropical Pacific Ocean assimilating sea level anomalies to reconstruct, monitor (and predict at a later stage) seasonal climate anomalies such as El Niño. Figure 4 illustrates the control of the model drift against in-situ data. The extension of this work to assimilate TOGA/TAO array measurements simultaneously with satellite data is currently in progress. Investigation of the assimilation of surface salinity data is underway [Durand et al., 2001].

The lessons learned from realistic data assimilation experiments suggest to proceed with iterations between methodological improvements and practical implementations, taking advantage of the Jason-1 mission. Indeed, our recent experience with TOPEX/POSEIDON and ERS data in the North Atlantic demonstrates the need for new developments such as

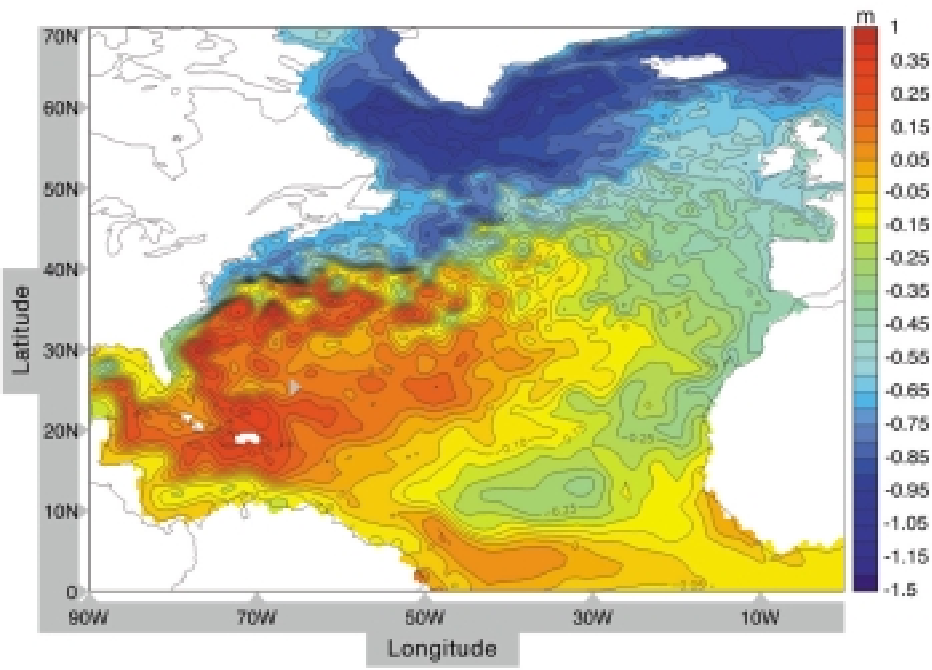

Figure 2: Real-time experiment of the DIADEM system: 14-day forecast of the SSH valid on November 15, 2000.

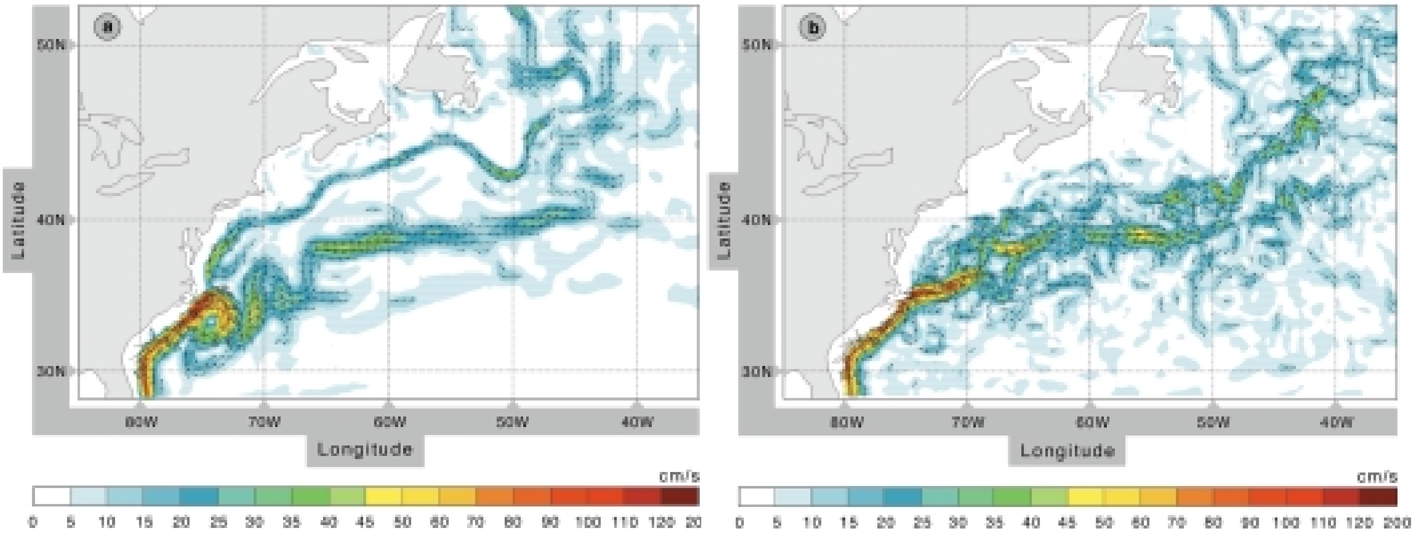

Figure 3: Mean currents at 50 metres (in cm/s) in the Western North Atlantic sector of the 1/3° Mercator prototype: (a) free run (NATL3), and (b) sequential assimilation of SST and SSH data using the SEEK filter (NATL3/ASS). The impact of the assimilation is seen mainly in the Gulf Stream separation at Cape Hatteras and the North Atlantic drift.

local error covariance, local gain and adaptive mechanisms in order to extract maximum benefit from altimetric data and deliver realistic and statistically consistent error estimates. Many questions related to the model error in variational and sequential algorithm are still open and need further investigations.

At the same time, a continuous effort will be devoted to validating the assimilation systems with independent in-situ measurements: up to now, residual misfits with TAO array data in the Tropical Pacific, and XBT profiles in the Atlantic Ocean, objectively demonstrate the benefit gained from assimilation, but additional diagnostics are needed to better characterize the strong and weak points of the assimilation systems. The next step will be the simultaneous assimilation of satellite and in-situ data, for example from the Argo program, and the evaluation of the complementarity of these various data types.

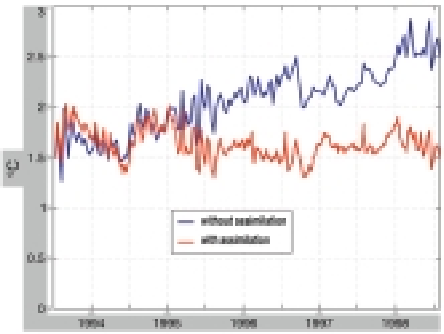

Figure 4: Impact of the assimilation of satellite altimetry in the Tropical Pacific: RMS misfit (in °C) between the model and thermal profiles from the TOGA/TAO array: an improvement of the temperature score of ~1°C is obtained after two years of assimilation.

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