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## Advanced Altimeter Data Assimilation for the Development of Operational Oceanography

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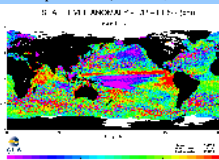
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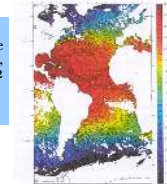
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## Ocean observation system

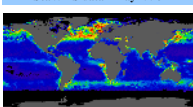
Sea-level anomalies  
Topex-Poseidon, ERS and Jason



Sea-surface temperature  
14° gridded SST,  
October 21<sup>st</sup> 1992  
from the NASA  
Pathfinder  
project



Ocean colour  
SeaWiFS data - May 1998



Satellite observations provide a unique opportunity to monitor the ocean evolution in real time, accurately, at the global scale, and with high resolution.

As the properties of the sea-surface only can be observed from space, data assimilation systems are useful to improve the consistency between data sets and model simulations, to dynamically extrapolate and interpolate data scattered in space/time, to better exploit the results of observation programs, and to make comprehensive interpretation of multivariate observations.

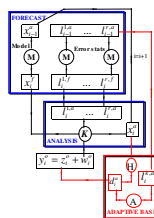
The data considered in the various assimilation activities of the MEOM team are mainly:  
- altimetric data from the Topex-Poseidon and ERS missions (fig. 1.1);  
- sea-surface temperature products from the NASA NOAA Pathfinder project (fig. 1.2);  
- ocean colour data from the SeaWiFS project (fig. 1.3).

## Assimilation methodology

**ABSTRACT:** Various developments of advanced data assimilation systems have been made to assimilate satellite observations such as altimetry, sea-surface temperature and ocean colour into high-resolution models of the ocean circulation and marine ecosystems. An ensemble of activities have been carried out, contributing to improve the understanding of assimilation methods with ocean models, and to help in the optimisation of ocean observing systems, in the perspective of developing realistic monitoring and prediction capabilities in an operational context.

Assimilation methods are variants of the reduced-order Kalman filter (SEK: Singular Evolutive Extended Kalman) or 4DVAR schemes, in which forecast error statistics are defined within a three-dimensional, multivariate sub-space. The most recent developments of the algorithms include (i) a non-linear integration method to propagate the error statistics according to the model dynamics, (ii) an improved definition of the reduced error space using EOFs, singular or breeding vectors, (iii) a "local" formulation designed to improve the analysis of high-resolution signals, and (iv) an adaptive mechanism used to extract pertinent information from the innovation vector. Experiments have been conducted in a variety of idealized models, in order to validate the methodologies, investigate the performance of assimilation in eddy-resolving configurations, and participate to the design of future satellite missions like AltiKa or SIMOS. On the one hand, a variety of multivariate altimetric scenarios have been simulated in twin assimilation experiments. Several sampling schemes achieved by various satellite constellations have been tested for their ability to monitor and predict the mesoscale ocean circulation of the mid-latitude jets. On the other hand, evaluation experiments were carried out to diagnose the impact of assimilating sea surface salinity observations in the Tropical Pacific.

Schematic representation of the sequential SEEK algorithm



The SESAM software is a flexible system of assimilation modules, that has been developed by the MEOM group to implement the SEEK filter. It consists of a library of numerical tools gathered in a single computer program which performs all tasks usually needed to solve a data assimilation problems.

The SEEK filter has been further implemented with two different realistic models of the Atlantic ocean: a coupled isopycnal ocean circulation and marine ecosystem model of the North Atlantic and Nordic Seas (European DIADEM and TOPAZ projects), and a z-coordinate primitive equation model of the Atlantic ocean circulation (French Mercator project), into which NASA Pathfinder SST, and combined Topex-Poseidon/ERS altimetric data have been assimilated. Hindcast experiments have been conducted from 1992 to 1999 in order to reconstruct the variability in the Atlantic Ocean from synoptic to seasonal scales and to examine the error statistics associated with the solutions. A real-time demonstration of the DIADEM/TOPAZ system (started in October 2000) weekly deliver an ocean forecast bulletin for the North Atlantic. The poster provides an overview of recent results obtained in the various projects.

## Optimisation of observation systems

The general objective of this study is to assess a variety of multi-satellite altimetric scenarios from the perspective of the future space missions (Jason-2, AltiKa, etc.) that will be launched to monitor the mesoscale ocean circulation. The approach taken for this work is based on the use of numerical models and assimilation methods using twin experiments. The numerical model is used to generate synthetic data sets following the multi-satellite sampling schemes that are aimed to be explored. The OPA primitive-equation model is used for this purpose in an academic configuration. The model is eddy-resolving (20 Km) and 11 layers on the vertical.

The Singular Evolutive Extended Kalman (SEK) filter is implemented (using the SESAM system) to assimilate the altimetric data, using an EOF basis to reduce the error sub-space. The sea-surface height data are sampled from the model output, along the ground track following the missions parameter of Topex-Poseidon (TP) and Jason-1 (Ja) and one scenario which is under consideration for the foreseen AltiKa (Alk) satellite mission (with 35 days orbital period). Different satellite sampling strategies are explored.

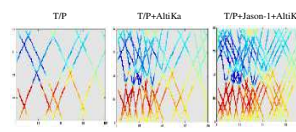


Figure 2.1: Tracks for one, two and three satellite configurations. Examples of track patterns for 5 days of observation

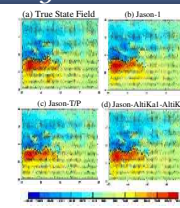
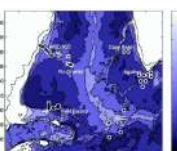


Figure 2.2: U,V,SSH fields for a) true state, b) Jason-1, c) Jason-TP and d) Jason-AltiKa. Figure 2.3: RMS error on velocity for the different observation scenarios.

## From WOCE to CLIVAR: the South Atlantic



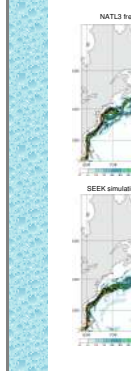
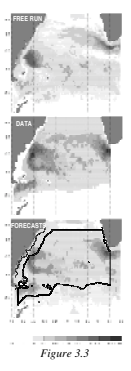
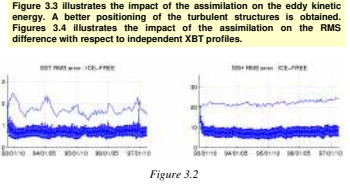
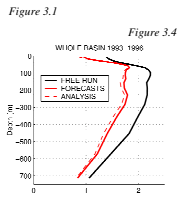
As a joint research effort between the LEGI (Grenoble) and LPO (Brest) laboratories, data assimilation experiments have been performed in the South Atlantic to reconstruct the ocean variability during the WOCE period.

The model configuration is extracted from the 1/3° Atlantic model developed by the Clipper project (OPA model), limited at 20°N with an open-sea boundary (figure 3.1).

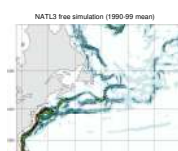
Hindcast experiments have been performed using a simplified SEEK filter, assimilating SST and SSH data between January 1993 and January 1997 in a similar way as in the North Atlantic experiments (see next frame).

The behaviour of the error statistics on SST and SSH is illustrated by figure 3.2, showing a stable reduction of the RMS model/data mismatch of about 1°C for temperature, and 12 cm for sea-level.

Figure 3.3 illustrates the impact of the assimilation on the eddy kinetic energy. A better positioning of the turbulent structures is obtained. Figure 3.4 illustrates the impact of the assimilation on the RMS difference with respect to independent XBT profiles.



## The MERCATOR project: the North Atlantic

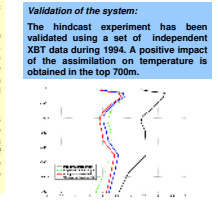
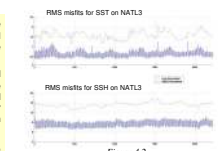


MERCATOR is a French initiative which aims at the implementation of an operational capacity of global ocean monitoring and prediction within the time frame of the GODAE experiment (2003-2005). As a contribution to the research activities conducted around the MERCATOR Project, a prototype assimilation system has been developed at LEGI based on the SEEK filter, the SESAM software, and a 1/3° resolution OPA model of the North Atlantic between 20°S and 70°N (Testud et al., 2002).

A series of hindcast experiments have been performed, assimilating SST and SSH data between October 1992 and November 1999 using ECMWF atmospheric forcings.

Figure 4.1 illustrates the impact of the assimilation on the mean currents during the nineties at 50 m depth. The Gulf Stream separation at Cape Hatteras, its northward extension and the associated meso-scale activity are significantly improved in the run with assimilation (bottom) compared to the free model simulation (top).

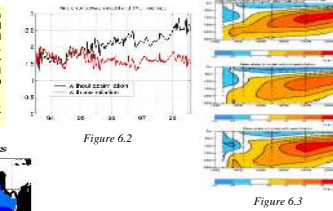
The behaviour of the error statistics on SST and SSH is illustrated (fig 4.2), showing a stable reduction of the model/data mismatch of ~0.8°C for temperature, and ~8 cm for sea-level. In addition, the adaptive mechanism of SEEK is useful to improve the consistency between the error standard deviation predicted by the filter and the actual assimilation errors.



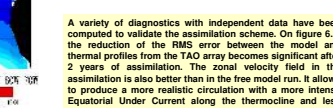
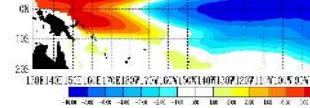
## The Tropical Pacific Ocean

The assimilation of satellite altimetry data (TP+ERS) has been performed, using the SEEK filter in a primitive equation model (OPA) of the whole Tropical Pacific ocean between 30°S and 30°N to reconstruct the ocean variability during the 1994-1998 period. The reduced basis of the SEEK filter is evaluated from a three-dimensional multivariate EOF analysis of a reference model simulation (fig. 6.1), which is forced at the surface with ERS/TAO wind stress fields and heat fluxes from the NCEP reanalysis.

The SESAM software allows an easy interface between the SEEK algorithm and the OPA ocean model.



A variety of diagnostics with independent data have been computed to validate the assimilation scheme. On figure 6.2, the reduction of the RMS error between the model and thermal profiles from the TAO array becomes significant after 2 years of assimilation. The zonal velocity field in the assimilation is also better than in the free model run. It allows to produce a more realistic circulation with a more intense Equatorial Under Current along the thermocline and less intense South Equatorial Current at the surface (fig. 6.3).



## Conclusions

- Advanced data assimilation methods have been developed to assimilate a variety of ocean circulation and ecosystem data in various ocean models. These studies are carried out in the perspective of operational oceanography, with a special focus on satellite observations of altimetry, sea-surface temperature and ocean colour.
- In particular, a reduced-rank Kalman filter (SEK) has been implemented in a variety of ocean models. The assimilation method has been first validated in a series of twin experiments conducted in idealized situations, and then implemented into real ocean simulation and prediction systems.
- Observation system simulations have been conducted in twin assimilation experiments in order to assess the ability of different multi-satellite scenarios to observe the ocean mesoscale activity. This study is carried out to help in the planification of future spatial mission to observe ocean altimetry.

- New methodological developments, such as local error covariance, local gain, and adaptive mechanisms have been undertaken to address specific issues raised by real assimilation problems. The capacity of the assimilation scheme to predict realistic and statistically consistent error bars on the field estimates has been examined and improved by "recycling" the residual innovation information.
- A special effort is currently dedicated to the validation of the assimilation system with independent *in situ* measurements: so far, the residual misfits with TAO array data in the Tropical Pacific, and XBT profiles in the Atlantic Ocean, objectively demonstrate the benefit gained from the assimilation.
- In addition to the hindcast experiments realized in a scientific perspective, a real-time demonstration of the DIADEM/TOPAZ system is currently underway in a technical perspective to deliver ocean circulation predictions on the North Atlantic within the european DIADEM/TOPAZ projects.

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