Advanced Altimeter Data Assimilation for the Development of Operational Oceanography

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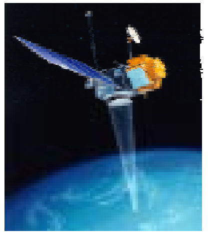


OBSERVATIONS FROM SPACE

Beyond 2000: Jason-1

Sea-level anomalies

Topex-Poseidon and ERS

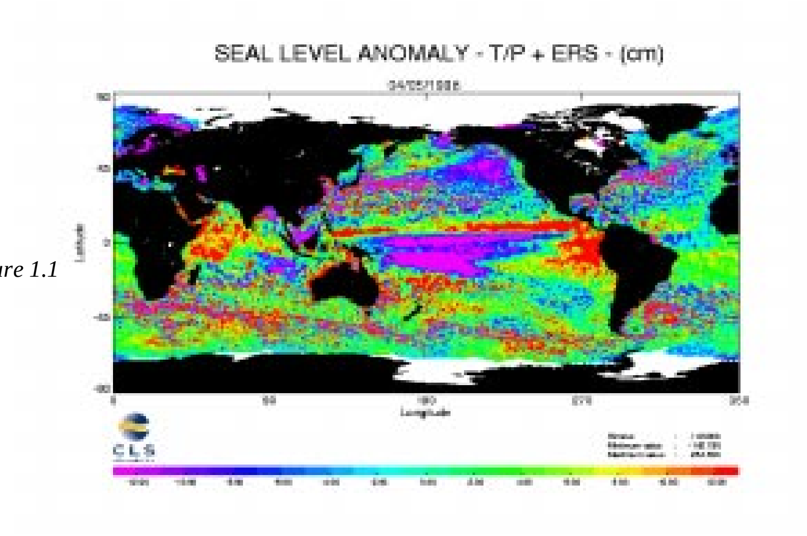


Figure 1.1

Sea-surface temperature

1/4° gridded SST, October 21st 1992 from the NASA Pathfinder project

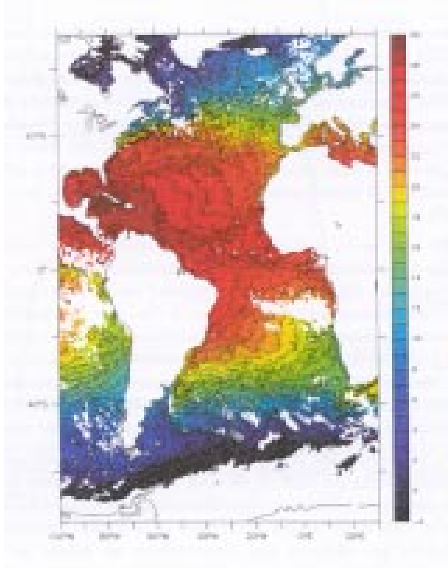


Figure 1.2

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 manly:
- **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).**

Ocean colour

SeaWiFS data - May 1998

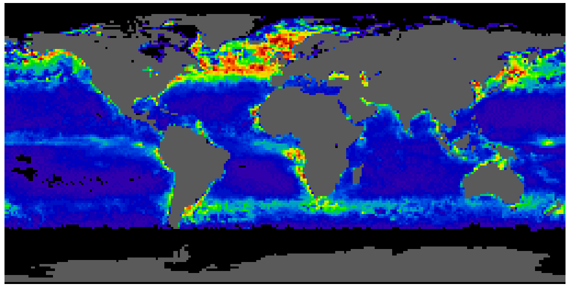


Figure 1.3

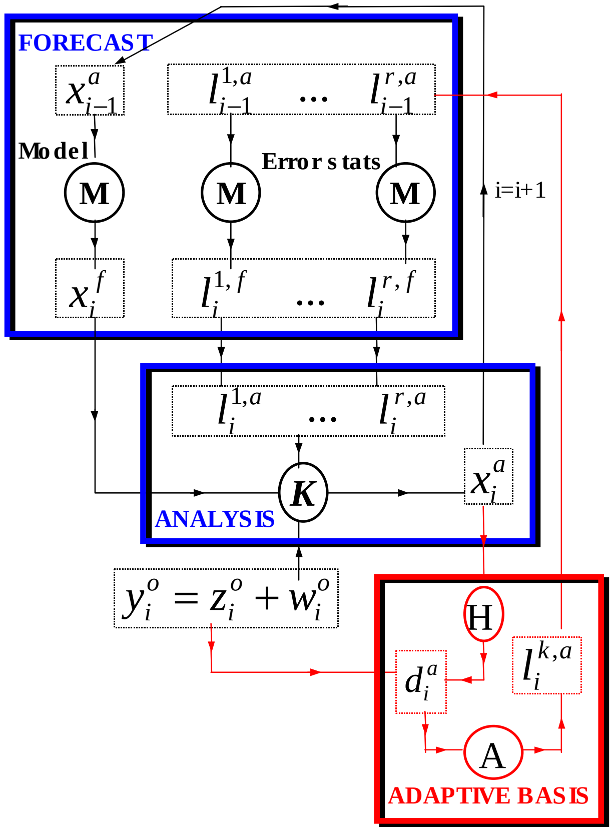
ASSIMILATION METHOD: the SEEK filter

An advanced data assimilation system has been developed in the MEOM group to assimilate satellite observations such as altimetry, sea-surface temperature and ocean colour into high-resolution models of the ocean circulations and marine ecosystems, in the perspective of operational ocean observing, monitoring and prediction capabilities.

The assimilation method is derived from the sequential estimation theory: a reduced-order Kalman filter, - SEEK (Singuler Evolutive Extended Kalman) -, has been developed in which the error statistics is expressed in terms of a three-dimensional, multivariate sub-space. (Pham *et al*., 1998; Verron *et al* 1999).

The reduced space is usually initialized from an EOF 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*., 2000).

In addition, an adaptive mechanism has been implemented to compensate for the lack of representativeness of the original EOF sub-space (Brasseur *et al*., 1999): the basic principle of adaptive schemes is to re-consider the information left in the innovation sequence before or after analysis.



Schematic representation of the sequential SEEK algorithm

The ingredients of SEEK

- Non-linear Kalman filter
- Order reduction to specify the error sub-space
- Forecast error computed explicitely using the model dynamics
- Multivariate observation and analysis

SEEK ?

Singular ....forecast and analysis error covariance are low-rank;
Evolutive .. the error covariance is propagating forward in time;
Extended .. the algorithm is extended to non-linear systems;
Kalman filter .... the scheme is basically a Kalman Filter.

Recent developments of the algorithm include (Testut 2000) :

(i) a "local" formulation designed to improve the impact of high-resolution data,

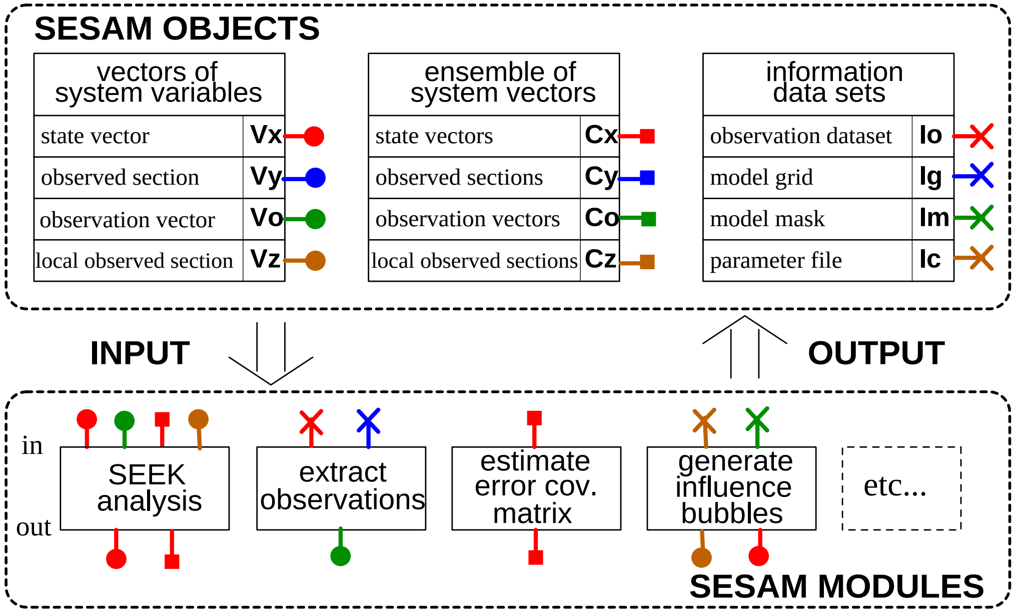
(ii) the adaptive mecanism to update the background error covariance matrix using all pertinent information of the innovation vector.

The SESAM software

an integrated SystEm of Sequential Assimilation Modules

(resp. C.E. Testut, J.M. Brankart)

SESAM is a flexible system of assimilation modules, that has been developed by the MEOM group to assimilate multivariate data sets in a variety of numerical models. 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 problem: analysis, diagnostics, data management, EOF decomposition, etc.



Objects

- vectors of system variables: state vector, observation vector; observed section;
- Error covariance matrices (global/local): background error covariance, observation error covariance, model error covariance;
- Information data sets: observation data bases, model grid, model mask;

Modules

- analysis tools: SEEK analysis, spatial filters;
- object management tools: extractions from data bases, error covariance rank reduction, domain partition;
- diagnostic tools: model/data misfits, RMS error statistics, algebraic operations ...

SESAM applications

SESAM is a generic code that can be easily interfaced with any type of ocean model code in arbitrary domains (1D, 2D or 3D).

Up to now, it has been coupled with:
- the z-coordinate OPA model;
- the sig-coordinate SPEM model;
- the isopycnic MICOM model;
- the ecosystem FDM model.

Algorithmic features:

- model independent;
- multivariate data and state vectors
- local/global analysis
- designed for reduced-rank systems

Technical features:

- modularity (one module for each task)
- Fortran-90 coding
- interactivity
- on-line vs. off-line operations
- portability

SESAM performs a series of well defined *actions* on a limited set of objects. These actions can produce or transform these objects grouped into modules.

More info available at:
http://meol715.hmg.inpg.fr/Web/Assimilation/SESAM/

The DIADEM project (1)

(resp. J.M. Brankart)

DIADEM : Development of operational data assimilation systems for the North Atlantic and the Nordic Seas

The main objective of this european project is to develop advanced data assimilation systems for coupled primitive equation ocean circulation and marine ecosystem models of the North Atlantic and the Nordic Seas, with enhanced resolution in the European coastal zones.

The SEEK filter has been interfaced with a North Atlantic implementation of the isopycnic MICOM model to assimilate Nasa Pathfinder SST and Topex-Poseidon/ERS altimetric data sequentially, every 10 days.

A hindcast experiment has been conducted between 1993 and 1997 using ECMWF atmospheric forcings. In figure 2.1, a zoom on the Gulf Stream region from the 10-day forecast of April 10, 1993, is compared to the observations: SSH (in m) is on the left, and SST (in °C) is on the right.

Figure 2.2a (resp. b) illustrate the RMS sea-level (resp. temperature) misfit in the Gulf Stream region between the data and the simulations, with (dashed line), and without (solid line) assimilation.

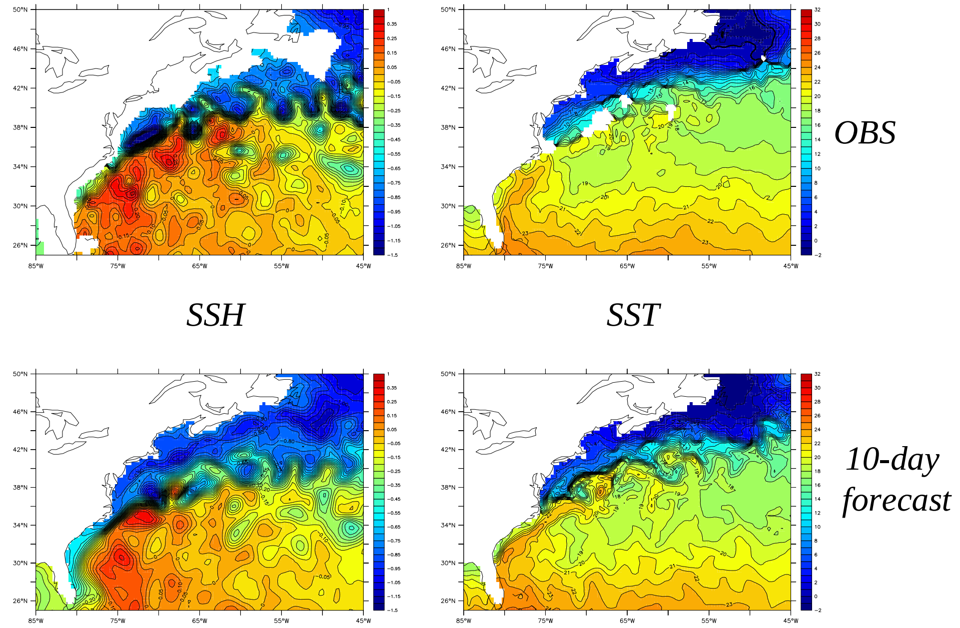


Figure 2.1

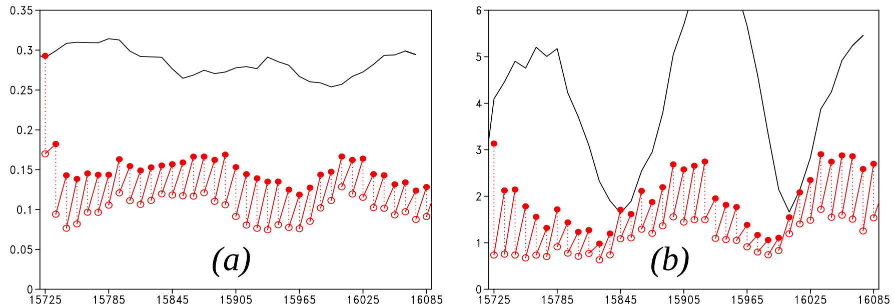


Figure 2.2

Validation of the system:

The 1993-1997 hindcast experiment has been validated using a set of independant XBT data. A positive impact of the assimilation on temperature is obtained in the top 600 m (fig. 2.3: solid line is the free model run; dotted line is the analysis and dashed line is the 10-day forecast).

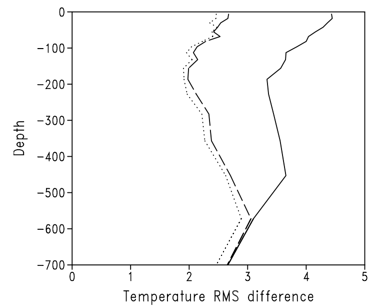


Figure 2.3

Contribution to Mercator : the North Atlantic

(resp. C.E. Testut)

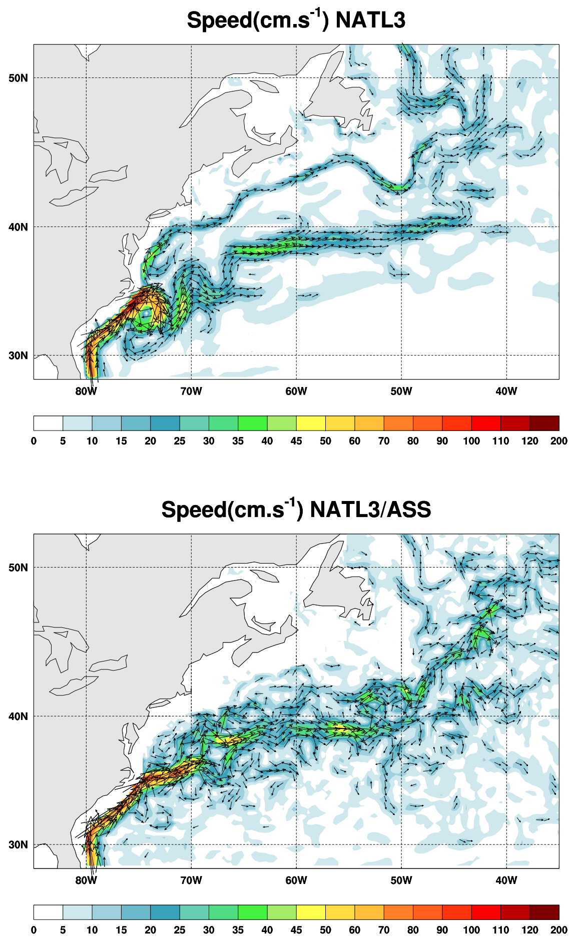


Figure 4.1

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 (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 4.1 illustrates the impact of the assimilation on the mean currents at 50 m depth. 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).

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

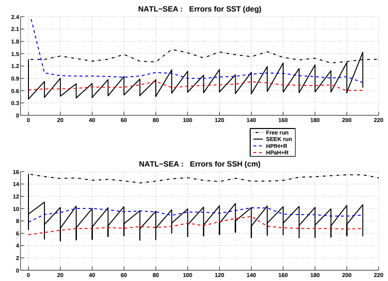


Figure 4.2

Validation of the system:

As in DIADEM, the 1993 hindcast experiment has been validated using a set of independant XBT data. A positive impact of the assimilation on temperature is obtained in the top 700 m (fig 4.3).

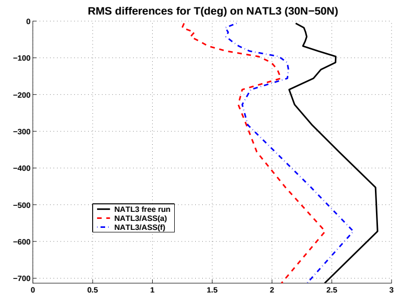


Figure 4.3

The DIADEM project (2)

(resp. V. Carmillet)

Within DIADEM, a significant body of work is dedicated to the sequential assimilation of ocean colour data into the FDM marine ecosystem model coupled to MICOM on the North Atlantic. A schematic diagram of the 11-compartment model and biological processes used to simulate the ecosystem dynamics within the euphotic zone is shown on figure 3.1.

Twin experiments have been conducted in a first stage to investigate the feasibility of the approach (Camillet *et al.*, 2000) and to calibrate the parameters of the SEEK for the biological assimilation problem.

Then, a hindcast experiment has been performed between during the spring bloom of 1998 (from april to june) using SeaWiFS data. Figure 3.2 illustrates the phytoplankton concentration (in mmol-N/m3) during the first assimilation cycle: (a) first guess; (b) SeaWIFS data centered on April 5th, 1998; (c) analysis on April 5th, 1998; and (d) 10-day forecast on April 15th, 1998.

Figure 3.3 illustrates the multivariate nature of the assimilation system, showing the impact of the assimilation on nitrate concentrations: (a) first guess, and (b) analysis on April 5th, 1998.

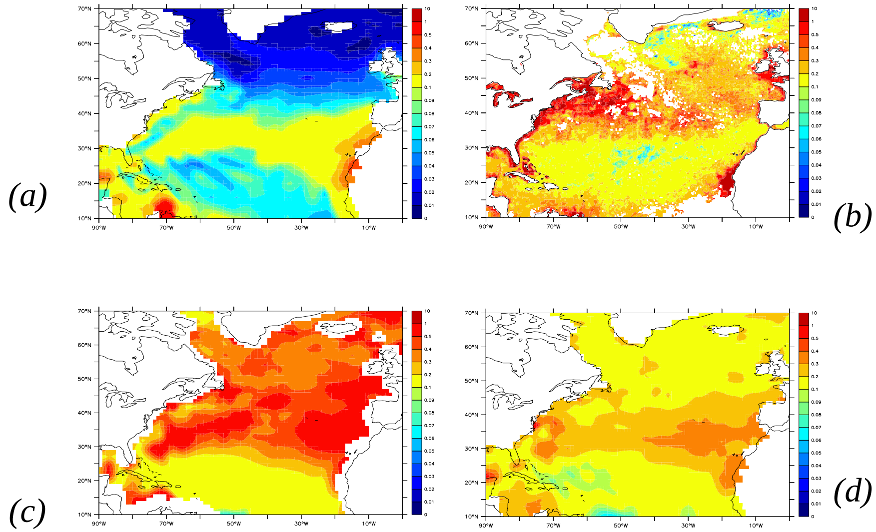


Figure 3.2

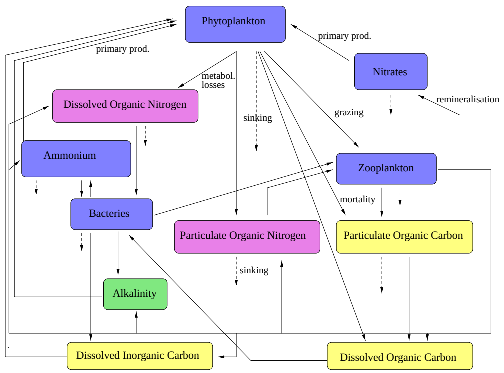


Figure 3.1

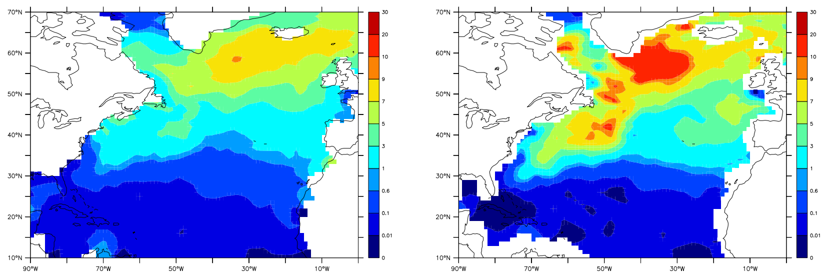


Figure 3.3

A *real-time demonstration of the DIADEM system* has started in October 2000 with the physical component of the coupled model only (see attached ocean forecast bulletin). It is planned to connect the ecosystem component to the real-time system during spring 2001.

Tropical Pacific ocean data assimilation

(resp. L. Parent)

The assimilation of satellite altimetry data (T/P+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 sofware allows an easy interface between the SEEK algorithm and the OPA ocean model.

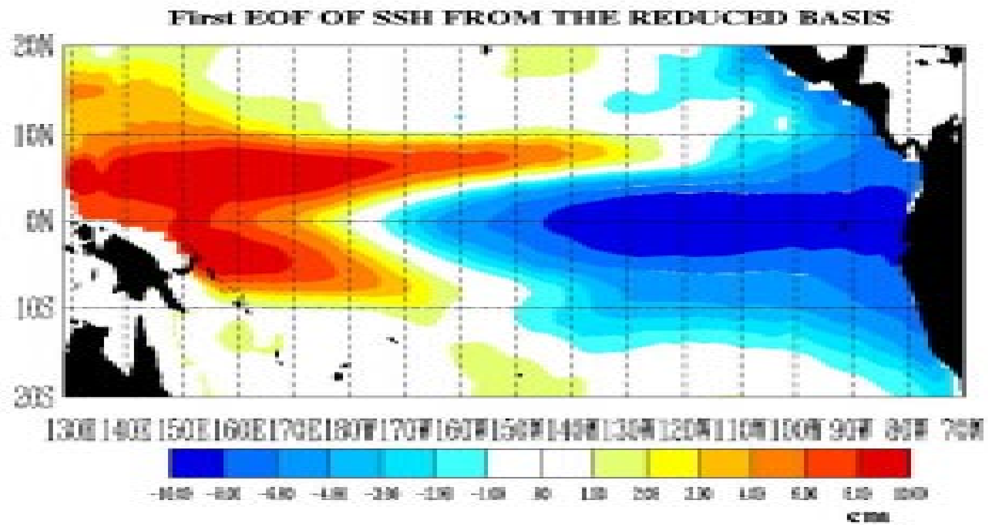


Figure 6.1

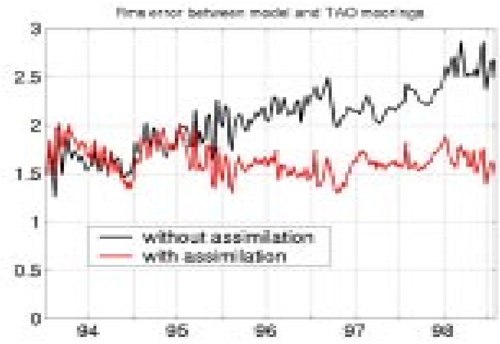


Figure 6.2

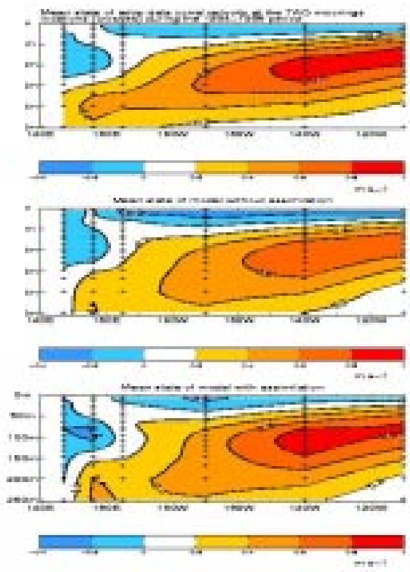


Figure 6.3

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).

From WOCE to CLIVAR : The South Atlantic

(resp. Th. Penduff)

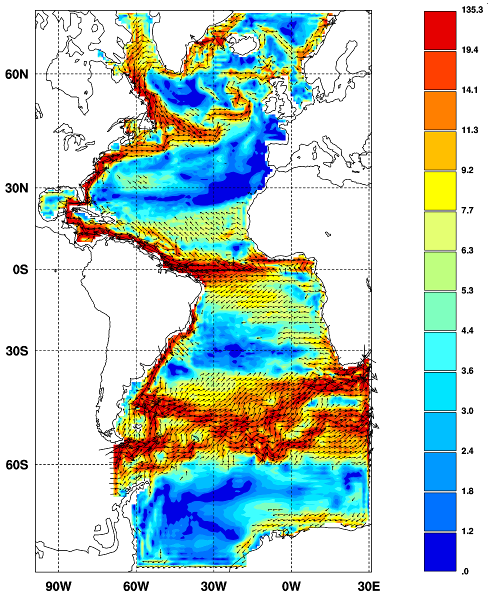


Figure 5.1

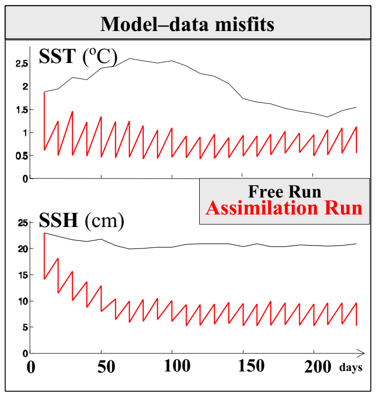


Figure 5.2

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's variability during the WOCE period.

The model configuration is extracted from the 1/3° Atlantic model developed by the Clipper project (Barnier et al. 1998), limited at 20°N with an open-sea boundary (fig. 5.1).

Hindcast experiments have been performed using a simplified SEEK filter, assimilating SST and SSH data between october 1992 and december 1993 in a similar way as in the North Atlantic experiments (see above).

The behaviour of the error statistics on SST and SSH is illustrated by figure 5.2, showing a stable reduction of the RMS model/data misfit of about 1°C for temperature, and 15 cm for sea-level.

Figure 5.3 illustrates the impact of the assimilation on the mean currents and temperature field at 1000 m depth. A better positioning of the Brazil current and associated frontal structures is obtained.

A more detailed description of those results is given on a dedicated poster by Penduff *et al*.

Velocity and temperature at 1000 m
in the South Atlantic Confluence region

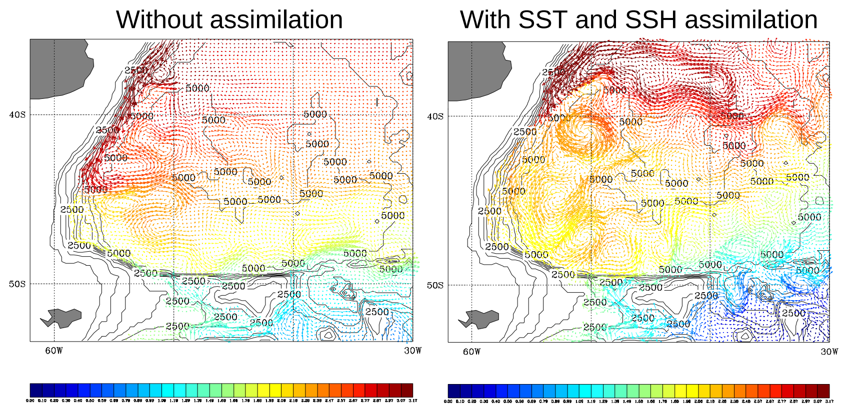


Figure 5.3

Conclusions

• An advanced data assimilation scheme, SEEK, has been developed in the MEOM group to assimilate a variety of ocean circulation and ecosystem data in the perspective of operational oceanography, with a special focus on satellite observations of altimetry, sea-surface temperature and ocean colour. The scheme is an reduced-rank adaptation of the Extended Kalman filter to basin-scale 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. This poster presents an overview of the realistic applications under development in the MEOM group.

• 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 "re-cycling" 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 msifits with TOA 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 system is currently underway in a technical perspective to deliver ocean circulation predictions on the North Atlantic within the european DIADEM project; this initiative will be pursued within the european TOPAZ project which will start soon.

References

Ballabrera-Poy J., P. Brasseur and J. Verron, 2000: Dynamical evolution of the error statistics with the SEEK filter to assimilate altimetric data in eddy-resolving ocean models, *Q. J. R. Met. Soc.*, in press.

Brasseur P., J. Ballabrera, and J. Verron , 1999: Assimilation of altimetric observations in a primitive equation model of the Gulf Stream using a Singular Evolutive Extended Kalman filter, *J. Mar. Systems*, **22**(4), 269-294.

Carmillet V., J.M. Brankart, P. Brasseur, H. Drange, G. Evensen and J. Verron, 2000: A Singular Evolutive Extended Kalman filter to assimilate ocean colour data in a coupled physical-biochemical model of the North Atlantic ocean, submitted.

Parent L., 2000: Assimilation de données dans l'océan Pacifique Tropical sur la période 1994-1998, Ph.D. thesis, Université J. Fourier - Grenoble I, 226 pp.

Penduff Th., B. Barnier, P. Brasseur and J. Verron 2000: Impact of altimetric and sea-surface temperature data assimilation in a high-resolution South Atlantic Ocean model with a reduced-order Kalman filter, submitted.

Pham D.T., J. Verron and M.C. Roubaud, 1998: Singular evolutive extended Kalman Filter with EOF initialization for data assimilation in oceanography, *J. Mar. Syst*, **16** (3-4), 323-340.

Testut C.E., 2000: Assimilation de données satellitales avec un filtre de Kalman de rang réduit dans un modèle aux Equations Primitives de l'océan Atlantique, Ph.D. thesis, Université J. Fourier - Grenoble I, 227 pp.

Verron J., L. Gourdeau, D.T. Pham, R. Murtugudde, and A. Busalacchi, 1999: An extended Kalman filter to assimilate satellite altimeter data into a non-linear numerical model of the tropical Pacific: method and validation, *J. Geophys. Res*, 104, 5441-5458.

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Towards a European research area

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