Development and validation of an ocean incremental 4D-Var assimilation scheme

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An advanced assimilation method based on incremental four-dimensional variational assimilation has been developed in a tropical Pacific configuration of the OPA Ocean General Circulation Model. This article evaluates the impact of assimilating in-situ temperature data in the OPA model and validates model fields (currents, dynamic height anomalies) against independent data. Assimilation of temperature data is shown to improve significantly the model representation of the tropical system of currents and countercurrents, as well as the amplitude and variability of sea level anomalies.

Introduction

Recent studies have underlined the importance of ocean data assimilation for seasonal forecasts with coupled ocean-atmosphere models [Alves et al., 1998; Ji et al., 1997; Rosati et al., 1997].
In particular, to predict seasonal anomalies associated with the El Niño-Southern Oscillation, initial conditions of the surface and subsurface ocean state in the tropical Pacific need to be set accurately. For this purpose, an advanced assimilation method based on incremental four-dimensional variational assimilation (4D-Var) has been developed for the OPA Ocean General Circulation Model (OGCM) [Madec et al., 1998] conceived by the Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC). While the general characteristics of the assimilation system have been presented in Weaver and Vialard [1999], this paper aims highlights the improvement in ocean analyses after assimilation of in-situ temperature data. The evaluation in this configuration is a first step towards implementing the 4D-Var system (called OPAVAR) in ORCA, the global ocean configuration of OPA, assimilating in-situ temperature and salinity data as well as TOPEX/POSEIDON and Jason altimeter data.
Basically, the OPAVAR scheme has three main characteristics. First, it is multivariate in the sense that the model parameters (currently temperature, salinity and horizontal currents) used to set the "analyzed" initial conditions of the control vector are all adjusted simultaneously when assimilating data. Second, this scheme is incremental in that minimization between observations and the model occurs month after month over one-month periods. Third, a major hypothesis is that the model is perfect and, thus, the "analyzed" trajectory exactly verifies the ocean model equations.

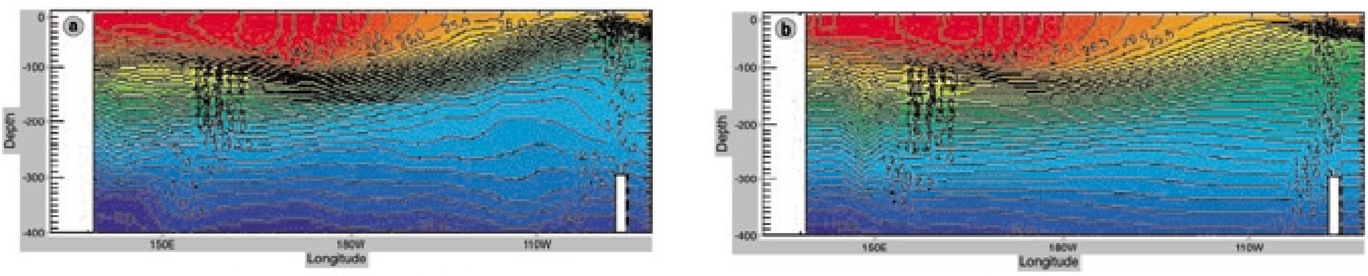

Figure 1: (a) Equatorial section of temperature over the first 400 m on 02/01/93 after assimilation of in-situ temperature data in January 1993 (isotherms are plotted every 0.5°C); (b) Same as (a) without assimilation. The model is forced by ERS wind stress data and ERA-15 climatological heat and fresh water fluxes.

Impact of in-situ temperature assimilation

In the equatorial region, the major impacts of assimilating observed in-situ temperature data are to correct model mean state biases and to improve its variability.
In particular, assimilation of temperature data considerably improves the model representation of the thermocline tightness in the equatorial region.
This improvement can be seen in figure 1 in the central and eastern Pacific in the upper ocean. First, below 150 meters, the model without data assimilation simulates a very weak zonal slope of the subsurface isotherms. In contrast, the model with data assimilation simulates a west-to-east slope characterizing a more intense upwelling at the subsurface in the eastern Pacific. Second, above 150 meters, the model with data assimilation exhibits a much tighter and shallower thermocline. For instance, at 110°W, the 15°C isotherm is upwelled by about 80 meters when temperature data are assimilated. Its is likely that such a change in the thermal structure of the equatorial upper ocean has an impact on seasonal climate forecasting.

Impacts on simulated currents

Here, in response to the tightening of the tropical thermocline, horizontal pressure gradients intensify. This leads to the strengthening of the tropical system of currents and countercurrents.
In particular, at the surface (not shown) the model mean surface currents are in better agreement with Reverdin et al. [1994] climatology. Such an improvement can be observed in a meridional section at 140°W (Figure 2). At the surface and at depth, the North Equatorial CounterCurrent is much more intense than in the model without assimilation.
The tighter and shallower thermocline in the eastern Pacific is responsible for an intensification of the Equatorial UnderCurrent, which contributes to a reduction of the equatorial surface currents east of 110°W and thus to the splitting in two branches of the South Equatorial Current.
Finally, the variability of the surface currents is also improved along the Equator. For example, at 140°W the correlation of the model zonal current to TAO surface zonal current over the 1993-1998 period improves from 0.75 to 0.81 while the rms difference decreases from 0.21 to 0.19 m/s.
Therefore, the OPAVAR scheme significantly improves the tropical upper ocean currents when assimilating only in-situ temperature data.

Comparisons with TOPEX/POSEIDON data

To evaluate the impact of in-situ temperature data assimilation on sea level anomalies, the model dynamic height anomalies (referenced to 1,000 dbar) are

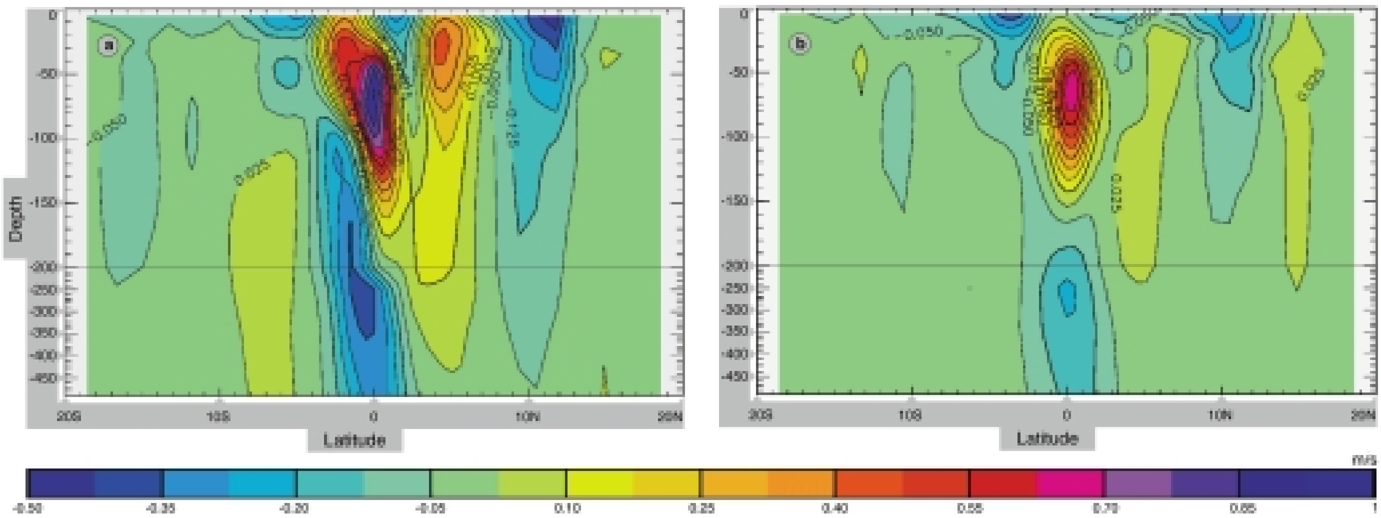

Figure 2: (a) Meridional-depth section of zonal currents at 140°W on 02/01/93 after assimilation of in-situ temperature data in January 1993; (b) Same as (a) without assimilation. The model is forced by ERS wind stress data and ERA-15 climatological heat and fresh water fluxes.

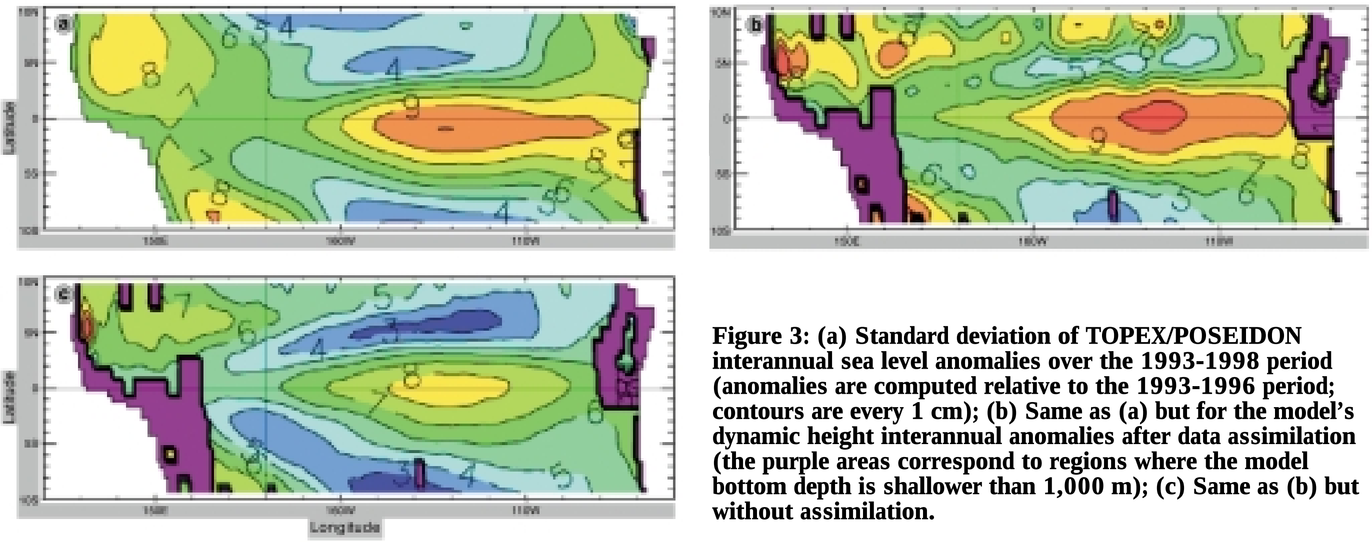

Figure 3: (a) Standard deviation of TOPEX/POSEIDON interannual sea level anomalies over the 1993-1998 period (anomalies are computed relative to the 1993-1996 period; contours are every 1 cm); (b) Same as (a) but for the model's dynamic height interannual anomalies after data assimilation (the purple areas correspond to regions where the model bottom depth is shallower than 1,000 m); (c) Same as (b) but without assimilation.

compared to TOPEX/POSEIDON (T/P) sea level anomalies over the 1993-1998 period (Figure 3). Without assimilation, the amplitude of the simulated interannual anomaly variability exhibits a reasonable pattern, but it is still weak compared to T/P [see Vialard et al., 2001]. When assimilating temperature data, the model recovers the 15% to 20% that were lacking in the simulation in the equatorial band without assimilation.
This result is confirmed when comparing the sea level time series: the 4D-Var assimilation improves both the correlation and rms difference with T/P over the entire equatorial Pacific basin (not shown).

Conclusion and perspectives

A 4D-Var assimilation scheme in a tropical Pacific configuration of the OPA model gives very promising results. Assimilating only in-situ temperature data improves the thermal description of the upper ocean, as well as the model currents and the model dynamic height anomalies. This result is very encouraging for the future, as these developments are a first step towards implementing this 4D-Var scheme in ORCA, the global configuration of the OPA model, with a view to assimilating in-situ temperature and salinity measurements and altimetric data.

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