Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 57-62.

Current Correction Methods After Temperature Data Assimilation in the Tropical Atlantic with MOM 3

Fabíola V. B. Teixeira *
Clemente A. S. Tanajura *
Laboratório Nacional de Computação Científica, Petrópolis, RJ

1. INTRODUCTION

The atmospheric and oceanic models are an important tool for the study and agreement of the mechanisms that integrate the climatic system. The initial conditions of these models normally are produced throughout the data assimilation methods. However, the scarcity of the data observations in the oceans difficults the assimilation of all prognostic models variables, becoming necessary the use of initialization techniques to balance the initial condition.

In a model simulation, before data assimilation, all model fields are in balance. However, when a variable is updated, an unbalanced state are generated. There are two ways to solve this problem: the first is to integrate the model until a new balance condition is found; and the second is to modify the new state to force the equilibirum. The last one is a procedure called initialization, and it is the goal of this work.

Here, temperature profiles were assimilated using the ocean model MOM_3; a version of Kalman filter based on Fokker-Planck equation; and the PIRATA database.

After this, two initialization procedures are proposed to correct the currents. The first method is a technique based on normal modes initialization already proposed by Belyaev and Tanajura (2005). However, a modification in the vertical momentum parameterization was introduced. The second method is a simplification of the first one, in which the perturbed linearized system was directly solved.

Some experiments were done to investigate the performance of the initialization procedures proposed here.

The article is organized as follows: in the second section a brief description of the ocean model and the data assimilation technique are presented. The formulation of the initialization methods are in section 3, and the experiments and results are in section 4. The last section presents the conclusions.

2. THE DATA ASSIMILATION METHOD AND THE OCEAN MODEL

The data assimilation method is a version of Kalman filter where the Fokker-Planck equation is used to calculate the error covariance matrix. A complete description of this methodology can be found in Belyaev et al. (2000), Belyaev et al. (2001) and Tanajura and Belyaev (2002).

The data set used in the assimilation procedure was provided by the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) (Servain et al. 1998). This array is composed by 12 Atlas buoys which measure operationally a number of ocean and atmosphere geophysical variables, such as surface wind and temperature, precipitation, and temperature on 11 different depths, from the sea surface down to 500 m. Figure 1 shows the spatial configuration of buoys until September of 2005.

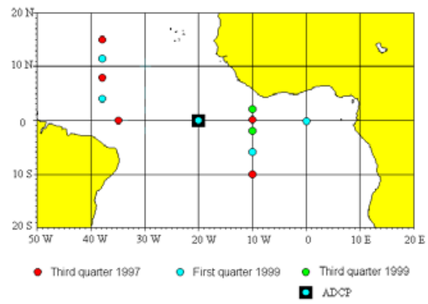


FIG. 1. PIRATA buoys until September of 2005.

The ocean model was the MOM_3 of the Geophysical Fluid Dynamics Laboratory (GFDL/NOAA) (Pacanowski 1999).

* *Corresponding author address:* Fabíola V. B. Teixeira, Laboratório Nacional de Computação Científica, CRH, Av. Getúlio Vargas, 333, Petrópolis, 25651-070, RJ, Brasil
e-mail: fabiola@lncc.br, cast@lncc.br

The main characteristics of model configuration are presented. The horizontal domain cover the whole globe, with spatial resolution 1° everywhere in the zonal and meridional directions; the vertical domain covered about 5,000 m broken down by 15 vertical layers with non-uniform thickness, in which the first 10 layers covered the top 500 m. The horizontal momentum diffusion coefficient was 10^6 dynes cm s^{-1}, and the vertical coefficient was 10^{-2} dynes cm s^{-1}. The numerical time step was 21600 *s*. The other model parameters do not need a special consideration.

A 15-year spin-up run was done, in which the model was initialized at rest with climatological temperature and salinity fields given by the Levitus World Ocean Atlas (Conkright et al., 1998) and forced with climatological atmospheric fluxes of momentum and salinity taken from GFDL .

3. INITIALIZATION METHODS

In the present work, two methodologies are proposed to correct the current fields of an ocean circulation model after assimilation of vertical profiles of temperature. The first is based on the calculation of the eigenvectors and eigenvalues of the linearized momentum equations of a non-linear hydrostatic ocean model as developed by Belyaev and Tanajura, but a modification in vertical momentum parameterization was included.

The linearized equations are as:

$$\frac{\partial u}{\partial t}+u_0\frac{\partial u}{\partial x}+u\frac{\partial u_0}{\partial x}+v_0\frac{\partial u}{\partial y}+v\frac{\partial u_0}{\partial y}-fv = A_h\Delta u - A_z(z)u + A_z u^* - \frac{g}{\bar{\rho}}\int_{z_{i-1}}^{z}\frac{\partial \rho_a}{\partial x}dz \quad (1)$$

$$\frac{\partial v}{\partial t}+u_0\frac{\partial v}{\partial x}+u\frac{\partial v_0}{\partial x}+v_0\frac{\partial v}{\partial y}+v\frac{\partial v_0}{\partial y}+fu = A_h\Delta v - A_z(z)v + A_z v^* - \frac{g}{\bar{\rho}}\int_{z_{i-1}}^{z}\frac{\partial \rho_a}{\partial y}dz \quad (2)$$

Here, the prognostic variables without indices are the sought perturbations; the variables with subscript 0 are the unperturbed velocities before the assimilation procedure and they are known.

In the original formulation, the coefficient of vertical momentum parameterization, $A_z(z)$, and the velocities, u^* and v^*, are

$$A_z(z) = \frac{A_z(z_{i-1}-z_{i-2})}{(z_{i+1}-z_i)(z_i-z_{i-2})} \quad (3)$$

$$u^* = \frac{u(z_{i-1})}{(z_{i+1}-z_i)} - \frac{u(z_{i-2})(z_{i+1}-z_{i-1})}{(z_i-z_{i-2})(z_{i+1}-z_i)} \quad (4)$$

$$v^* = \frac{v(z_{i-1})}{(z_{i+1}-z_i)} - \frac{v(z_{i-2})(z_{i+1}-z_{i-1})}{(z_i-z_{i-2})(z_{i+1}-z_i)} \quad (5)$$

Here, a modification in $A_z(z)$ was included to guarantee a reduction of vertical momentum transport with depth. Then, it is

$$A'_z = \frac{z_o}{z_i - z_o}A_z \quad (6)$$

The boundary conditions for the perturbations are imposed naturally taking *u* and *v* equal to zero over the bottom and lateral boundaries. The initial conditions for the perturbations are also assumed to be zero, since before assimilation the model variables are in equilibrium. The homogeneous part of equations (1) and (2) allows separation of variables in time and space according to

$$u(t,x,y,z) = \Gamma(t)U(x,y,z) \qquad v(t,x,y,z) = \Gamma(t)V(x,y,z) \quad (7)$$

The following spectral problem is obtained:

$$\Delta U - u_0\frac{\partial U}{\partial x} - v_0\frac{\partial U}{\partial y} + (A(z) - \frac{\partial u_0}{\partial x})U + (f - \frac{\partial u_0}{\partial y})V = \lambda U \quad (8)$$

$$\Delta V - u_0\frac{\partial V}{\partial x} - v_0\frac{\partial V}{\partial y} + (A(z) - \frac{\partial v_0}{\partial y})V - (f + \frac{\partial v_0}{\partial x})U = \lambda V \quad (9)$$

$$\frac{dT}{dt} = \lambda T \quad (10)$$

Finding the eigenvectors of the system (8-10) and projecting the forcing terms (F) into this basis, the coefficients (c_l) of the expansion are found

$$F = \sum_{l=1}^{\infty} c_l g_l \quad (11)$$

where

$$F_u = A_z u^* - \frac{g}{\bar{\rho}}\int_{z_{i-1}}^{z}\frac{\partial \rho_a}{\partial x}dz$$

$$F_v = A_z v^* - \frac{g}{\bar{\rho}}\int_{z_{i-1}}^{z}\frac{\partial \rho_a}{\partial y}dz$$

To calculate the eigenvectors and eigenvalues, the LAPACK library (Anderson et al., 1999) has been used.

Then, the resulting velocities are given by

$$u(t,x,y,z)=u_0(x,y,z)-\frac{1}{\tau}\sum_{l=1}^{\infty}\frac{(1-e^{\lambda_l\tau})}{\lambda_l^2}c_l^u g_l^u \quad (12)$$

$$v(t,x,y,z)=v_0(x,y,z)-\frac{1}{\tau}\sum_{l=1}^{\infty}\frac{(1-e^{\lambda_l\tau})}{\lambda_l^2}c_l^v g_l^v \quad (13)$$

The second method is a simplification of the first, where an instantaneous adjustment between currents and density fields is supposed. Then, the time dependence is discarded and the perturbed linearized system is directly solved

$$u_0\frac{\partial u}{\partial x}+u\frac{\partial u_0}{\partial x}+v_0\frac{\partial u}{\partial y}+v\frac{\partial u_0}{\partial y}-fv-A_h\Delta u + A_z(z)u = A_z u^* - \frac{g}{\bar{\rho}}\int_{z_{i-1}}^{z}\frac{\partial\rho_a}{\partial x}dz \quad (14)$$

$$u_0\frac{\partial v}{\partial x}+u\frac{\partial v_0}{\partial x}+v_0\frac{\partial v}{\partial y}+v\frac{\partial v_0}{\partial y}+fu-A_h\Delta v + A_z(z)v = A_z v^* - \frac{g}{\bar{\rho}}\int_{z_{i-1}}^{z}\frac{\partial\rho_a}{\partial y}dz \quad (15)$$

The new currents are given by the sum between the velocities before the assimilation and the perturbations calculated with equations (14-15):

$$u(t_a,x,y,z)=u_0(t_a,x,y,z)+u'(t_a,x,y,z) \quad (16)$$

$$v(t_a,x,y,z)=v_0(t_a,x,y,z)+v'(t_a,x,y,z) \quad (17)$$

4. THE EXPERIMENTS AND THE RESULTS

The initialization methods presented in last section have been applied to correct currents after data assimilation of temperature profiles. Hereafter, the first will be referenced as modified Normal Mode (mNM) and the second as Direct Solution (SD).

Four experiments were done to investigate the performance of those methods. These experiments included a control run, in which no data assimilation and no velocity correction were applied; a data assimilation experiment without the velocity correction (ASSIM); a data assimilation plus mNM velocity correction (EXP I); and a data assimilation plus SD velocity correction (EXP II). The model was integrated for three months in all experiments, starting at March of 1999. Assimilation and velocity correction were performed each 5 days during the first two months. In the last month of simulations, no assimilation and no correction method were applied. The summary of experiments is showed in table 1.

The results of the control run are summarized in figures 2 and 3. Figure 2 shows the first level model (a) and the equatorial profile (b) of mean temperature.

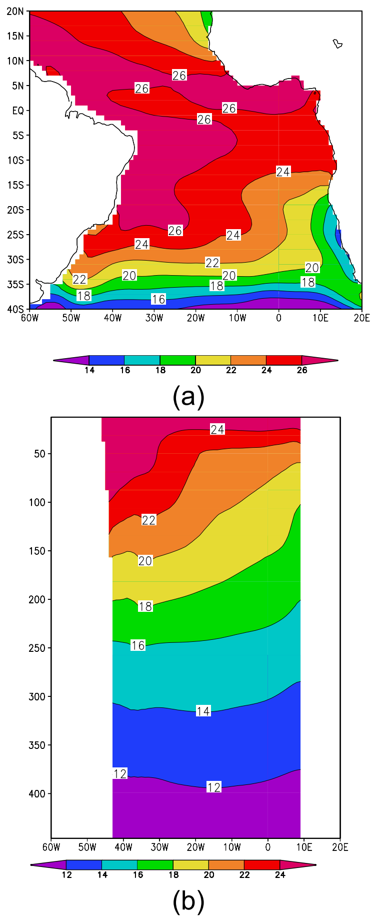


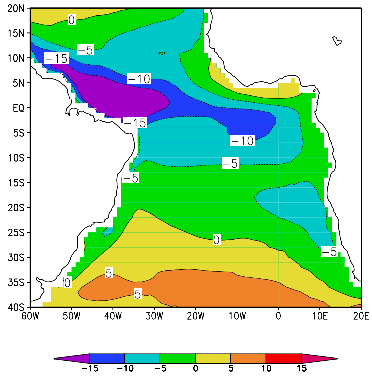
FIG. 2. Mean temperature (°C) at first level model (a) and equatorial profile (b) for the control run.

The isotherms configuration, in figure 2a, shows an accumulation of warm water in the west side of tropical Atlantic associated with the Brazil Current and the colder water next to the African coastline, corresponding to Benguela Current. A signal of the Malvinas Current can be also identified in the southwest Atlantic.

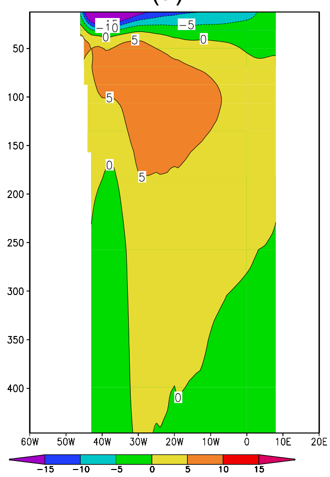
In figure 2b, the thermocline can be identified through the zonal slope of isotherms. As in figure 2a, the warmer water is concentrated next to South America and the colder water is next to Africa. Note the largest temperature variation occurs in the first 150 m in the east side of the basin.

Table 1. Summary of experiments.

Experiments	*Assimilation Method*	*Correction Method*
Control	no	none
ASSIM	yes	none
EXP I	yes	mNM
EXP II	yes	SD



(a)



(b)

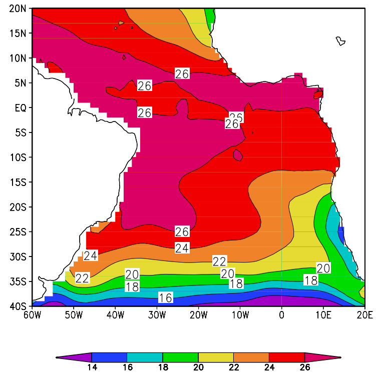
FIG. 3. Mean zonal currents (cm/s) at first level model (a) and equatorial profile (b), for control run.

The mean zonal component of currents at first model level and equatorial cross section is represented in figure 3. The negative values in almost all tropical region observed in figure 3a mean westward flow. The greatest values are observed at northeast coast of South America where is found the North Brazil Current. An eastward flow is noted in a narrow band next to Gulf of Guinea, representing the North Equatorial Countercurrent. It is highly seasonal, being weaker in north hemisphere winter because the strongest trades winds.

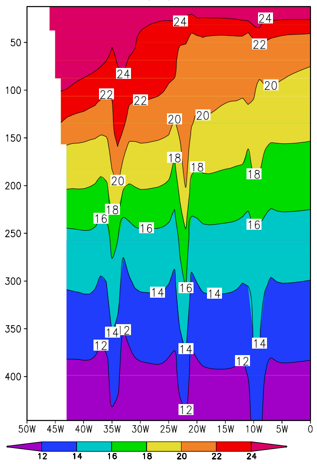
The equatorial profile of zonal currents is showed in figure 3b. At surface the flow is westward corresponding to South Equatorial Current, and an eastward flow at sub-surface, between 50 m and 200 m, corresponding to the Equatorial Undercurrent (EUC).

The control run, in general, reproduced well the Atlantic temperature and circulation patterns but underestimated the velocities and thermocline was quite diffuse.

The ASSIM results are shown in figures 4 and 5. The March and April mean temperatures and zonal currents in the first model level are in figures 4a and 5a. Note that the temperature data assimilation produces great increments around the buoys locations. The same patterns can be observed in the equatorial profiles (figures 4b and 5b).



(a)



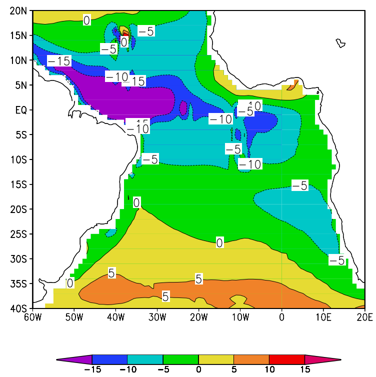
(b)

FIG. 4. Mean temperature (^oC) at first level model (a) and equatorial profile (b), for ASSIM experiment.

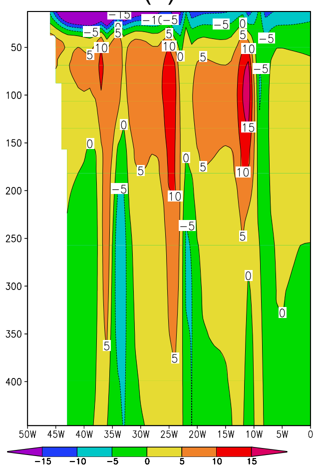
Comparing the temperature equatorial profiles of control run and ASSIM, it can be noted larger values in the second one. It demonstrates a tendency of model underestimate the temperature. However, the analysis generates bigger increments closer to buoys resulting in an unrealistic circulation around them (figure 5b). The Equatorial Undercurrent appears divided in three parts.
The correction currents methods were applied to solve these problems.

The first correction method is based in the normal mode initialization technique proposed by Belyaev and Tanajura (2005) with a modification in the vertical momentum parameterization. The result of EXP I is shown in figure 7.

The horizontal and vertical patterns of currents are improved. The convergence and divergence regions generated around the buoys by data assimilation are reduced. The Equatorial Undercurrent is not divided, and an increase in its velocity is observed.



(a)



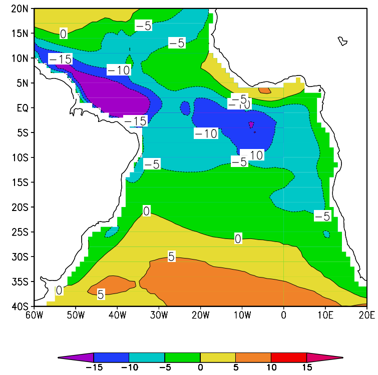
(b)

FIG. 5. Mean zonal currents (cm/s) at first level model (a) and equatorial profile (b), for ASSIM experiment.

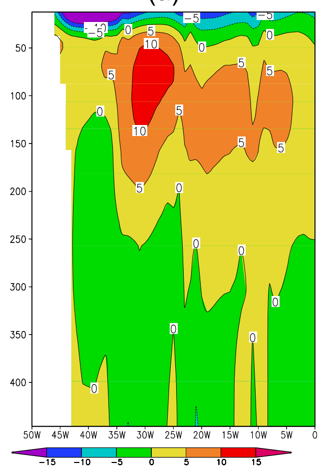
The second correction method is a simplification of the first, in which the increments are directly calculated of equations 14 and 15. Figure 8 shows the EXP II results.

As in EXP I, the currents are improved. However, in this experiment, the contour fields are smoother, and the EUC does not have a lot of meanders.

The horizontal zonal current shows an increase in the velocity in the equatorial region, next to the African coastline, because of the temperature increase caused by data assimilation.



(a)



(b)

FIG. 6. As fig 5, fo EXP I experiment.

4. CONCLUSIONS

In present work, two methodologies of currents corrections after temperature data assimilation were presented. Four experiments were done to show their performance.

The ocean model used here was MOM_3, the data assimilation method was based on a Kalman filter and the database was from PIRATA.

The data assimilation caused an increase of temperature in the mixed layer, indicating a tendency of the model to underestimate the temperature. However, the analysis increments were very concentrated around the buoys positions. This pattern resulted in large perturbations on the velocity fields and unrealistic convergence and divergence zones.

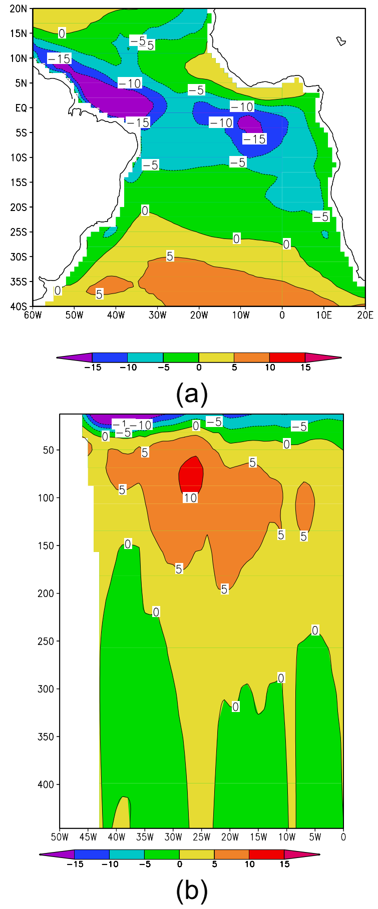


FIG. 7. As fig. 6, for EXP II experiment.

The correction methods presented consistent results. They modified the currents in the locations in which the perturbations of temperature and density were higher and improved the velocities results.

Both methods reduced the perturbations, but the SD method produced smoother velocity fields than mNM.

5. REFERENCES

Anderson, E. et al., 1999: LAPACK User's Guide, SIAM, UniversityCity Science Center, Philadelphia, PA.

Belyaev, K. P. and Tanajura, C. A. S., 2005: On the correction of perturbations due to data assimilation in ocean circulation models. *Appl. Math. Modelling*, **29**, 690-709.

Belyaev, K. P., Tanajura, C. A. S. and O'Brien, J. J., 2001: A data assimilation method used with an ocean circulation model and its application to the tropical Atlantic, *Appl. Math. Modelling*, **25**, 655-670.

Belyaev, K. P., Meyers, S. and O'Brien, J. J., 2000: Fokker-Planck equation application to data assimilation into the hydrodynamic models, *J. Math. Sciences*, **99**, 4, 1393-1403.

Conkright, M. E. and Co-authors, 1998: World Ocean Database: documentation and quality control. NOAA/NODC Internal Report, 14.

Pacanowski, R., 1999: MOM 3.0 Documentation Users Guide and Reference Manual, NOAA/GFDL. Ocean Technical Report, 4.

Servain, J. et al., 1998: A pilot research moored array in the tropical Atlantic (PIRATA). *Bull. Am. Meteor*. Soc., **29**, 2019-2031.

Tanajura, C. A. S. and Belyaev, K. P., 2002: On the oceanic impact of a data-assimilation method in a coupled ocean-land-atmosphere model. *Ocean Dyn.*, **52**, 123-132.