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TEMPERATURE AND SALINITY DATA ASSIMILATION EXPERIMENTS IN THE TROPICAL ATLANTIC WITH MOM3

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1. INTRODUCTION

Ocean data assimilation (ODA) is a key-issue for climate predictability and ocean monitoring (e.g., Ji and Leetmaa 1998). However, it is a relatively new area and there are many challenges to overcome. Data assimilation has been developed and mostly used for the atmosphere, and not all ocean model prognostic variables are well monitored, such as salinity and currents. Sea surface temperature and sea surface height data are collected by satellites with high resolution, but they only indirectly provide information about the subsurface structure. ODA of in situ temperature vertical profiles are today mostly used in the estimation of the ocean state. The data offered by the Tropical Atmosphere-Ocean Experiment (TAO) project and the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) are crucial for monitoring the oceans (e.g., Thacker et al. 2002) but they are located in only in the tropics. Recently, a big effort is under way to improve ocean monitoring with new systems like Argos and the integration of observation regional systems through the Global Ocean Observing System (GOOS).

To maximize the information contained in the available data, data assimilation methods can be used (Derber and Rosati 1989; Kalnay et al. 1996; Evensen 2004). These methods combine data and models to produce the best possible estimation of the ocean state.

Predictability of weather and climate depend directly on the initial condition. To generate a good initial condition in ocean models, it is necessary create a good [23]thermo-saline structure. Some researchers emphasize that a good representation of temperature (T) and salinity (S) is more relevant than a good representation of the circulation (Gill 1982; Philander 1987; Moore et. al. 1987), because of the low frequency circulation is guided by the density gradients which depends on temperature, salinity and pressure. Because of the lack of salinity data, ODA is used mostly with temperature only. It is expected that assimilation of temperature will slowly alter the model dynamics and will reconstruct the whole ocean state.

However, Cooper (1988) showed that it is essential to include salinity in the assimilation process if the objective is to reduce the model errors in the velocity fields. He showed that temperature data assimilation only could degenerate the model circulation. In high-latitudes, Raverdin et.al. (1997) also proved that salinity is important to determine the density.

Another solution to the lack salinity data is to assume a climatological relation between T and S to produce salinity having temperature data (Troccoli and Haines 1999), but this hypothesis implies in restricted variability and it could not be used in regions with high space-time variability like the tropical Pacific (Vossepoel et. al. 1999).

In this work, temperature assimilation experiments in the Tropical Atlantic are presented with the Modular Ocean Model version 3 (MOM3) of the Geophysical Fluid Dynamics Laboratory (GFDL/NOAA) and Levitus data (Levitus and Boyer 94) in a climatological run. It is presented in section 2 a small description of the ocean model. In section 3, it is presented the ODA scheme used here. In sections 4 and 5, the data and the experiments are described. In section 6, the results are discussed. The conclusions are in section 7.

2. THE MOM3 MODEL

MOM3 was developed in GFDL/NOAA to study the ocean circulation and variability (Pacanowsky e Griffies 2000). The model equations are formulated in spherical coordinates. The Boussinesq approximation and the hydrostatic equations are used.

The model is discretized by finite

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differences on an Arakawa B-grid. It was considered a global horizontal resolution of $1^o x 1^o$ in the horizontal domain. In the vertical direction, the model was discretized by 15 levels {12.5, 37.5, 62.5, 87.5, 112.5, 156.75, 257.15, 446.08, 748.76, 1181.16, 1748.76, 2446.08, 3257.14, 4156.74, 5112.5} m .

This configuration is considered as low resolution, and it was adopted because of limited memory machine and computational cost. The spin-up was made in DEC-alpha computer with 256 MB RAM. The assimilation experiments were made in a SGI Octane workstation with 2 GB RAM. In future experiments, it will be used the newest MOM version, MOM4, with higher resolution.

3. THE ASSIMILATION SCHEME

The method used here is based in the Bergthorsson and Doos scheme (Daley 1991) with a single correction. This scheme uses prescribed weights depending on the relative distance between the observational point and the analysis point. They also depend on a radius of influence R. The analysis is given by:

$$f_A(x_i) = f_B(x_i) + \sum_{k=1}^{K} W_{ki}\left[f_O(x_k) - f_B(x_k)\right]$$

where x_i denotes the coordinate of the analysis point; x_k is the coordinate of the observational point; f_A, f_B, f_O are the analysis, the background (model) and the observational variables, respectively; W_{ki} is the weight matrix. This matrix is given by:

$$W_{ik} = \frac{w(r_{ik})}{\sum_{k=1}^{K_i} w(r_{ik}) + \varepsilon_0^2},$$

$$w(r_{ik}) = \exp\left\{-\frac{6\,|r_{ik}|^2}{R^2}\right\}$$

$|r_{ik}|$ is the distance between x_k and x_i, $\varepsilon_O = E_O / E_B$; E_O, E_B are the expected observation error and the expected background error, respectively. In this work, it was considered that the observational error is null.

4. DATA

To force the model, climatological data available in www.gfdl.noaa.gov was used. This climatology was based in the period between 1900 e 1992. The data horizontal resolution is 1x1 degrees with 33 vertical levels. For the climatological experiments, 44 points with 5^o spacing were selected in the Atlantic according to Figure 1. At these points, vertical profiles of temperature data were taken and interpolated to the model levels.

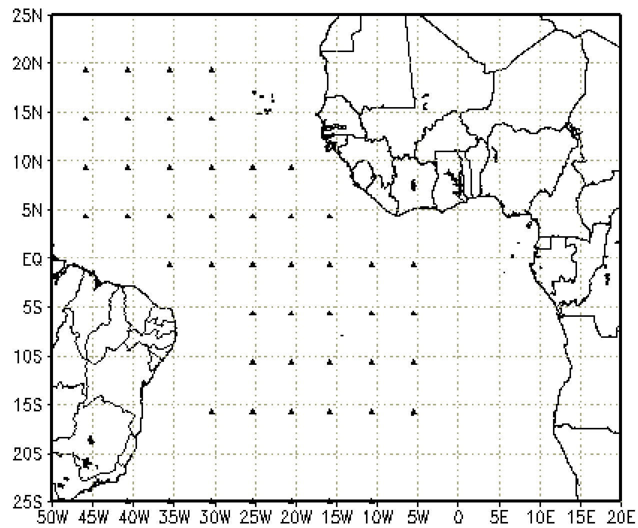

Figura 1. Location of the Levitus data points used in the assimilation experiments.

5. EXPERIMENT DESIGN

First, MOM3 was integrated from rest for 15 years forced with climatological monthly mean wind stresses from Hellerman (1983) and surface air temperature from Oort (1983). The model has relaxation for sea surface temperature and sea surface salinity. The temperature and salinity initial conditions were the January mean, according to Levitus and Boyer (1994). The model time step was

4h. This was the spin-up run.

After the spin-up, the control run is performed. It consists of a one-year integration forced by the same way the spin-up was forced but the time step was reduced to 1h. This reduction was made to augment the numerical stability when the assimilation is introduced.

The temperature assimilation run is similar to the control run but assimilation of temperature is imposed in the first 9 model levels each 5 days during one year. The first assimilation happened on January 5 and the last on December 31. The radius of influence was 11.25°. No assimilation was realized if the difference between data and the background was larger than 5°C. This experiment was called Tassim.

Similar to Tassim, assimilation is done only for salinity. No assimilation was realized if the difference between data and the background was larger than 1PSU. This experiment is called Sassim.

Similar to Tassim and Sassim, assimilation was also performed for both temperature and salinity data. This experiment is called TSassim.

Another run was performed in which salinity is corrected after temperature assimilation only is done using the model T-S relation available in the previous time step (before assimilation). This experiment is called Tassim-Scorr.

6 RESULTS

Figure 2a shows the monthly mean temperature along the year from the Levitus climatology averaged between 2.5°S – 2.5°N, 35°W – 25°W in the Atlantic to the first 750 m. It shows a well-defined mixed layer varying between 50 and 70 m during the year. Below it, the strong vertical gradient characterizes the thermocline region near 150 m. The temperature in the thermocline changes from 25°C to 15°C with depth, and below it the temperature decreases from 14°C to 5°C on 750 m. Figure 2b shows the temperature produced by the control integration. The model couldn’t capture the climatological thermal structure. On the mixing layer, the model temperature is about 3°C colder than climatology. These differences are larger in the thermocline region, almost 6°C. In the deeper regions, the model error decreases to about 2°C. The errors are large, and the challenge of the ODA is substantial to reconstruct the model state in the direction of observations.

Figure 2c is similar to 2b, but for Tassim. The representation of the mixed layer is much better, despite the fact that it is deeper than climatology. In the mixed layer, the differences are reduced to less than 1°C. In the thermocline region, the differences are less than 2°C, and this error is even smaller. In January, the structure is similar to control. However, in February and March there is a substantial adjustment in the temperature vertical structure, so that in April the model with assimilation is much closer to the Levitus data than the control run. Below the thermocline, a wavy pattern is observed with ridges in April and October and troughs in July and December. This is associated with the model adjustment to temperature assimilation only. The misbalance among the model prognostic variables may the substantially reduced by initialization schemes, but these schemes were not used here (e.g., Daley, 1991; Moore 1987; Belyaev and Tanajura 2005).

Figure 2d is similar to 2b-2c, but it shows results from Sassim. There is a small impact in the temperature when only salinity is assimilated. The mixed layer becomes thicker and the temperature is about 1°C smaller than the control. Figure 2e presents the results for TSassim. In this experiment, the thermal structure is quite similar to the Levitus data in the mixed layer, in the thermocline region and in the deeper ocean. There is no oscillation in the temperature below the thermocline as those produced in Tassim. Figure 2f shows the results for Tassim-Scorr. The thermal structure is quite close to TSassim. The oscillations are not produced too. It means the correction of salinity after temperature assimilation produced better results than Tassim.

The vertical profiles of the salinity along the year were also investigated (not shown). The control produced a very diffuse field, without a clear characterization of the vertical gradient of salinity observed between 100 and 150 m in the Levitus data. The impact of Tassim in the salinity profiles was observed between April and May, and after that oscillations in the salinity are observed until the end of the year. A region with stronger vertical gradient of salinity is also produced after May. The assimilation of salinity worked as expected, taking the model toward the observation after one month. The experiment TSassim produced a very good approximation of the Levitus salinity in about one month. The experiment Tassim-Scorr provided a result much better than Tassim, but could not reproduce the quality of the TSassim results.

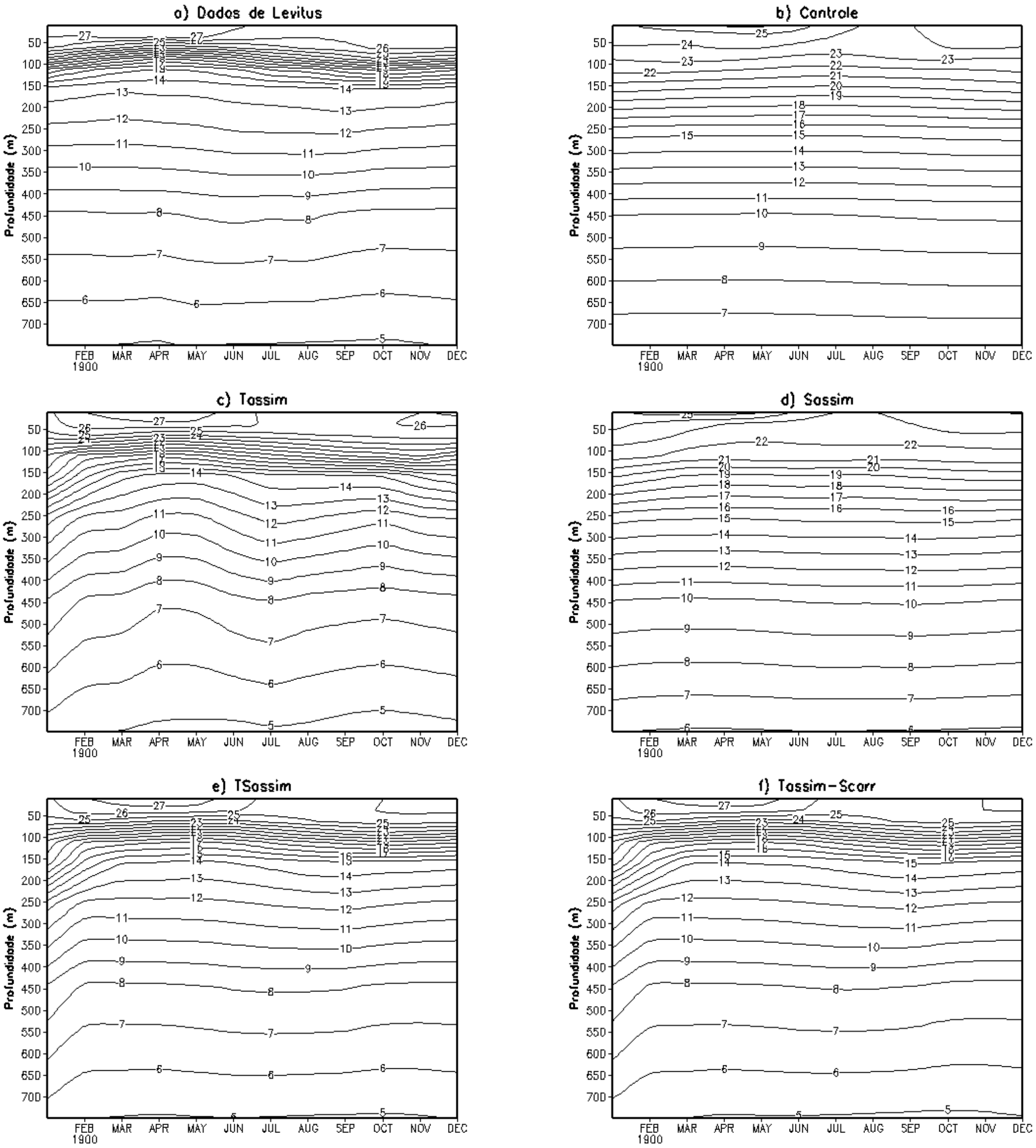

Figure 2: Time evolution of the monthly mean temperature (^oC) averaged in the area 2.5^{o}S-2.5^{o}N e 35^{o}W-25^{o}W for the first nine model levels for: (a) the Levitus data; (b) control run; (c) temperature assimilation run; (d) salinity assimilation run; (e) temperature and salinity assimilation; and (f) temperature assimilation and salinity correction.

In order to investigate the impact of the assimilation in the whole area in which assimilation was performed, the root mean squared error (RMSE) for the temperature and salinity was calculated for the fourth model layer (87.5 m). This layer is in the thermocline region, where the model produced the largest errors. Figure 3 presents the RMSE of temperature and salinity averaged in the region 25^{o}S – 25^{o}N and 60^{o}W – 0^{o}W. The errors were calculated in the points in which assimilation and no assimilation was considered, since the Levitus data has a 1^o resolution and the data used in the assimilation were taken at a 5^o spacing. The RMSE for the temperature is shown in Figure 3a. It clearly shows that the control run produced an error larger than 2.1^o along all year. Sassim also produced the same error, showing, as mentioned above, that the assimilation of temperature only had not a substantial impact in the temperature field. Tassim presented a sharp drop in the error with respect to the control run. In February, the error reached 0.9^{o}C. However, after this, the RMSE had a monotonic increase and in December it reached about 1.5^{o}C. The experiments TSassim e Tassim-

Scorr provided the same errors in this level. After January, when the RMSE was 1.5^{o}C, the maximum RMSE was about 1^{o}C. The same RMSE in TSassim e Tassim-Scorr was not observed in another model levels (not shown). In other levels, TSassim produced slightly smaller errors of temperature.

The RMSE for the salinity is shown in Figure 3b. It shows the salinity RMSE of the control run was smaller than the RMSE of Tassim and Tassim-Scorr. The experiment Tassim produced increasingly larger errors along the year. These errors can be explained only by the impact of temperature assimilation and the misbalance that it caused in the model variables. It excited the model dynamics and produced unrealistic salinity fields by diffusion and advection. The smallest RSME of salinity were attained by TSassim and Sassim. Since Sassim also produced large RMSE of temperature, the results presented here show that TSassim were the best among the integrations.

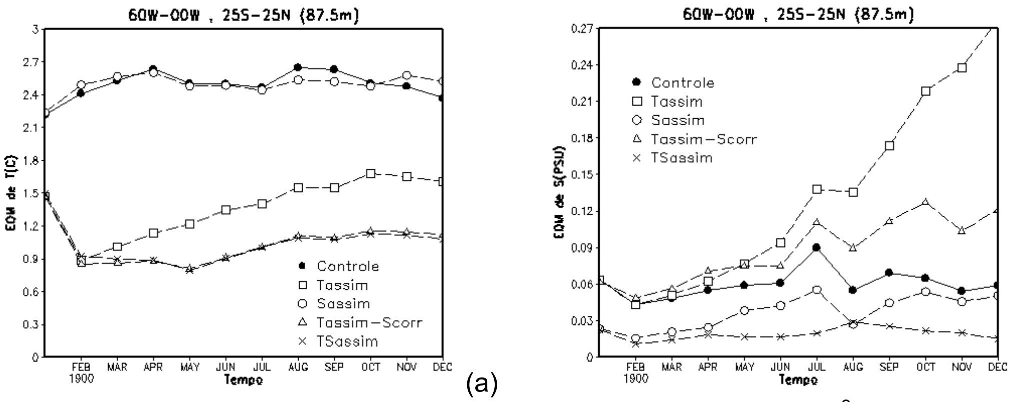

Figure 3: Root mean squared error of the monthly mean (a) temperature (^{o}C) and (b) salinity (PSU) averaged in the area 25^{o}S – 25^{o}N and 60^{o}W – 0^{o}W for the fourth model level (87.5 m).

7. CONCLUSIONS

Temperature and/or assimilation experiments were performed with a climatological run of the GFDL/NOAA global ocean model MOM_3, the Levitus climatological data and the Bergthorsson and Doos data assimilation method with prescribed weights. The experiments focused on the tropical Atlantic in which 44 vertical profiles of temperature and salinity were used. Assimilation of temperature only, salinity only, temperature and salinity were performed at each five days during one year after a 15 year spin-up. Another experiment was done in which only temperature was assimilated, but salinity was corrected assuming a local relationship between temperature and salinity.

The results showed that the assimilation of temperature only could improve the control run results in which no assimilation was realized. The assimilation of temperature caused some positive impacts in the salinity field in the beginning of the integration. However, in the end of the integration the errors in the salinity were augmented in relation to the control run. The assimilation of salinity caused a very small impact in the temperature field, despite the improvement in the salinity representation. The assimilation of both temperature and salinity provided the best results among the runs, including the experiment in which temperature was assimilated and salinity was corrected.

The assimilation of temperature only imposed large impacts in the temperature, particularly in the thermocline region. It caused a misbalance among the model variables and a degradation of the model fields with time through the model circulation and dynamics. The inclusion of salinity controlled this behavior and provided a much better analysis. In the future, new experiments with MOM4 with higher resolution will be used with assimilation of temperature and salinity for a deeper investigation of the ocean state and variability.

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