Proceedings of 8 ICSHMO, Foz do Iguaçu, Brazil, April 24-28, 2006, INPE, p. 1343-1348.

RegCM SIMULATED LATENT AND SENSIBLE HEAT FLUXES OVER THE SOUTH ATLANTIC OCEAN: SEASONAL MEAN VARIATIONS

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1 Introduction

The knowledge of the air-sea fluxes is of great importance to several meteorological and oceanographic studies. For example, authors as Nuss and Anthes (1987), Kuo et al. (1991), and Neiman and Shapiro (1993) have shown that latent and sensible heat fluxes contribute to bomb cyclones development.

Observational datasets of turbulent fluxes can barely be obtained due to the high financial costs involving the measurements. The heat and moisture fluxes are usually acquired through bulk aerodynamic algorithms where each turbulent exchange coefficients differ in parametrization. An intercomparison among six parametrizations algorithms for the Tropical Atlantic can be found in Zeng et al. (1998). The authors have shown that although moment and heat fluxes have significant differences among the algorithms, under both very weak and very strong wind conditions, they agree with each other under moderate wind conditions. Wainer et al. (2003) presented a comparison of the latent and sensible heat fluxes which were obtained from four algorithms and by NCAR CCSM model (Paleoclimate Comunity Climate System Model) over the South Atlantic. Their results showed that there are great differences in the fluxes intensity, as function of the algorithm.

Reboita et al. (2005 a) performed an analysis of latent and sensible heat fluxes, from 1990 to 1994, on the South Atlantic and in three sub domains close to the east South America coast. In this study, it was noted that the turbulent fluxes annual cycle was well simulated by the RegCM (Regional Climate Model - Elguindi et al., 2004) when compared to those in WHOI (Woods Hole Oceanographic Institution) and ECMWF (European Centre of Medium Range Weather Forecasting) analysis. The intensity of the latent heat fluxes simulated was closer to the analysed than that of the sensible heat fluxes. The simulated sensible heat fluxes were more intense than the analyzed. This was mainly attributed to the large temperature vertical gradients in the simulation. Reboita et al. (2005 a) showed yet that the differences between simulated and analysed heat fluxes were greater in the tropics than in the high latitude.

The objective of this work is to validate the latent and sensible heat fluxes seasonal climatology (summer and winter) simulated by RegCM from 1990 to 1999 on the South Atlantic. The simulations were compared to the analyses of the WHOI and of the ECMWF. Furthermore we will also examine the turbulent fluxes annual cycle.

2 Data and Methods

2.1 Analysed Datasets

WHOI

The WHOI provides daily and monthly average data over South Atlantic (64.5°S - 64.5°N and 100.5°W - 25.5°E) with 1° of the horizontal resolution from 1981 to 2002 (Yu et al., 2004). These data are available at http://oaflux.whoi.edu. The turbulent flux product was developed by using a variational objective analysis approach to obtain best estimates of the flux-related basic surface meteorological variables (e.g., wind speed, air moisture, air temperature, and sea surface temperature) through synthesizing satellite data and outputs of numerical weather prediction models of the National Centers for Environmental Prediction (NCEP) and European Centre for Medium - Range Weather Forecasts (ECMWF). The fluxes parametrization was carried out through a bulk algorithm described in Fairral et al. (1996) and Fairral et al. (2003).

ECMWF

The ECMWF provides data of two global reanalyses projects: ERA-15 and ERA-40 with 2.5° of horizontal resolution. These data are available at http://www.ecmwf.int. In this study, the ERA-40

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(Uppala et al., 2005) which includes the period from 1957 to 2002 was used. The ERA-40 parametrization description can be found in Beljaars (1995; 1997).

2.2 Turbulent Fluxes Simulation

The RegCM model was used to simulate the turbulent fluxes. It is a limited area model and its first generation was built upon the National Center for Atmospheric Research-Pennsylvania State University (NCAR-PSU) Mesoscale Model version MM4 in the late 1980s. The RegCM is a hydrostatic model, compressible, using primitive equations (Elguindi et al., 2004). The latent (LH) and sensible (SH) heat fluxes are parametrizaded through bulk aerodynamic algorithms (Zeng et al., 1998):

$$LH = -\rho_a L_e u_* q_* \quad (1)$$

$$SH = \rho_a C_p u_* \theta_* \quad (2)$$

where u_* is the frictional wind velocity, θ_* and q_* are the temperature and specific moisture scaling parameter, respectively, ρ_a is air density, C_p is specific heat at constant pressure, and L_e is the latent heat of vaporization.

The climatic simulation was accomplished on the South Atlantic (60°S - 5°S and 84°W - 15°E) from September 1989 to January 2000. Due to the spin-up time, the first three months of the simulations were excluded of the analyses. A 60 km horizontal resolution and 18 vertical sigma levels were used and the domain is showed in Figure 1. The initial and boundaries conditions for the simulations were provided by NCEP-DOE (National Centers for Atmospheric Research; Kanamitsu et al., 2002) reanalyses. The SST was specified by the mean monthly dataset of the Reynolds and Smith (1995).

2.3 Methodology

The simulated turbulent fluxes seasonal climatology (summer and winter), calculated as the average of 1990 to 1999, were validated comparing with the WHOI and ECMWF analyses. The summer was defined as DJF (Dec-Jan-Feb) and the winter as JJA (Jun-Jul-Aug). The annual cycle pattern was investigated through monthly climatologic means determined for the South Atlantic and three sub domains indicated in Figure 1. The small regions from 1 to 3 in Figure 1 represent the main favorable South Atlantic areas for cyclogenesis (Reboita et al., 2005 b).

3 Results

3.1 Seasonal Variation

The seasonal climatology (summer and winter) of the latent and sensible heat fluxes simulated and of the WHOI and ECMWF analyses are shown in figures 2 and 3 respectively. Table 1 presents the seasonal average to the South Atlantic. Positive fluxes indicate the transference of the heat and moisture from ocean to atmosphere.

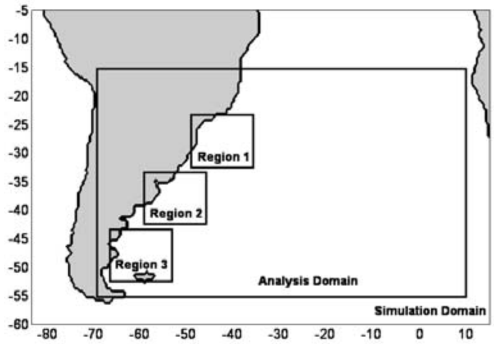

Figure 1. Simulation domain (outer) and analysis domain (inner). The boxes 1, 2, and 3 indicate the favorable regions to cyclone development. The RegCM results over the continent were not included in the analysis.

Table 1 Latent and sensible heat fluxes seasonal average (W m^{-2}) on the South Atlantic from 1990 to 1999. S denotes summer and W winter.

	Latent Heat Fluxes			Sensible Heat Fluxes		
	RegCM	WHOI	ECMWF	RegCM	WHOI	ECMWF
S	69.8	67.6	77.1	8.5	0.9	3.6
W	84.1	93.9	100.3	20.9	10.7	16.2

According to Table 1, the latent and sensible heat fluxes seasonal average simulated and also of the analyses are more intense in the winter than in the summer. This is associated with more intense vertical gradients of temperature and air moisture during the winter. In this season, there is higher thermal contrast between ocean and atmosphere due to the higher thermal capacity of the former. Thus, in the winter, the ocean is relatively warm while the atmosphere is colder and dryer and that, associated to stronger winds in this season, favors more intense vertical turbulent heat fluxes. In the summer, the thermal contrast ocean-atmosphere is smaller, associated with weak winds, and it reduces the turbulent heat fluxes. In both seasons, the simulated averages of the latent heat fluxes are closer to those in the WHOI analysis. In terms of intensity, the differences between simulated and analysed values do not overcome 16 Wm^{-2}. This result shows improvement of the comparison achieved by Wainer et al. (2003) that found differences of up to 80 Wm^{-2} among five different algorithms over South Atlantic.

For the sensible heat fluxes, the values simulated are higher than those of the analyses in the two seasons, but they are closer to the ECMWF analysis. As discussed in Reboita et al. (2005 a), this is due to the more intense temperature vertical gradients of the simulation.

Maps showing the latent heat fluxes seasonal mean are presented in Figure 2. In the summer (Figure 2 a,b,c) the simulation presents spatial distribution and intensity very similar to that in WHOI and ECMWF analyses. The simulated fluxes intensity in the latitude band of 15°S to 40°S is closer to the ECMWF analysis. South of 40°S there are fewer differences in the analyses spatial pattern and the model reproduces well the horizontal gradients. Some differences were found in the region between 15° to 30°S, where the maximum showed in the analyses was not simulated by RegCM.

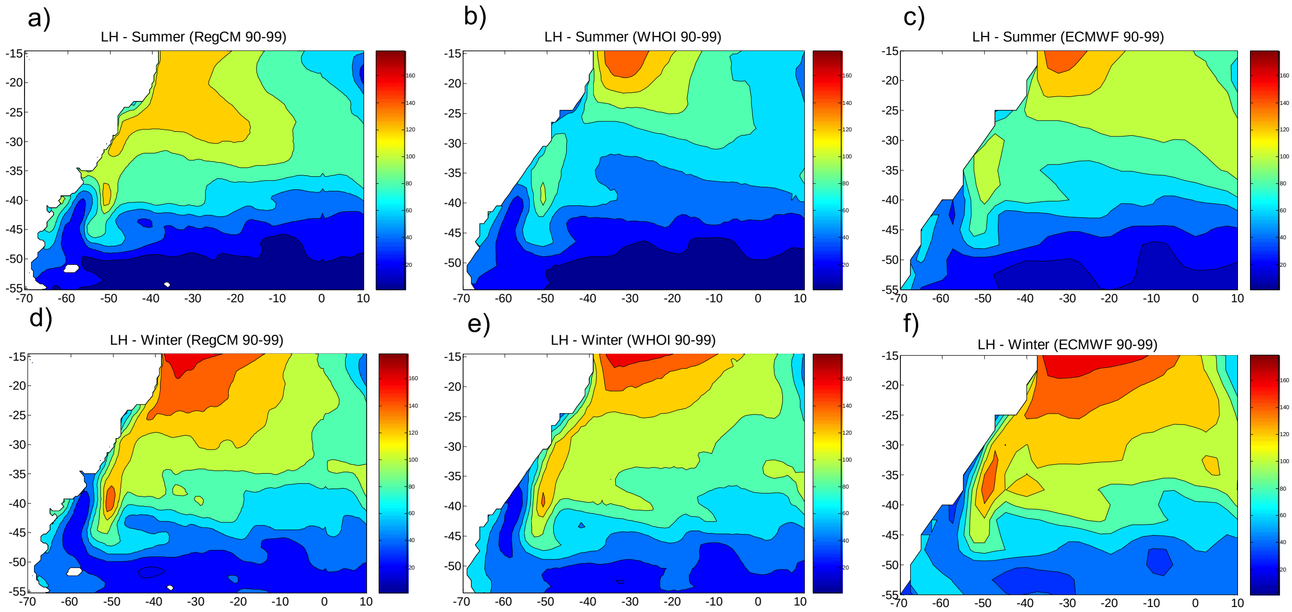

Figure 2. Latent heat fluxes seasonal average (LH - Wm^{-2}) of the RegCM simulation and the WHOI and ECMWF analyses, for the South Atlantic from 1990 to 1999. (a), (b), and (c) represents the summer season and (d), (e), and (f) the winter.

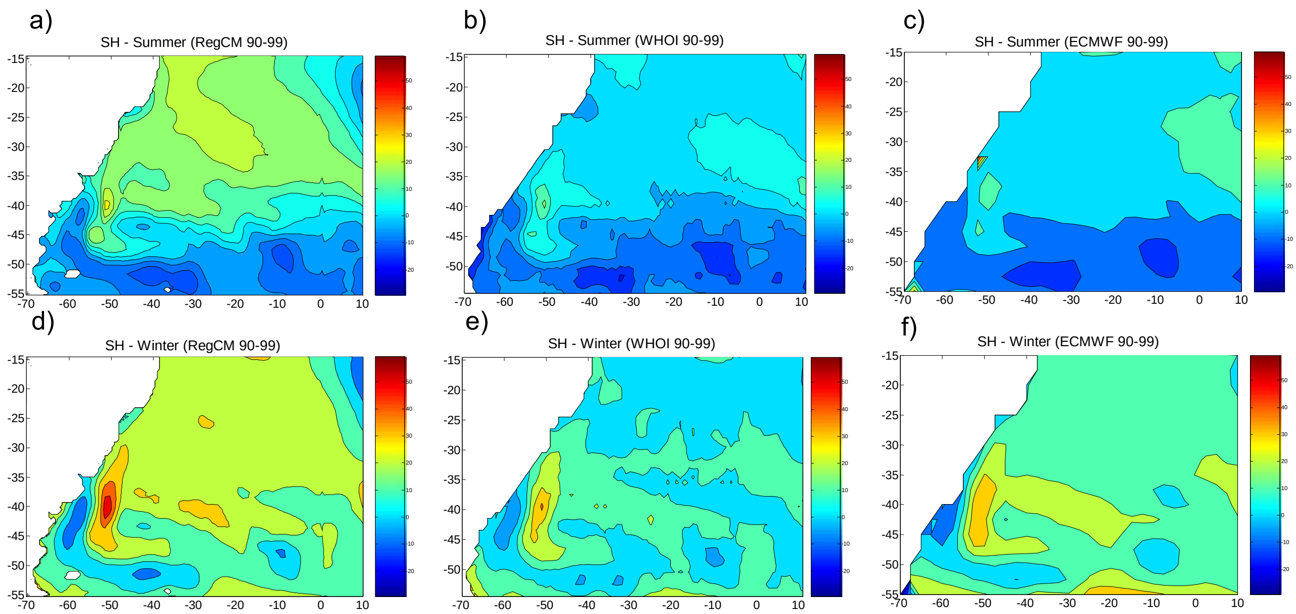

Figura 3. Sensible heat fluxes seasonal average (SH - Wm^{-2}) of the RegCM simulation and of WHOI and ECMWF analyses, for the South Atlantic from 1990 to 1999. (a), (b), and (c) represents the summer season and (d), (e), and (f) the winter.

Another good agreement between simulation and analyses is related to the gradient produced by the Brazil-Malvinas currents confluence, between 35° to 45°S near the coast. It can also be pointed out that the maximum over the Brazil current around 40°S simulated is seen in the WHOI analysis.

In the winter, the simulated latent heat fluxes spatial pattern (Figure 2 d) present the main spatial structures found in the analysis of WHOI (Figure 2 e) and ECMWF (Figure 2 f) which are the maximum in the tropics that decrease in the direction to the subtropics (until ~ 30°S); the strong fluxes difference in the Brazil-Malvinas confluence; the north-south gradients around 45°S.

The sensible heat fluxes (Figure 3) present more complex spatial structures than the latent heat fluxes. In the two seasons, the simulation showed more intense fluxes for the latitudes north of 40°S. However, south of that the simulated intensity is closer to the analyses. The standout spatial structure in the sensible heat fluxes seasonal maps is the region of the Brazil-Malvinas currents confluence. In this region, the fresh and cold waters of the Malvinas current are characterized by negative fluxes and the warm and salty waters of the Brazil current are characterized by positive fluxes. Although the sensible heat fluxes intensity of the Malvinas current simulated by the RegCM is near to the analyses, these fluxes are larger in the Brazil current.

In the summer (Figure 3 a,b,c), the simulated sensible heat fluxes showed north-south and east-west gradients more intense near 40°S than the ones in WHOI and ECMWF. However, the RegCM is able to represent the spatial structures in the band of the 50° to 55°S present in the WHOI and ECMWF analyses. In the winter (Figure 3 d,e,f), the model simulates well two analysed structures in the south of 45°S: one at the longitudes of 70° to 30°W, and another in the 15° to 5°W.

The study of Wainer et al. (2003) also compared the latent and sensible heat fluxes over the South Atlantic using four different algorithms and of the NCAR CCSM model. The latent heat fluxes for the five datasets presented some similarity in the spatial pattern, but showed differences up to 80 Wm^{-2} in intensity. The simulated fluxes by NCAR CCSM model were more intense than those of the analyses for the whole South Atlantic, except for the Brazil-Malvinas confluence. The authors concluded that the sensible heat fluxes did not have any contribution to the net fluxes and did not present any comparison between the different datasets.

As can be noted in Table 1 and Figures 2 and 3, the RegCM is able to simulate both the spatial pattern and intensity for heat fluxes in good agreement with the WHOI and ECMWF analyses. These results indicate a better performance of RegCM than NCAR CCSM model and this can be associated to several aspects: greater horizontal resolution, the algorithm used, the use of ideal boundaryes conditions, etc.

Figure 4 shows latent and sensible heat fluxes monthly climatology for the three sub domains presented in Figure 1 and to the South Atlantic. In this figure, two important characteristics can be identifyed: the annual cycle and the latitudinal dependence of the fluxes. It can be noted that the latitude increases the simulations are closer to the analyses.

The latent heat fluxes in region 1 (Figure 4 a) from January to April are more intense than those in the analyses. However, for the other months, the intensity is closer to the ECMWF. In the region 2 (Figure 4 b) the simulated fluxes are stronger than those of the analyses between January and February but after March, they are greater than in the WHOI and smaller than in the ECMWF. In region 3 (Figure 4 c), the model and WHOI time series are almost coincident, but they are less intense than in the ECMWF. For the entire domain (Figure 4 d), the intensity of the latent heat fluxes is near to the WHOI. The maximum fluxes occur in May in the simulation and in June in the analyses; the minimum fluxes occur in November in the simulation and in December in the analyses.

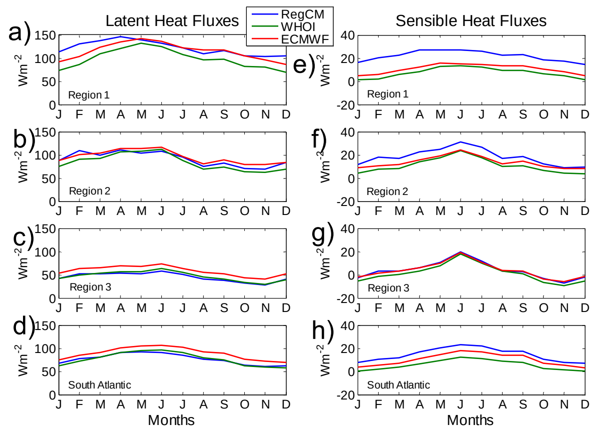

Figure 4. Climatological monthly average of the latent and sensible heat fluxes for the RegCM (blue line), WHOI (green line) and ECMWF (red line). From 1990 to 1999 to the regions indicated in figure 1 and the entire South Atlantic

The simulated sensible heat fluxes annual cycle (Figure 4 e,f,g,h) for each sub domain and over the South Atlantic agree with the analyses.

Both, simulation and analyses show a period with constant fluxes between August and September. However, large differences in intensity between simulation and analyses are founded in the region 1 (Figure 4 e). Comparing region 1 (Figure 4 e) with 2 and 3 (Figure 4 f and g) is apparent that these differences decrease with increase of the latitude. At the region 3 (Figure 4 g) the RegCM results almost match the ECMWF. For the entire domain, the fluxes simulated are more intense than analyses, but it is closer to the ECMWF.

4 Conclusions

This work evaluates the seasonal climatology (summer and winter) of the latent and sensible heat fluxes simulated by RegCM from 1990 to 1999 over the South Atlantic. The validation of the model was accomplished by comparing the simulated climatological values to WHOI and ECMWF analyses. The simulated latent heat fluxes seasonal average agree better to the analyses than the sensible heat fluxes. The spatial pattern of the simulated turbulent fluxes in the summer and winter also show good agreement with both WHOI and ECMWF analyses, mainly in the region of the Brazil-Malvinas confluence. It was well reproduced in intensity as well as in spatial pattern.

According to the results presented it can be concluded that the RegCM simulates satisfactorily the latent and sensible heat fluxes. The difference among seasonal latent heat fluxes simulated by RegCM and analysed is lower than 16 Wm^{-2}. This represents a better result than that obtained by Wainer et al. (2003) also over South Atlantic that founded a difference of the 80 Wm^{-2} among the NCAR CCSM model and four different algorithms.

5 Acknowledgments

The authors would like to acknowledge FAPESP - 04/02446-7 and CNPq - 475281/03-9 for the financial support. WHOI and ECMWF for providing the dataset, and Weather and Climate Physics Group of the ICTP (International Centre for Theoretical Physics) for the RegCM3 availability. Tércio Ambrizzi has also received partial support from FAPESP, CNPq, and IAI (CRN055).

6 Referências

Beljaars, A. C. M., 1995: The Parametrization of Surface Fluxes in Large Scale Models under Free Convection. *Quart. J. Roy. Meteor. Soc.*, **121**, 255-270.

Beljaars, A. C. M., 1997: *Air-sea interaction in the ECMWF model*. Proc. Seminar on Atmosphere-Surface Interaction. Reading, United Kingdom, ECMWF, 31-52.

Elguindi, N., X. Bi, F. Giorgi, B. Nagarajan, J. Pal, and F. Solmon, 2004: *RegCM Version 3.0 User's Guide*. PWCG Abdus Salam ICTP, 48 pp.

Fairall, C. W., E. F. Bradley, D. P. Rogers, J. B. Edson, and G. S. Young, 1996: Bulk Parametrization of Air-Sea Fluxes for Tropical Ocean-Global Atmosphere Coupled-Ocean Atmosphere Response Experiment. *J. Geophys. Res.*, **101** (C2), 3747-3764.

Fairall, C. W., E. F. Bradley, J. E., Hare, A. A. Grachev, and J. B. Edson, 2003: Bulk Parameterization of Air-Sea Fluxes: Updates and Verification for the COARE Algorithm. *J. Climate*, **16**, 571-591.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S. –K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter, 2002: NCEP-DOE AMIP-II Reanalysis (R-2). *Bull. Am. Met. Soc*., **83**, 1631-1643.

Kuo Y. –H., R. J. Reed, and S. Low-Nam, 1991: Effects of Surface Energy during the early Development and Rapid Intensification Stages of Seven Explosive Cyclones in the Western Atlantic. *Mon. Wea. Rev*., **119**, 457-476.

Neiman, P. J., and M. A. Shapiro, 1993: The Life Cycle of an Extratropical Marine Cyclone. Part I: Frontal-Cyclone Evolution and Thermodynamic Air-Sea Interaction. *Mon. Wea. Rev*., **121**, 2153-2176.

Nuss, W. A., and R. A. Anthes, 1987: A Numerical Investigation of Low-Level Processes in Rapid Cyclogenesis. *Mon. Wea. Rev*., **115**, 2728-2743.

Reboita, M. S., R. P. Rocha, and T. Ambrizzi, 2005 a: Evaluation of the Latent and Sensible Heat Fluxes Simulated by RegCM3 over the South Atlantic from 1990 to 1994. *CLIVAR Exchanges*, **35** (10 – 4), 58-60.

Reboita, M. S., R. P. Rocha, and T. Ambrizzi, 2005 b: Climatologia de Ciclones sobre o Atlântico Sul Utilizando Métodos Objetivos na Detecção destes Sistemas. In: *IX CONGREMET*, Congresso Argentino de Meteorologia, Buenos Aires, AR, October 3-7, 2005.

Reynolds, R. W., and T. M. Smith, 1995: A High Resolution Global Sea Surface Temperature Climatology. *J Climate*, **8**, 1571-1583.

Uppala, S.M. et al., 2005: The ERA-40 re-analysis. *Quart. J. R. Meteorol. Soc*., **131**, 2961 3012.

Wainer, I., A. Taschetto, J. Soares, A. P. Oliveira, B. O. Bliesner, and E. Brady, 2003: Intercomparison of Heat Fluxes in the South Atlantic. Part I: The Seasonal Cycle. *J. Climate*, **16**, 706-714.

Yu, L., R. A. Weller, and B. Sun, 2004: Mean and Variability of the WHOI Daily Latent and Sensible Heat Fluxes at in Situ Flux Measurement Sites in the Atlantic Ocean. *J. Climate*, **17**, 2096-2118.

Zeng, X., M. Zhao, and R. E. Dickinson, 1998: Intercomparison of Bulk Aerodynamic Algorithms for the Computation of Sea Surface Fluxes Using TOGA COARE and TAO Data. *J. Climate*, **11**, 2628-2644.