A multisatellite data study of the interactions of Hurricane Catarina (2004) with the mesoscale structures of the Southwestern Atlantic Ocean upper-layer

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Abstract. A detailed study of boundary layer processes which occurred during the evolution of the first recorded Hurricane Catarina in March 2004 was made feasible by the large and disparate global-scale satellite data sets made available by several organizations at less than 50 km resolutions. Specifically, the high resolution multi-satellite-derived products included three microwave-based SST datasets, multi-satellite collinear data of sea surface height (SSH) anomalies, significant wave heights and wind speeds, four Quikscat ocean surface wind vector products (including the 12.5km resolution swath data), daily fields of absolute objectively analysed SSH and corresponding upper-layer geostrophic currents, and additionally TRIMM-based precipitation data and ocean weekly vertical profiles of temperature and salinity obtained from Argo floats. Analysis of daily displacements and abrupt variations in surface intensity of Catarina winds with the upper-layer water gave the following results: (1) The track of Catarina was over homogeneous sea surface temperatures (SST) of 24°C; (2) Catarina intensified over four geostrophic Warm Core Rings (WCRs) detected and mapped by altimetry but not by SST; (3) regressed SSH with the depth of the 17°C isotherm permits daily estimates of upwelling-downwelling cells of subsurface isotherms forced during the passage of Catarina over WCRs, suggesting that the role of ocean heat storage is more important than SST for predictions of intensifications. The observed ocean perturbations reached deeper than the thermocline depths, the air-sea interactions being comparable to those of strong hurricanes.

Keywords: multisatellite altimetry, hurricane, warm core rings altimetria multisatelite, furacões, vórtices

1. Introduction

The cyclone Catarina developed between March 19 and 28 2004 near the Brazilian coast (25-29°S) and became the first documented hurricane in the South Atlantic Ocean (DIAS et al., 2004; PEZZA; SIMMONDS, 2005; MCTAGGART-COWAN et al., 2006; BONATTI; RAO; DIAS, 2006; FILHO et al., 2010). In addition to the damage it caused on land, this cyclone has two unique aspects: it formed in a region previously thought to be hurricane free, and it took place over SSTs of 24°C-25°C, slightly cooler than the 26°C usually known to be the minimum SST required for the intensification of tropical cyclones into a hurricane status. While the initial phases of Catarina seemed to be well accounted by atmospheric processes only, all forecast models grossly underestimated its maximum observed intensity (e.g. the eye's low surface pressure was lower than predicted) and gave conflicting trajectories (DIAS et al., 2004).

On the other hand, Catarina developed in an oceanic area with a conspicuous subsurface ocean mesoscale eddy channel (EC) around 30°S, first discovered with GEOSAT (GEOdetic

SATellite) altimetry data (FORBES et al., 1993). Could the missing link which prevented a skillful forecasting of the anomalous intensification of Catarina be due to the lack of knowledge of the presence of this subsurface EC with which it could have interacted, in analogy to, e.g., supertyphoon Maemi or hurricane Opal and Katrina?

The present work is a overview of our paper (VIANNA et al., 2010) just published in *Journal of Geophysical Research*. We showed that daily intensity variations of Catarina occured after its passage over Warm Core rings (WCRs), which were quiescent before and after its passage, but were suddenly deformed during interaction. A synergy of several high-level data sets obtained from orbital microwave cloud-penetrating sounders (three satellite altimeters and four QuikScat scatterometer products) and three high resolution SST products has been used. We also used the GRACE-based/altimeter-derived MDT for estimates of absolute geostrophic current, and vertical temperature/salinity profiles from ARGO floats to support the subsurface ocean analysis

2. Data sets

2.1. Sea Surface Height, Waves and Wind Speeds

We used sea surface height anomaly (SSHA), significant wave height (SWH) and wind speed datasets aquired by satellite altimeters (ERS2/ENVISAT, JASON-1, GFO), distributed by the NRLSSC (Naval Research Laboratory at Stennis Space Center). These datasets span from January 2003 to December 2005. Data from each satellite has been processed with the standard altimetric corrections. The SSHA processing includes the inverse barometer correction, interpolation onto reference ground-tracks at 1s sampling (approximately 7 km), intercalibration among the various datasets, and referencing to the NRLSSC 1993-2001 mean sea surface (MSS).

An objective daily-updated mapping of collinear SSHA data, usually of three concurrent satellites (ERS2 or ENVISAT and JASON-1 and GFO) was made. For the mapping, all SSHA collinear data passed by a quality control (QC) that includes outlier removal, interpolation of small gaps, and a low-pass filtering by Singular Spectrum Analysis (SSA), mainly to remove unwanted internal wave signatures present in the collinear data. The SSA cutoff scale is 80 km, since we are interested only in the meso and large scales.

The gridded fields have a spatial resolution of 1/8°× 1/8°. It were computed by use of a binned space-time Gaussian covariance function with decorrelation scales of 150 km in latitude and longitude and 15 days in time. The grid limits are 55°W-29°W and 33°S-22°S. These SSHA analysed fields were then summed to the high-resolution 0.1°× 0.1°EGM08-based MDT (linearly interpolated to 1/8°× 1/8°) (VIANNA; MENEZES, 2010) to obtain the daily Absolute Dynamic Topography (here denoted as SSH), as a proxy for the upper thermocline depth field in high spatial resolution.

2.2. Sea Surface Temperatures

Three different higher-resolution daily gridded sea surface temperature (SST) products are used, all spanning the period between March 1 and 31 2004. The first dataset is the daily optimally interpolated microwave SST (MW-OI) made available by Remote Sensing Systems, Inc (REMSS). It is a daily grid with spatial resolution of 0.25°× 0.25°based on the AMSR-E (Advanced Microwave Scanning Radiometer) from the EOS-NASA AQUA satellite and on the TMI/TRMM (Microwave Imager/Tropical Rainfall Measuring Mission) sensors. The second is the newest Reynolds blended Objetively Interpolated SST based on the AVHRR (Advanced Very High Resolution Radiometer) and AMSR-E sensors. The last dataset is from the US Navy MODAS-2D (Modular Ocean Data Assimilation System) with a higher spatial resolution of

0.125°× 0.125°.

2.3. Temperature and Salinity profiles from ARGO floats

We use the temperature and salinity profiles collected by ARGO free drifting subsurface floats. The ARGO profiling float typically measures the temperature and salinity in the upper 2000 m ocean at 10-day intervals when it rises to the surface.

In our region there are profiles available since June 2003, and we choose all profiles from this date to December 2005. A quality control against outliers, spikes, lack of consistency, etc, was subsequently performed. Various parameters were retrieved from these ARGO profiles: the mixed layer depth (MLD), the depth of 17°C isotherm (D17), the heat content of the mixed layer (Q_{ML}), and the total D17-to-surface (Q_{D17}) columns. The MLD was determined as the depth where the potential density changes by 0.125 kg/m^3 relative to the one at 10 m depth. The heat content was computed as

$$Q_h = \int_{-h}^{0} \rho c_p (\theta - \theta_{-h})\, dz \tag{1}$$

where ρ and c_p are the depth-dependent sea water density and heat capacity, both computed from potential temperatures (θ), salinities and pressures. θ is referenced to the surface, and $-h$ is the mixed layer or D17 depths.

2.4. Upper layer thickness

The general availability of ARGO floats in the study area since 2003, surfacing every 10 days, with the daily high resolution SSH fields constructed for the period, makes feasible the construction of a data set of upper layer thickness through regressions between upper thermocline isotherm depths and SSH, since the varying SSH field largely reflects changes in the thermocline depth. We chose the depth of the 17°C isotherm as the parameter representing the lower limit of the upper ocean thermally active layer. The regression between the D17 from ARGO with satellite-derived SSH was computed at a 95 percent confidence level and gave the equation 2, with a correlation of 0.45:

$$\widehat{D}17(\mathrm{m}) = -42.66(\pm 22.12) + 2.55(\pm 0.64) * SSH(\mathrm{cm}) \tag{2}$$

2.5. Wind Velocity and Stress Fields from Quikscat

We used Seawinds ocean surface vector wind (OSVW) products distributed by two research groups, one from the REMSS and the other from the PODAAC/JPL/NASA. The REMSS products are made available in two processing levels: level-3 (version 3a) and level-2B. The level-3 consists of global gridded 0.25°× 0.25°OSVW. In the Catarina region, the ascending pass is around UTC 09:00 (AM) and the descending one at UTC 19:00-20:00 (PM). The level-2 product provides OSVW in swaths that are 1800 Km wide and have a nominal spatial resolution of 25 Km. The JPL products are also distributed in the same two processing levels. The level-3 dataset has the same resolution as the REMSS and the level-2B is available in two resolutions: 25 Km and 12.5 Km.

From OSVW fields we calculated the corresponding wind stress using the bulk formula $\tau = \rho_a C_d U_{10}^2$, where ρ_a is the density of air, C_d is the drag coefficient and U_{10} is the wind speed at 10 meters. The C_d adopted here is the same one used by (OEY et al., 2007)

$$\begin{aligned} C_d * 10^3 &= 1.2, U_{10} \leq 11 \text{ m/s} \\ &= 0.49 + 0.065 * U_{10}, 11 < U_{10} \leq 19 \text{ m/s} \\ &= 1.364 + 0.0234 * U_{10} - 0.00023158 * U_{10}^2, \\ & \quad U_{10} > 19 \text{ m/s} \end{aligned}$$

3. Results

In March 2004, inside the Catarina region, there were only four ARGO floats, all placed between 30.5°-32.5°S and 33°-48°W. These floats gave ten good vertical temperature profiles, eight being before Catarina (March 7, 8, 17, and 18), one during (March 27) and one just after the storm (March 28). The near surface temperatures measured by these floats show that SSTs in March 2004 were between 22.04 and 24.17°C. But, only two floats gave profiles immediately before, during and at the end of Catarina. We call these two surface positions of A1 and A2 (see Figure 1).

Figure 1a shows the SST distribution on March 19, immediately before Catarina was formed. Two important facts can be observed: (1) Except for the SST tongue centered at 44°W, all SSTs were below 26°C south of 26°S. This means that Palmen precondition for hurricane genesis fails in the Catarina case as noted by (MCTAGGART-COWAN et al., 2006). (2) There is no definite signature of mesoscale ocean features in the vicinity of that track, except for the tongue centered at 44°W. These partial results suggest that intensification cannot be ascribed to parameterizations based on SST alone.

When we look at the distribution of SSH the situation is radically different as can be observed in Figure 1b. Now we can see clear eddy structures present under the future Catarina track. The most notable are three WCRs in a ridge-like distribution located around 27-31°S and 40-45°W (WCR-1, WCR-2 and WCR-4 in Figure 1b), and an eastern WCR centered at 30°S-36°W (WCR-4). These 200-300 km features were present almost without change since the end of February 2004.

On March 20 AM, the wind field do not display any cyclone signature yet. But, on March 20 PM the surface wind field organizes into a cyclonic circulation, centered at 26.5°S, 44°W. The south winds strengthened over the 200 km width warm 26°C ocean SST tongue and also over the deep WCR-1, where the D17 maximum depth was 170.5 m.

One standard and useful oceanographic measure of the direct effect of wind stresses on upper-layer ocean structure is the Ekman Pumping (vertical) velocity W_e. If the surface (Ekman) wind-forced horizontal water transport is divergent, water from below must replace the displaced surface water. If the water pumped up by the horizontally-moving cyclonic wind has the same temperature as on the surface, which is the case if the MLD is large enough in the presence of a WCR, the surface cooling by subsurface water upwelling will be remain small. Based on the Quikscat wind stresses, we have computed the W_e fields. On March 20 PM, in the W_e map a strong upward Ekman Pumping velocity W_e greater than 30 m/day maxima over the 26°C SST tongue/WCR-1 complex can be seen.

On March 21 the storm progresses to the southeast from 27.5°S, 42°W to 30°S, 39.5°W. This displacement takes Catarina, which is then over a 25°C waters, to a region of lower SST (24°C). Catarina becomes a little disorganized while it progresses southeastward on March 22 AM, with its center away from any WCR. This situation changes on the afternoon pass of this day, just when it encounters the largest and equally deep WCR, WCR-2, at 30°S, 36°W, with D17 being 160 m at its center, and more than 400 km in diameter. The cyclonic wind becomes re-organized into a circularly symmetric closed velocity contours, with speeds of 22 to 24 m/s. The

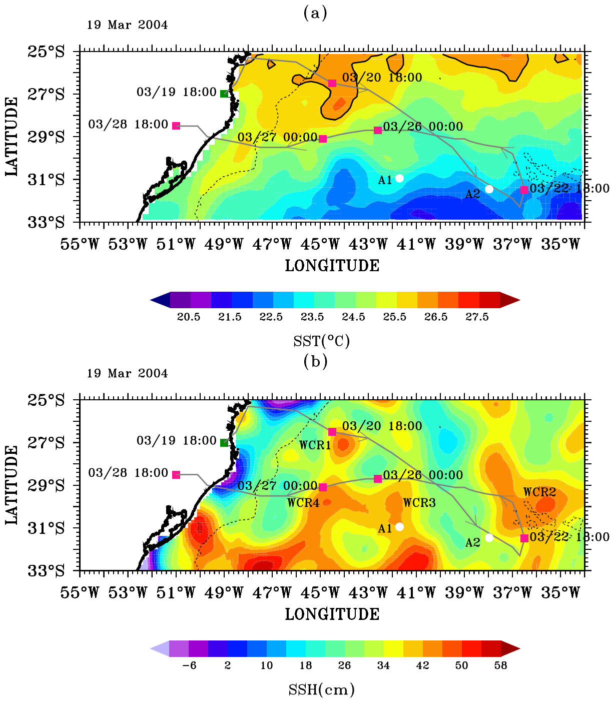

Figure 1: SST and SSH on March 19, one day before the onset of the Catarina storm, overlaid with the future centroid track of Catarina: (a) Reynolds SST exhibiting only one tongue with 26°C over a background of lower temperatures south of 27°S; (b) the SSH data showing the complex ocean topography featuring four main WCR signatures traversed by the track, with two nearby ARGO floats at positions A1 (over WCR-3) and A2 away from any WCR. Red squares denote daily storm center positions, dotted line is the 1000 m depth isobath.

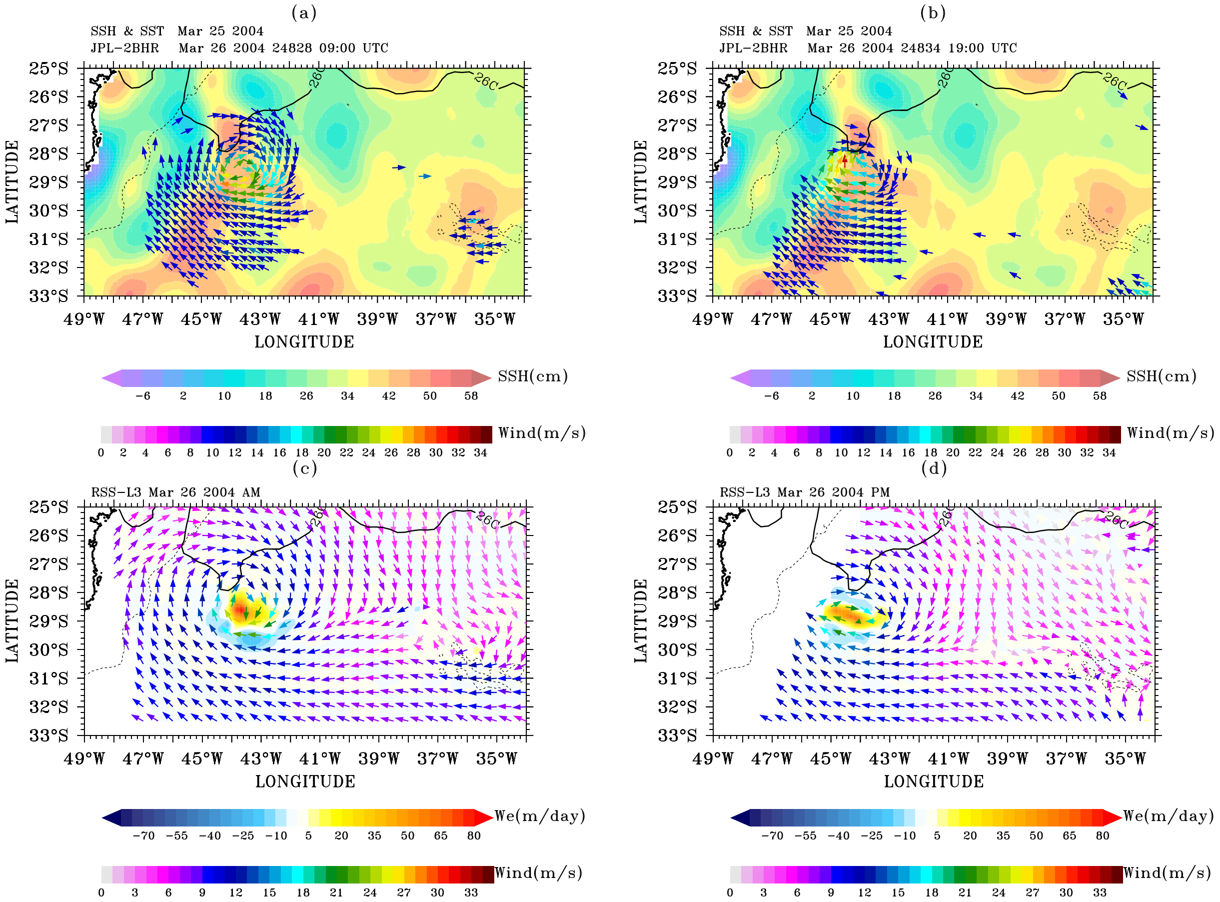

Figure 2: (a) and (b), Quikscat JPL-2BHR wind vectors, March 26 AM (PM) overlayed to SSH and the 26°C SST contour from Reynolds, vectors with U >10 m/s are plotted; (c) and (d): W_e (color) computed from RSS-L3 and corresponding wind vectors. The large sudden intensification of Catarina concentrated in the south limb due to its swift westward displacement, and corresponding intense W_e patch. SSH and SST from one day earlier, dotted line for the 1000 m isobath.

upwelling cell becomes concentrated at 31°S, 37°W, with an increased strength of 40-50 m/day. It is at this time (March 22 PM) that the cyclone track abruptly changes direction northwards, but still maintaining itself over WCR-2.

On March 26 AM Catarina suddenly intensifies, with maximum surface winds forming a westward patch of 27-30 m/s on its southern limb at 29°S, 43.5°W, and reaching 30.7 m/s in JPL-2BHR, (Figure 2a). The wind field symmetrically spans the large deep thermocline region of about 400 km width with D17 being more than 160 m depth, comprising the cores of WCR-1, WCR-3 and WCR-4. The circular upwelling cell has Ekman vertical velocity of more than 80 m/day on the eye, and more than 140 m/day in JPL-2BHR. In the afternoon pass, the maximum wind speed attains 34.42 m/s (Figure 2b). According to the JPL-2BHR OSVW, Catarina reaches category-1 on Saffir-Simpson hurricane scale on March 26 PM. The W_e is more than 100 m/day in JPL-2BHR, and slightly displaced to the west at 44.5°W. The eye is now at 29°S, 44.5°W.

It is considered that Catarina attains a Category 1 hurricane status on March 26 and maintain this status during March 27. Although there is no Quikscat pass on March 27 AM, on 27 PM the Quikscat OSVWs show a small maximum westward wind patch (50 km width) of 30-32.5 m/s at 29.5-30°S and 48°W, already over the continental shelf. In the RSS-2B product, the intensity field exhibits a maximum wind speed of 34.67 m/s. Unfortunately, on March 27 PM, all Quikscat products show cross-track vector winds that are a known sign of rain contamination in the Ku-band. It is important to mention here that SST is still not larger than 25°C in all regions south of 28°S.

One way to evaluate the rapid impacts of Catarina on the ocean is by computing differences from initial and final ocean state variables. We computed the δSST map as the change of SSTs between March 19 and 28. We notice the general prevalence of negative δSST, the maximum amplitudes being around 1.5°C, with a leftward bias. In the vicinity of the Catarina's loop the δSST is slightly positive (less than +0.5°C). On the continental slope, where the slope bottom cooler water is forced to upwell, the SST negative difference presents a blob with the maximum amplitude observed during the Catarina lifetime of 1.5°C at 30°S. Over the WCR-1, WCR-3 and WCR-4, corresponding to the fast displacement speed of Catarina, the amplitude of the mean cooling is between -1.2°C and -0.2°C, while for the smaller speeds over WCR-2 δSST is slightly positive. We also computed the changes in D17 in the same 8-day period as the δSST, with the predictable leftward biased mean upward D17 difference. Over the four WCRs we found on average an upward jump about 20 m.

4. Conclusions

The Catarina genesis (March 20), its sharp changes in surface structure (March 23) and its sudden intensification (March 26-27) are clearly related with its higher speed winds crossing over the deeper D17 isotherm mesoscale structures related to the WCRs. Its vigorous interactions with the water column goes down to 170 m depth, which is a result consistent with present-day knowledge of air-sea interactions under tropical cyclones up to Category 5.

The main goal of this work was to establish a rigorous oceanographic-based data analysis of the Catarina hurricane. The results suggest that dynamical ocean processes need to be accounted for in traditional analysis and prediction models. It is believed that the Catarina transition was primarily initiated by the atmospheric blocking (PEZZA; SIMMONDS, 2005; MCTAGGART-COWAN et al., 2006), and the subsequent intensification was achived via the fundamental ocean interactions here described, although in the present work we do not attempt any modeling of the physics of the air-sea interactions.

Our results reinforce the comment of (HONG et al., 2000) that perhaps hurricane forecast models with prescribed SSTs fail to predict the observed hurricane intensification, if such models are not coupled to a high resolution ocean circulation model in the simulation. This work may be considered as a pre-requisite to a future analysis of the air-sea interaction physics during Catarina, and the formulation of a realistic storm prediction model for the southwest Atlantic ocean including both atmospheric and oceanic processes.

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