The first South Atlantic hurricane: Unprecedented blocking, low shear and climate change

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[1] In March 2004 the first-ever reported hurricane in the South Atlantic hit southern Brazil. Here we show that Catarina initiated as an extratropical cyclone in a frontal system, undergoing Tropical Transition two days later under persistent low vertical wind shear over near-average water temperatures. The trajectory derived from an automatic tracking scheme showed a rare loop before the cyclone approached the coast for a second time. The vertical structure presented anticyclonic relative vorticity above and a small 300 hPa warm core embedded in a cold area. A mid-to-high latitude-blocking index showed that the five days before the genesis were in the 0.6% first percentile of intensity considered over the last 25 years, followed by an unprecedented combination with low shear. The observed and predicted trends towards an increasingly positive phase of the Southern Annular Mode in global warming scenarios could favor similar conditions, increasing the probability of more Tropical Cyclones in the South Atlantic. **Citation:** Pezza, A. B., and I. Simmonds (2005), The first South Atlantic hurricane: Unprecedented blocking, low shear and climate change, *Geophys. Res. Lett.*, *32*, L15712, doi:10.1029/2005GL023390.

1. Introduction

[2] Tropical cyclones (TCs), hurricanes or typhoons are generic terms for synoptic-scale low pressure systems without fronts, occurring over tropical or subtropical waters with organized thunderstorm activity [*Anthes*, 1982; *Holland and Lander*, 1993]. Their typical diameter is 300–800 km, with a minimum central pressure around 950 hPa but dropping below 880 hPa in some extreme cases [*Hoarau*, 2000]. By definition, a TC must have sustained winds greater than 33 m/s to be classified at least as a weak hurricane (category I), according to the Saffir-Simpson scale.

[3] Sea Surface Temperatures (SSTs) warmer than 26.5°C and Environmental Vertical Wind Shear (EVWS, defined as the magnitude of the difference between the 200 and 850 hPa vector winds) lower than 8 m/s offer the ideal conditions for TC development, given that the large scale humidity and the cyclonic vorticity are sufficiently high as usually found in easterly waves [*Gray*, 1968; *Zehr*, 1992; *De Maria et al.*, 2001; *Gallina and Velden*, 2002; *Davis and Bosart*, 2003]. The term TT for Tropical Transition [*Hart*, 2003; *Davis and Bosart*, 2003], as opposed to ET for Extratropical Transition [*Hart*, 2003; *Jones et al.*, 2003], refers to an initial Extratropical Cyclone (EC) changing into a TC.

[4] Not a single South Atlantic hurricane case had ever been documented before March 2004, although it has been suggested that at least two very rare cases of weak TCs below the hurricane strength may have happened after the satellite era [*Silva Dias et al.*, 2004]. Here, we show that the Catarina event, which was named after Saint Catarina State in Brazil (where landfall occurred), initiated off the Brazilian coast around the 20th of March 2004 as an EC, undergoing TT three days later and reaching a category I hurricane strength under an unprecedented combination of low wind shear and strong mid-to-high latitude blocking. Emphasis is given to the large scale mechanisms associated with this event, and a possible link between the large scale anomalies and the increase in the positive phase of the most important mode of circulation in the Southern Hemisphere, the Southern Annular Mode (SAM), is discussed in terms of climate change and future Atlantic storms.

2. Data, Automatic Tracking Scheme and Methods

[5] The cyclone trajectory was obtained through an automatic procedure using the Melbourne University tracking algorithm [*Murray and Simmonds*, 1991], which is a state of the art method for diagnosing low and high pressure centers on a sphere and calculating the trajectories [*Jones and Simmonds*, 1993; *Simmonds and Keay*, 2000; *Pezza and Ambrizzi*, 2003]. All the parameters and specifications used were the same as described by *Pezza and Ambrizzi* [2003], who did an extensive calibration for the Southern Hemisphere.

[6] The tracking was calculated based on the Sea Level Pressure derived from the high resolution data (0.5° × 0.5°) from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational model. For the SST and upper level variables during the event's life cycle, data from the ECMWF operational model with a resolution of 1 × 1° was used, and for the atmospheric indices we used the National Centers of Environmental Prediction/Department of Energy (NCEP/DOE) reanalysis II dataset, with a resolution of 2.5 × 2.5°.

[7] The EVWS is defined here as the magnitude of the difference between the 200 and 850 hPa vector winds (in m/s). A shear index was defined as the average of the EVWS between 35 and 60°W along the 30°S latitude. This domain is representative of the midlatitude environment in the surroundings of Catarina's track. A blocking-like index (B) was defined as the average geopotential anomaly in the area between 47.5 and 55°S and 20 and 60°W. From a

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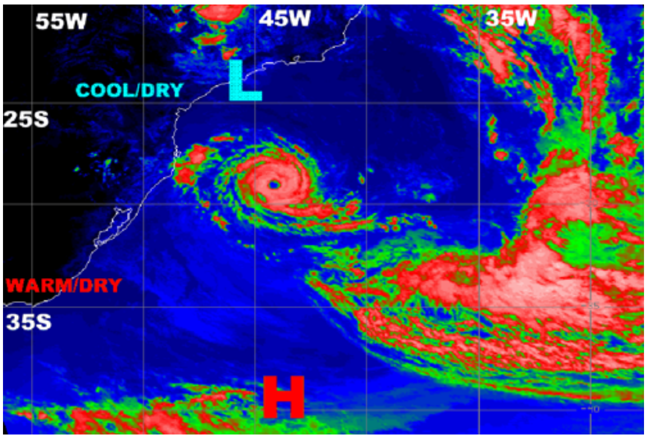

Figure 1. Enhanced satellite image from the GOES-12 Infrared channel at 16:39 UTC 26th March 2004 showing the Tropical Cyclone Catarina approaching the Brazilian coast. The letters H and L indicate the position of the upper level ridge and trough respectively associated with warm/dry and cool/dry surface air over the continent. Estimated minimum central pressure inside the eye of 974 hPa, total cyclone diameter of around 400 km and eye diameter between 25 and 40 km, with estimated sustained surface winds with hurricane I force (between 33 m/s and 42 m/s) and translational speed of 11 km/h to the west. Image available for download from the University of Wisconsin – Madison Space Science and Engineering Center (http://cimss.ssec.wisc.edu).

dynamic point of view it is expected that when this index is high the westerlies should be weaker than normal at midlatitudes in the South American sector, therefore being associated with less large scale baroclinicity (also depending on the static stability) and physically consistent with the TT [*Hart*, 2003; *Davis and Bosart*, 2003]. However, the association between the blocking index and the shear is not direct because the former pertains to conditions at higher latitudes. The temporal series were calculated for the 1979–2004 period, when the NCEP/DOE reanalysis II dataset offers a reliable climatology to put Catarina in perspective with the natural variability in the last 25 years.

3. Results

[8] Figure 1 shows the enhanced GOES-12 infrared channel satellite image for 26 Mar 2004 at 16:39 UTC, when TC Catarina reached its mature phase while approaching the southern Brazilian coast. The system first originated as a classical EC embedded in the baroclinic wave seen by the dying cold front to the northeast, but at the stage depicted in the image the ECMWF operational $1 \times 1°$ resolution data captured anticyclonic relative vorticity above 250 hPa and a small 300 hPa warm core embedded in a cold area (figure not shown), and Catarina was already being treated as a category I hurricane by NASA and other research institutions around the world. This classification was also given by the independent combination of high resolution indirect satellite estimations giving further diagnosis of the warm core [*Silva Dias et al.*, 2004], and results from operational hurricane models using a fine mesh grid (usually around one sixth of a degree) centered on the storm, as for instance the model from the Department of Meteorology at Pennsylvania State University (PSU). For the time shown in Figure 1, a diameter of around 400 km was estimated, with an eye diameter of 25 to 40 km, and sustained hurricane I force winds with a central pressure of 974 hPa given by the PSU model. Interestingly even the half degree resolution ECMWF operational data significantly underestimated the central pressure and the surface winds, and this contributed to generating much controversy at the time Catarina approached the coast.

[9] Most of the continental area appearing in the picture was cloud free due to an anomalous upper level pattern with a strong barotropic ridge to the south and a semi-stationary upper level cyclonic vortex to the north (indicated by H and L respectively), with cold, dry-stable conditions being reported in southern Brazil and warm and dry conditions in central/north Argentina. Such conditions were triggered by the passage of the frontal system before Catarina acquired a tropical signature, and contributed to create relatively stable conditions given by a small amount of convection and a southward shift of the westerlies. It is believed that these relative stable conditions help to explain the fact that only a small warm core appeared during the mature phase shown in Figure 1.

[10] Figure 2 shows the trajectory described by Catarina from the first time of its appearance with a typical extra-tropical signature, until the TT occurred and the track started to move backwards finally making landfall. The day and hour in UTC time are indicated next to some positions. The maximum SST (°C) for the period 20–28th March and the high resolution (2 km) topography over South America (elevations above 500 m) are also plotted. The TT phase [*Hart*, 2003; *Davis and Bosart*, 2003] was given by the beginning of the backwards trajectory in Figure 2, further evidenced by the development of anticyclonic relative

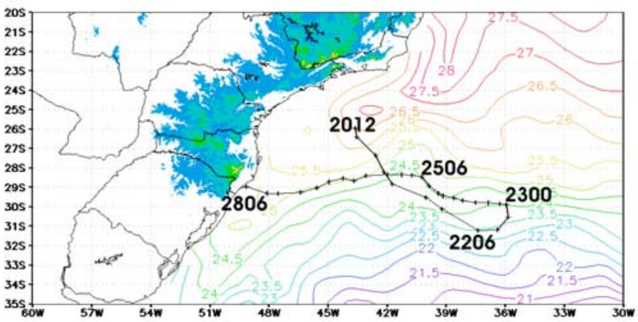

Figure 2. Tropical Cyclone Catarina's trajectory in perspective with the surrounding maximum Sea Surface Temperatures (SSTs). The South American sector is showing: I) 2 km resolution topography plotted for elevations above 500 m, with darker yellow tones indicating elevations above 1500 m; II) Tropical cyclone Catarina's trajectory as derived from the University of Melbourne automatic tracking algorithm showing the central locations every 06 hours and III) Maximum SSTs (°C) for the period between the 20th and the 28th of March. The day and hour (UTC) are indicated next to the trajectory for some selected periods.

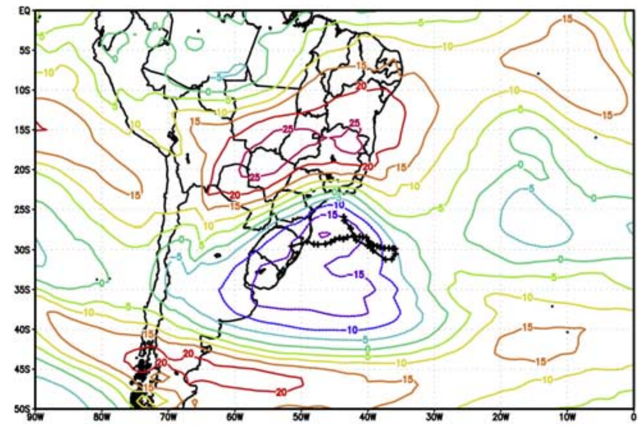

Figure 3. Environmental Vertical Wind Shear (200/850 hPa) anomaly (m/s) averaged over the 23rd–28th March 2004 period. The whole Catarina's trajectory as seen in Figure 2 is also indicated. The −15 m/s wind shear anomaly near the southern Brazilian coast approximately corresponds to an average wind shear value of 8 m/s, which is the ideal threshold for EVWS in hurricanes.

vorticity above 250 hPa and a small 300 hPa warm core as discussed before, leading to the strong tropical signature seen in Figure 1. A persistent large scale tropopause undulation, as indicated by strong 150 hPa warm anomalies (figure not shown), also formed several days before the system appeared and was associated with a large scale vortex and cold anomalies below 200 hPa, suggesting that Catarina was part of a large scale blocking-like system [*Coughlan*, 1983] with a very complex hybrid structure.

[11] The cyclone started just off the coast (26°S) over relatively warm waters (above 26.5°C) on the 20th of March. It initiated as a cold core classical extratropical cyclone embedded in the cold front shown in Figure 1 and first moved rapidly to the southeast following the baroclinic wave above. Around the 23rd, when the TT began, the trajectory changed by 180° going slowly to the northwest, approximately parallel to the first track and roughly following the 24.5°C isotherm. It then turned west and slightly southwestward when approaching the coast, and just before landfall the track changed again to the northwest, entering the continent at 29°S on the 28th at 06 UTC. Over the continent, the tracking algorithm plotted it to the southwest apparently avoiding the mountain ranges in excess of 1500 m only 50 km inland, when in reality it died out over the mountains near 28.5°S, 50°W (not shown). In terms of SST anomalies, most regions presented slightly negative values with the exception of the areas above 26.5°C near Sao Paulo and Rio de Janeiro's coast where the cyclogenesis occurred, indicating that the SSTs were not particularly favorable for TC formation.

[12] Figure 3 shows the anomaly of the EVWS magnitude averaged for the period 23rd–28th March for the South American sector. A pronounced negative anomalous shear region between 25 and 40°S and 35 and 60°W is observed lying just to the south of the cyclone track, with a local minimum shear anomaly of −20 m/s next to the place where the system made landfall. The negative 15 m/s shear anomaly roughly corresponds to mean values below the ideal threshold of 8 m/s. The vortex itself may have exerted only a very limited influence in the EVWS given Catarina's small scale and the fact that the anomalies presented a well defined large scale pattern and were present before the TT started, with negative anomalies prevailing in all longitudes around 30°S suggesting a blocking pattern to the south.

[13] Figure 4 shows the time series of the 700 hPa blocking B index (in red, right hand scale) and the EVWS index (in blue, left hand scale) using all March data for the period 1979–2004. The EVWS index is given in m/s and the B index is given in geopotential meters. A 1-2-1 time filter was applied twenty times for six hourly data in order to eliminate the very high frequency variations for visualization purposes. The horizontal lines show the maximum B threshold (in red) of +162 geopotential meters and the minimum wind shear threshold (in blue) of 9.4 m/s associated with TC Catarina, corresponding to the two arrows drawn on the map. The maximum B index occurred on the 15th of March (first arrow), i.e., five days before the cyclogenesis identified by the automatic tracking scheme, and the low wind shear period started seven days later on the 22nd, just before the TT started to occur, followed by a minimum wind shear peak around the 26th of March (second arrow), i.e., two days before landfall and when the maximum growth rate was experienced, completing the TT phase. The regression line according to the least squares method is given for the EVWS index.

[14] For the unfiltered data, the minimum EVWS index during Catarina was 7.0 m/s (only +1.8 m/s for the u-component) and the maximum B index corresponded to +181 geopotential meters. Further indicating the extreme and large scale nature of the circulation anomalies leading up to the event, we have found that the 5-point average of the B index during Catarina was exceeded for only 0.62% of the record of all Marchs 1979–2004. This shows that

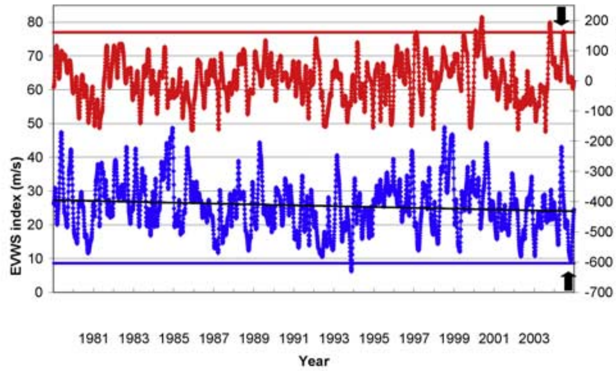

Figure 4. Time series of the blocking index B at 700 hPa and the Environmental Vertical Wind Shear (EVWS) index for all March months during 1979–2004. The horizontal red line indicates the maximum B index reached five days prior to Catarina's genesis (upper arrow), and the blue line indicates the minimum wind shear reached during the Tropical Transition phase (lower arrow). A 1-2-1 time filter was applied twenty times in order to eliminate the very high frequency variations. Data plotted every six hours.

from a climatological point of view the blocking-like pattern at mid-to-high latitudes was very intense. In addition the low EVWS phase which started seven days after the blocking peak was exceptionally long, with almost five consecutive days with below 12 m/s EVWS index during the whole time (06 hourly data) in a region subjected to high climatological shears (25.7 ± 8.8 m/s for the EVWS index). Only 0.40% of the total unfiltered six-hourly sample exhibited an EVWS index below the minimum during Catarina (0.25% for the filtered data presented in Figure 4), but such condition was only seen during March 1993 when the blocking index did not show any significant positive anomaly.

[15] Although the temporal variability in both series is high, the combination of a B index higher than Catarina followed by a wind shear lower than Catarina is not found anywhere else in the record, indicating unprecedented conditions for the whole 1979–2004 period. It is physically consistent to expect that these very anomalous large scale conditions favored the occurrence of the TT, generating the sufficiently low EVWS in the period of the year when the climatological SST is maximum and relatively close to the hurricane threshold, and in the present case when a previously high relative vorticity environment was present over the surrounding area given by the passage of a cold front.

4. Comments

[16] Speculation about threshold phenomena related to climate change is a matter which naturally arises after this unique episode [*Silva Dias et al.*, 2004], but at the present it is not clear the extent to which TC frequency will change in a warmer environment [*Royer et al.*, 1998; *Henderson-Sellers et al.*, 1998; *Walsh and Ryan*, 2000], particularly in this region which has not experienced documented TC heretofore. Our results suggest that the persistence of very unusual large scale conditions at mid-to-high latitudes was the primarily mechanism leading to the hurricane, and hence any climate change mechanism in the Southern Hemisphere increasing the chance of extremes should be addressed. Figure 4 shows that there has been a weakening of the EVWS in the area of interest over the last 25 years of about 3.1 m/s. Given the high variability expected in the area as depicted in Figure 4, this trend might be strong enough to increase the probability of events under the ideal hurricane threshold of 8 m/s, and therefore increasing the chance of more future TCs in the area during the time of the year when the SSTs are relatively close to the hurricane threshold.

[17] Recent research has also shown an increase in the positive phase of the Southern Annular Mode (SAM) during the SH summer time given from both reanalysis and station data sets [*Fyfe et al.*, 1999; *Thompson and Solomon*, 2002; *Marshall*, 2003]. Such increase has been associated with ozone losses at a certain stage [*Thompson and Solomon*, 2002], and with global warming due to greenhouse gases [*Fyfe et al.*, 1999]. During March 2004, the SAM reached its highest peak of +2.7 eight days before Catarina's genesis and three days before the peak of our blocking B index, but its value was not exceptional. The definition of our blocking index approximately coincides with the northernmost relative high pressure belt in the South Atlantic derived from the leading mode of the Empirical Orthogonal Function analysis of monthly 700 hPa height (or SAM) during 1979–2000 [*Marshall*, 2003]. It is reasonable to expect that an increasing high phase of the SAM could favor more episodes of large scale conditions similar to the one which triggered Catarina, and in particular to increase the positive anomalies in the B index. Although this may be speculative, it is also physically consistent with the slight negative trend (though not statistically significant) in the wind shear for the area of interest. Therefore there is evidence to suggest that Catarina could be linked to climate change in the SH circulation, and other possible future South Atlantic hurricanes could be more likely to occur under global warming conditions.

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