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CATARINA: THE FIRST SOUTH ATLANTIC HURRICANE AND ITS ASSOCIATION WITH VERTICAL WIND SHEAR AND HIGH LATITUDE BLOCKING

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1. INTRODUCTION

1.1 Traditional background of tropical cyclones

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.

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 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.

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1.2 The Catarina phenomenon and its implications

It has been accepted that hurricanes could not form over the South Atlantic Ocean due to a couple of main reasons, these being a very intense climatological vertical wind shear and not sufficiently warm SSTs. This concept has been consistently portrayed in text books and in the more specialized literature, being so strongly present in the day to day experience of the forecasters and climate researchers that it was difficult to accept that nature could present a different behavior.

However, changing global climate (Alexander et al 2006) has forced us to rethink the nature of the background flow against which synoptic systems (and TCs) are found. This is particularly true in the South Atlantic basin.

At the end of March 2004 the cyclone Catarina hit Brazil. This was the first documented time when a system reaching a category I hurricane strength made landfall anywhere in the South Atlantic basin. This is not to say that a phenomenon like Catarina had not existed in the past, but there is very strong evidence that at least during the satellite era this is unprecedented.

A few important questions arise after March 2004. First, what Catarina really was and how should we refer to it? Second, was Catarina a result of natural climate variability only, or could it also be related to climate change due to anthropogenic influences?

The Brazilian Meteorological Society officially agreed to call Catarina a hurricane (http://www.sbmet.org.br/internas/publicacoes/informativo/2005_07/index_en.html), in agreement with the major perception adopted by researchers from different countries. However, as expected in any case of observational unprecedented behavior, a few researchers prefer not to call it a hurricane given its hybrid structure and lack of in situ data that would be required to classify it with the same accuracy as normally done in the case of North Atlantic hurricanes.

At this stage there is no agreement as to whether Catarina is or is not related to climate change. Pezza and Simmonds (2005) suggested the former possibility in linking Catarina with a very unusual large scale pattern which had a character very similar to the highly significant observed increase in the positive phase of the most important mode of circulation in the Southern Hemisphere, the Southern Annular Mode (SAM) (Cai et al, 2005). However, more research is clearly needed.

The surrounding large scale sea surface temperature was slightly colder than normal when Catarina was formed, being slightly warmer than normal (and close to the hurricane threshold of about 26.5^{o}C) only over limited local regions. This fact contributed to puzzling the scientific community as to explain why and how Catarina developed into a hurricane-I strength phenomenon. However, as pointed out by Pezza and Simmonds (2005), some aspects of the large scale circulation which may be related to climate change could have an indirect effect on hurricane development over the South Atlantic.

Here, we show that the Catarina phenomenon, 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. METHODOLOGY

The cyclone trajectory was obtained through an automatic procedure using the Melbourne University tracking algorithm (Murray and Simmonds, 1991a,b), which is a state of the art method for diagnosing low and high pressure centers on a sphere and calculating the trajectories. This scheme was chosen because of its proven reliability in capturing the most important climatic features in the Southern Hemisphere (Murray and Simmonds 1991a,b, Jones and Simmonds 1993, Simmonds et al 1999, Simmonds and Keay 2000 a,b, Simmonds et al 2003, Pezza and Ambrizzi 2003, 2005).

The tracking was calculated based on the Sea Level Pressure derived from the high resolution data (0.5^o x 0.5^o) 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 x 1^o 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 x 2.5^o. (Uppala et al 2005).

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^{o}W along the 30^{o}S latitude. This domain is representative of the midlatitude environment in the environs 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 dynamic point of view it is expected that when this index is high the westerlies will 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 AND DISCUSSION

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 reflected in the dying cold front to the northeast, but during the mature stage prior to landfall the ECMWF operational 1x1° resolution data captured anticyclonic relative vorticity above 250 hPa and a small 300 hPa warm core embedded in a cold area, as shown by figures 2 and 3 respectively.

Due to this strong combination of evidence given by the satellite photo signature and the upper level warm core and anticyclonic vorticity given by high resolution operational data, Catarina was already being treated as a category I hurricane by NASA and other research institutions around the world before it had made landfall. This classification was also given by the independent combination of high resolution indirect satellite estimations giving further diagnosis of the warm core 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).

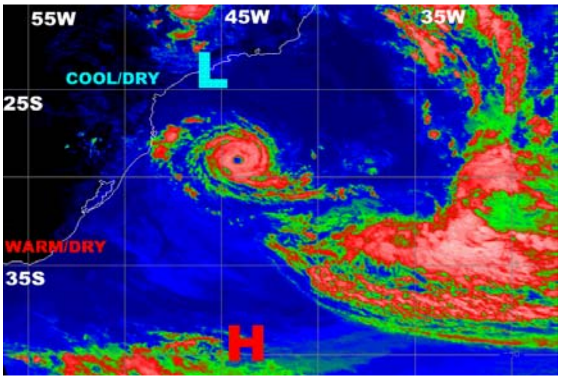

Figure 1: Enhanced satellite image from the GOES-12 Infrared channel at 16:39 UTC 26th March 2004 showing the Tropical Cyclone Catarina approaching the Brazilian coast. The letters H and L indicate the position of the upper level ridge and trough respectively associated with warm/dry and cool/dry surface 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)

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.

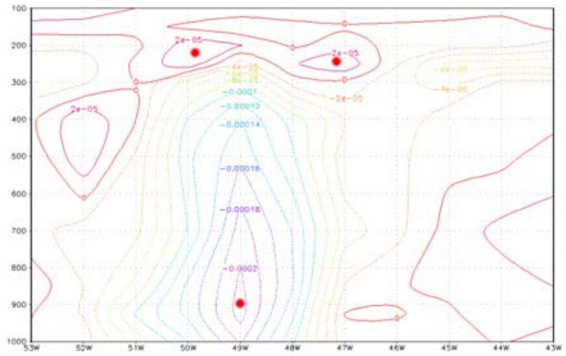

Figure 2: Relative vorticity between 1000 and 100 hPa averaged for the latitude of Catarina as given by the automatic tracking scheme during 28th of March at 06 UTC, representing the mature phase during landfall. The red dots show the anomalous centers associated with the cyclone. ECMWF operational 1x1° resolution used.

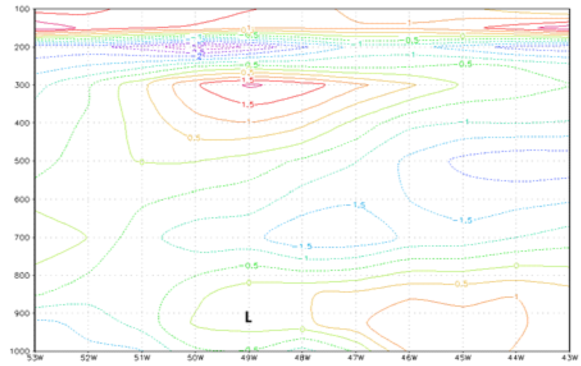

Figure 3: Temperature anomaly between 1000 and 100 hPa averaged for the latitude of Catarina as given by the automatic tracking scheme on the 28th of March at 06 UTC (between 28 and 30°S), representing the mature phase during landfall. The L indicates the position of the cyclone near the surface. ECMWF operational 1x1° resolution used.

However, after landfall occurred, station data confirmed the pressure and wind signatures typical of category 1 hurricane strength. Figure 4 shows hourly data between the 26th and the 28th of March 2004 (local time) of station pressure (elevation 135 m) and 10 m height wind speed at São Bento (28° 36' S; 49° 33' W, 135 m). This meteorological station was the closest available to the region where the eye made landfall, being about 40 km directly to the north of the eye at that time.

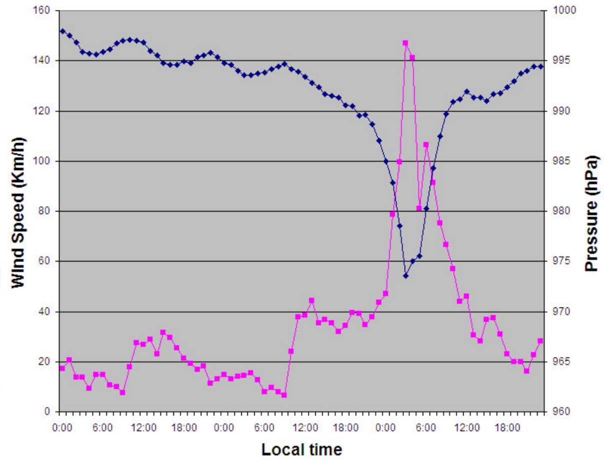

Figure 4: Wind speed (in red, left hand scale) and station level pressure (in blue, right hand scale) from the 26th of March at 0:00 local time to March 29th at 00:00 local time for São Bento (28° 36'S, 49° 33'W, 135 m).

The maximum hourly wind of more than 140 Km/h occurred at 03 am local time (easterly wind) and coincided with the lowest station pressure of about 973 hPa (elevation 135 m). At that stage the eye was found just to the west of the station, being channeled through the valley of the Pelotas River, in the mountains between Santa Catarina and Rio Grande do Sul states.

Figure 5 shows the high resolution (2 Km) topography of the region with an estimation of the final path of Catarina after it made landfall, with the real diameter of the eye prior and after landfall estimated by the full colored circles in the figure. Figure 6 shows the trajectory described by Catarina from the first time of its appearance with a typical extratropical signature, until the TT occurred and the track started to move backwards finally making landfall. The date and hour in UTC time are indicated next to some positions. The maximum SST (^{o}C) for the period 20-28th March and the high resolution topography over South America (elevations above 500 m) are also plotted.

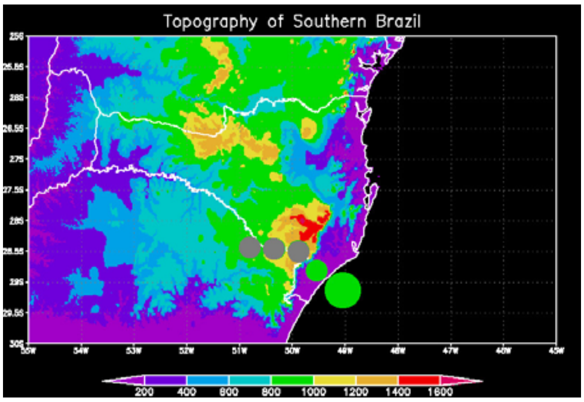

Figure 5: High resolution topography (2km) of southern Brazil showing an estimation of the final path of Catarina from just prior to and after landfall, until dying out over the mountains. The estimated diameter of the eye just prior to, and after landfall is also estimated by the size of the full circles.

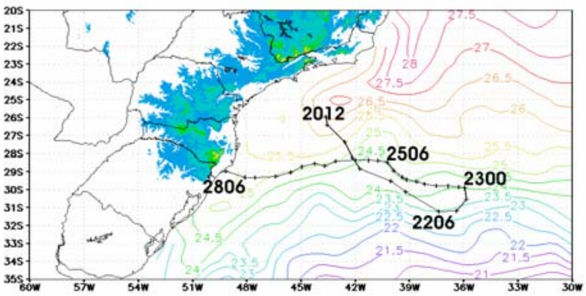

Figure 6: Tropical Cyclone Catarina's trajectory in perspective with the surrounding maximum Sea Surface Temperatures (SSTs). The South American sector is showing: I) 2 km resolution topography plotted for elevations above 500 m, with darker yellow tones indicating elevations above 1500 m; II) Tropical 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 (^{o}C) for the period between the 20th and the 28th of March. The date and hour (UTC) are indicated next to the trajectory for some selected periods.

The cyclone started just off the coast (26^{o}S) over relatively warm waters (above 26.5^{o}C) on the 20th of March. It initiated as a cold core classical extratropical cyclone embedded in the cold front shown to the north 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^{o} going slowly to the northwest, approximately parallel to the first track and roughly following the 24.5^{o}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^{o}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 about 50 km inland, when in reality it died out over the mountains as shown in figure 5.

The TT phase [Hart, 2003; Davis and Bosart, 2003] was given by the beginning of the backwards trajectory in figure 6, further evidenced by the development of anticyclonic relative vorticity above 250 hPa and a small 300 hPa warm core as discussed before, leading to the strong tropical signature seen in figure 1.

Figure 7 shows the 150 hPa temperature and 200 hPa wind anomalies averaged over the 17 – 28th March period in perspective with the Catarina's track previously seen in figure 6, indicating the environmental large scale conditions during the whole life cycle of the cyclone.

A persistent large scale tropopause undulation, as given by the 150 hPa temperature anomalies was formed several days before the system appeared and is seen in association with a large scale vortex in figure 7. This pattern was associated with 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.

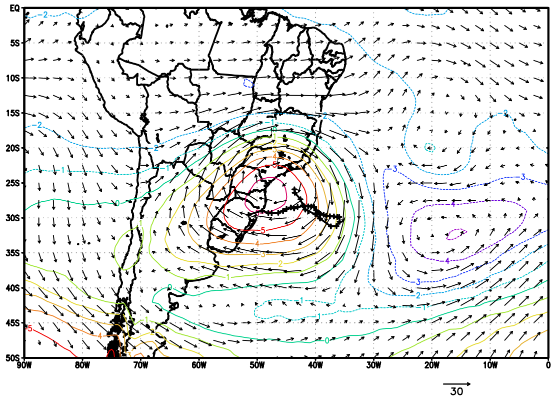

Figure 7: 150 hPa temperature and 200 hPa wind anomalies averaged over the 17 – 28th March period. The whole trajectory is also indicated. European Centre for Medium-Range Weather Forecasts (ECMWF) operational 1° x 1° data and National Centers for Environmental Prediction / National Center for Atmospheric Research (NCEP/NCAR) reanalysis climatology (1968 – 1996) used.

In terms of SST anomalies, most regions presented slightly negative values with the exception of the areas above 26.5°C near São Paulo and Rio de Janeiro's coast (figure 6) where the cyclogenesis occurred, indicating that the SSTs were not particularly favorable for TC formation.

Figure 8 shows the visible channel satellite image for the 27th of March 2004 at 15:24 local time, when the cyclone was very close to making landfall. 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 in figure 1), 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 had acquired a tropical signature, and contributed to creating relatively stable conditions given by a small amount of convection and a southward shift of the westerlies. These relative stable conditions help to explain the fact that only a small warm core appeared during the mature phase depicted in figure 8.

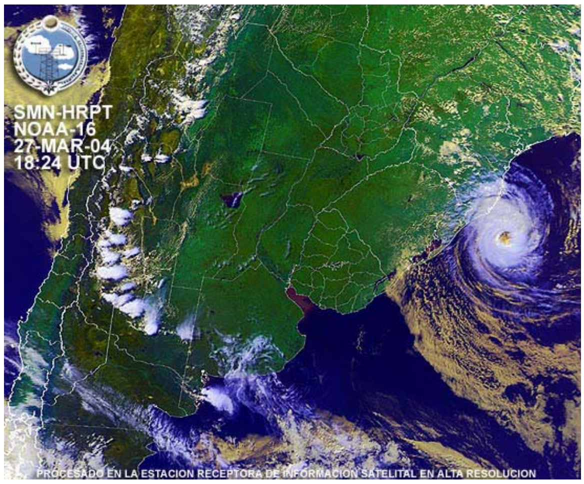

Figure 8: Visible channel satellite image for the 27th March 2004 at 15:24 local time showing TC Catarina approaching the coast and the continental large scale conditions associated. Image publicly available from: Servicio Meteorologico Nacional, Argentina (www.meteofa.mil.ar)

Figure 9 shows the winds at the upper levels of the troposphere (in colors) estimated by the quickscat sensor of the Goes-12 satellite on the 26th of March 2004 at 03 pm local time. The heavy colored arrows approximately indicate the northwesterly mid-to-upper level circulation to the northeast of Catarina in association with the dying cold front and the westerlies further south (green arrows), the anomalous southeasterly circulation just to the south of the cyclone (blue arrow) and the 300 hPa divergence immediately above Catarina (red arrows). The quick scat winds further reinforce the anomalous large scale circulation associated with the cyclone and the hurricane signature evident during the mature phase.

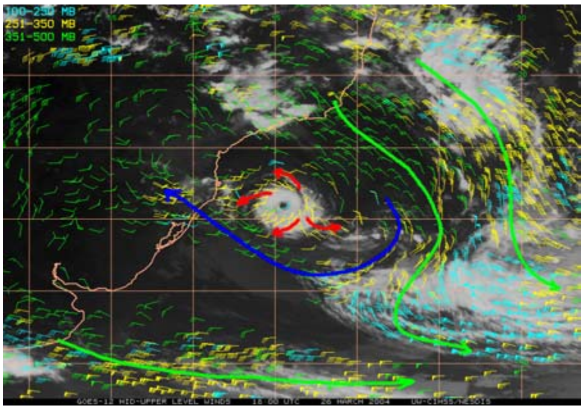

Figure 9: Satellite image for the 26th March 2004 at 15:00 local time superposed to the estimated upper level winds derived from the quick scat sensor of the GOES-12. The green arrows indicate the westerlies associated with the cold front to the north of Catarina and with the indisturbed westerly flow in the far south. The blue arrows indicate the anomalous environmental easterly 350-500 hPa winds just to the south of Catarina reaching south Brazil. The red arrows indicate the upper level divergent winds directly associated with the cyclone. Adapted from original image available for download from the University of Wisconsin – Madison Space Science and Engineering Center (http://cimss.ssec.wisc.edu)

Figure 10 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 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 the small scale of the Catarina 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.

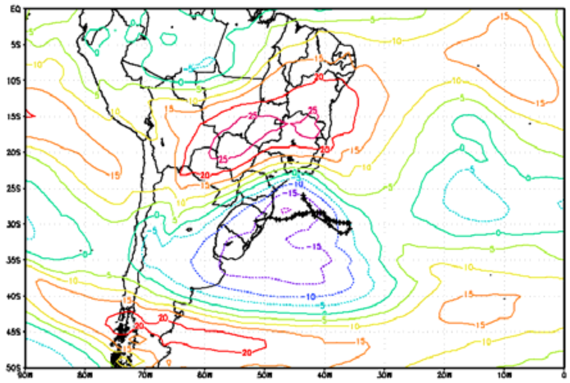

Figure 10: Environmental Vertical Wind Shear (200/850 hPa) anomaly (m/s) averaged over the 23rd – 28th March 2004 period. The whole Catarina's trajectory as seen in figure 6 is also indicated. The –15 m/s wind shear anomaly near the southern Brazilian coast approximately corresponds to an average wind shear value of 8 m/s, which is the ideal threshold for EVWS in hurricanes.

Figure 11 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 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 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.

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 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 11), but such condition was only seen during March 1993 when the blocking index did not show any significant positive anomaly.

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's 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.

Speculation about threshold phenomenon related to climate change is a matter which naturally arises after this unique episode, 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, Trenberth, 2005; Emanuel, 2005, Pielke, 2005; Landsea, 2005], particularly in this region which has not experienced documented TC in the past.

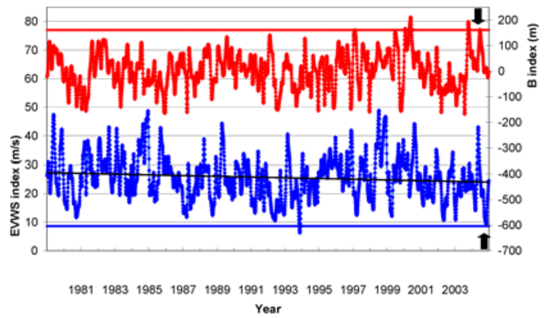

Figure 11: Time series of the blocking index B at 700 hPa and the Environmental Vertical Wind Shear (EVWS) index for all March months during 1979-2004. The horizontal red line indicates the maximum B index reached five days prior to Catarina's genesis (upper arrow), and the blue line indicates the minimum 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.

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 that could potentially change the large scale circulation should be addressed.

Figure 11 also 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, 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.

However, the problem seems to be significantly more complex than a simply direct change in the wind shear pattern over the region. Recent research has also shown that there has been a very significant increase in the positive phase of the SAM (Marshall, 2003) which has been attributed partially to ozone losses (Thompson and Solomon, 2002, Cai, 2006) and to an increase in greenhouse gases (Fyfe et al 1999, Cai et al 2006)

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. However, the definition of SAM involves an average for the whole Southern Hemisphere. The definition of our local blocking index, however, 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). Therefore, 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.

Figure 12 shows the March 200 hPa wind anomaly composite for years when the SAM index was stronger than one standard deviation above the mean during the period 1979 - 2005. The figure shows a very interesting cyclonic pattern dominating the large scale circulation in the South Atlantic which significantly resembles the pattern during Catarina shown in figure 7, therefore suggesting large scale conditions more conducive to cyclogenesis in the area when the SAM is positive.

Although this does not fully explain how a hurricane would be formed, it gives additional insight into the possible indirect connections between the large scale mechanisms directly involved with Catarina and climate change.

If global warming is changing the SAM (Cai et al 2006) it could then indirectly change the hurricane formation in the South Atlantic Ocean via the possible links described above, even without directly making the SSTs over the South Atlantic significantly warmer, as seen during March 2004. Although this may be still speculative, it is also physically consistent with the slight negative trend (though not statistically significant) in the wind shear for the area of interest to the south of where Catarina was formed.

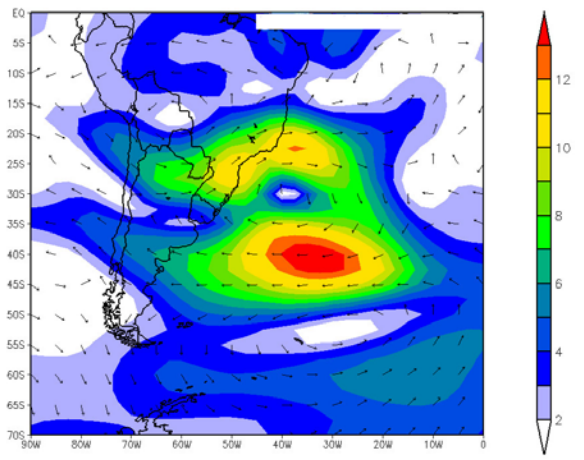

Figure 12: 200 hPa wind anomaly composite for years when the SAM index was stronger than one standard deviation above the mean, for the period March 1979 – 2005. NCEP reanalysis online used (www.cdc.noaa.gov)

We are conducting further research on this unprecedented event, and further findings will be published in the specialized literature.

3. ACKNOWLEDGMENTS

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