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SYNOPTIC AND MESOSCALE ANALYSIS OF HURRICANE CATARINA, BRAZIL

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1. INTRODUCTION

Hurricane Catarina, depicted in Fig. 1, was an unusual weather event in South America. it was formed at approximately 27° S and 49° W over warm waters of the Atlantic Ocean as a coma cloud in the wake of a decaying baroclinic wave in 19 March 2004; a classical low over high blocking that created the right environment for this hybrid hurricane to form and to develop. It caused a dozen deaths, destroyed thousands of houses, business and facilities in excess of half a billion dollar in damages mainly in Santa Catarina State, Southern Brazil.

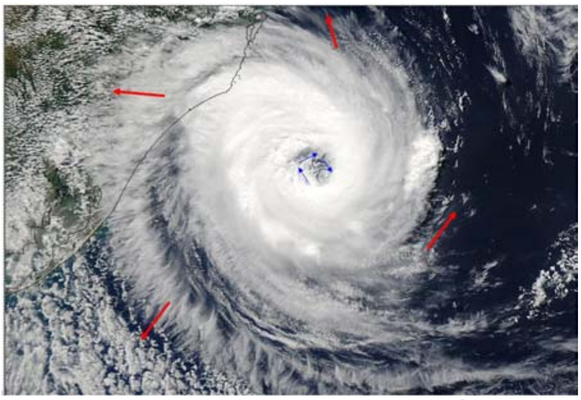

Figure 1: High resolution visible image of Hurricane Catarina obtained by the ACQUA Satellite at 1630 UTC on 27 March 2004. Coastal contours, the Atlantic Ocean and land features are apparent. Arrows indicate air motion at upper (red) and lower (blue) levels

This study presents a synoptic and mesoscale analysis of Hurricane Catarina. It might indicate a symptom of regional climate changes associated with global warming. Cold waters, high wind shear and strong subsidence are among some of the reasons why hurricanes were not likely to form over the South Atlantic Ocean.

Initially, Catarina was classified as an extra-tropical cyclone. Since this type of weather system moves eastward, should not had posed any threats in land. Later attempts to classify this weather system also included a polar low event because in the early stages of development it produced a typical comma cloud pattern, sometimes observed, for instance, over the Mediterranean Sea (Reale and Atlas, 2001).

The initial forecasts were based on model outputs and climatology with less emphasis to satellite data and conceptual models. Hurricane Catarina indicated an urgent need for more specific training programs, observing platforms and procedures to analyze and to forecast unusual and highly destructive weather systems such as the one analyzed in this work.

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2. METHODOLOGY

Most data sets used in this study are from satellite sensors onboard ACQUA, GOES-12, TRMM, NOAA-16 and METEOSAT-7. Upper level fields are from NCEP analysis and surface and lightning data from various sources in Brazil. The dynamic and thermodynamic analyses are based on the above mentioned data sets taking into account their strengths and limitations. Each variable is analyzed individually and later compared to other variables to verify consistencies and or discrepancies among them.

Five basic conditions to form and to maintain a tropical cyclone were considered in the present study (Vaquez, 2002): 1- Sea surface temperature above 26° C; 2- Low static instability; 3- Planetary vorticity; 4- Low vertical wind shear (<10 m s^{-1}); 5- Low pressure anomaly caused by gravity waves or a CISK mechanism. A conceptual model of a Southern Hemisphere hurricane was adapted from Conway (1997) to summarize the three stages Catarina underwent.

3. RESULTS

Fig. 2 shows the mean surface temperature field estimated from microwave measurements during the development stage of Catarina. The trajectory of the low pressure center was closely parallel to the 24 °C isotherm. A tongue of warmer waters is apparent near the coast due to the Brazilian current that brings warmer waters from lower latitudes. It indicates that as the low pressure center moved towards the continent, the fluxes of sensible and latent heat increased downwind the trajectory of the hurricane. The weekly average works as a low pass filter and yields a much smoother temperature field. Positive and negative small scale anomalies could be embedded in the sea surface temperature as one instantaneous field (not shown) seems to indicate a region of warmer temperatures near the area where the low pressure disturbance occurred on 22 March. Hurricanes are more likely to form where the SST is above 26 °C. The initial northward displacement of Catarina shifted southward at 43° W. Axisymmetric vortices move towards the most favorable environmental conditions to sustain its development. A continuous northward moved would lower the planetary vorticity and increase the environment wind shear (Fig. 3) both detrimental to hurricane Catarina.

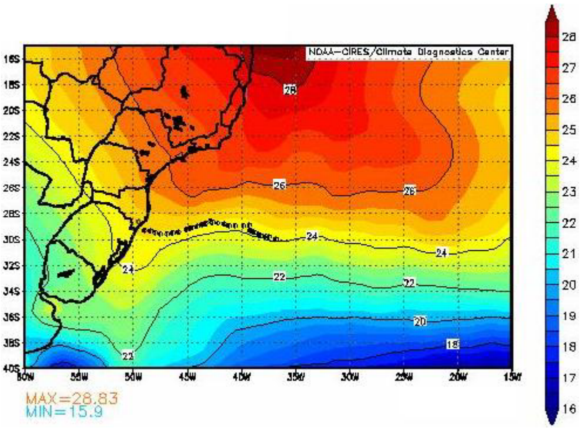


Figure 2: Field of weekly mean surface temperature between 22 and 28 March 2004. Latitudes and Longitudes are shown as well as geographic contours of Brazilian States, Paraguay, Uruguay and Argentina. Colors and isotherms indicate surface temperatures (^{o}C). Small dots indicate the position of the eastward movement of the eye of Hurricane Catarina from 0815 UTC 23 to 0245 28 March 2004. The dot over the continent indicates the location of a surface weather station in Siderópolis, Santa Catarina, Brazil. Source: CDC/NOAA.

Fig. 3 shows the vertical wind shear between 850 hPa and 500 hPa at 1200 UTC on 27 and 29 March. One can notice that the wind shear on the path of Catarina was below 5 m s^{-1} on 27 March between latitudes 25^{o} and 35^{o} S and between longitudes 35^{o} and 50^{o} W. The wind shear was stronger along the wave train formed by a ridge over Northern Argentina and a through over Southeast Brazil.

The wind shear associated with the subtropical jet on 29 March was stronger between latitudes 34^{o} and 50^{o} S with maximum intensity above 30 m s^{-1} over South Pacific. In the path of Catarina, the wind shear increased to above 15 m s^{-1} in its decaying stage.

Tropical cyclones depend on latent heat release to develop and so it is important to have high moisture contend where they form. Wind shear above 10 m s^{-1} tends to disperse moisture and inhibit the formation of tropical storms (Bracken and Bosart, 2000).

Thus, the low wind shear over the region where Catarina formed and developed was favorable. This right environment was maintained by a low over high blocking, clearly seen on 29 March (Fig. 3).

The GOES-12 IR images in Fig. 4 show the time evolution of Catarina from 23 to 29 March. Catarina was formed behind a baroclinic zone produced by an upper level through and a moving surface cold front. The cluster of clouds behind the cold front from which Catarina formed had cyclone rotation. It increased as the system developed and moved westward. The IR image at 0000 UTC on 26 March shows a distinct eye in the center of hurricane Catarina. It increased in size till landfall.

A sequence of daily average geopotential heights fields at 200 hPa from 23 to 29 March 2004 is shown in Fig. 5. The upper level trough ax was initially negatively tilted, a more favorable condition for convective activity (Bluestein, 1993). Geopotential heights were packed together around the trough with more intense winds that gradually tilted it positively. In this manner, lower angular momentum and anti-cyclonic advection were upwind of the trough. Thus, as Catarina passed through this region it experienced higher static stability and subsidence in the environment. This can partially explain why cloud tops in eye cloud were lower than expected as discussed later in this manuscript.

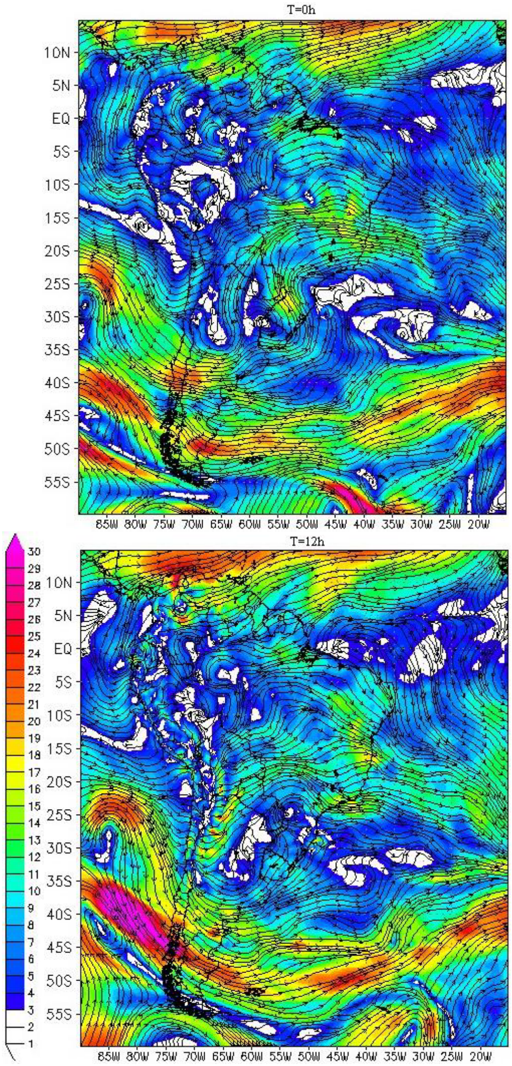


Figure 3: Wind shear filed between 850 and 500 hPa at 1200 UTC on 27 (above) and 29 (below) March 2004. Color scale indicates wind shear (m s^{-1}). Latitudes, longitudes and geographic contours are indicated.

Fig. 6 shows a sequence water vapor channel images from METOSAT-7 in the vicinity of Catarina always at 0000 UTC between 23 and 29 March. Water vapor contend was higher in the area where Catarina formed and ahead of the trough near the surface cold and warm fronts on 23 March. Mid-level air was dry behind the cold front due to an associated jet which is consistent with geopotential field (Fig. 5) and south of Catarina due to subsidence. A small region of deeper moisture is seen on March 24 associated to the region of thunderstorms from which Catarina developed. A well defined eye is seen in the WV image on 26 March and indicates subsidence in the center of the system as it organized itself. Moisture contends increase north of Catarina and around it from the east.

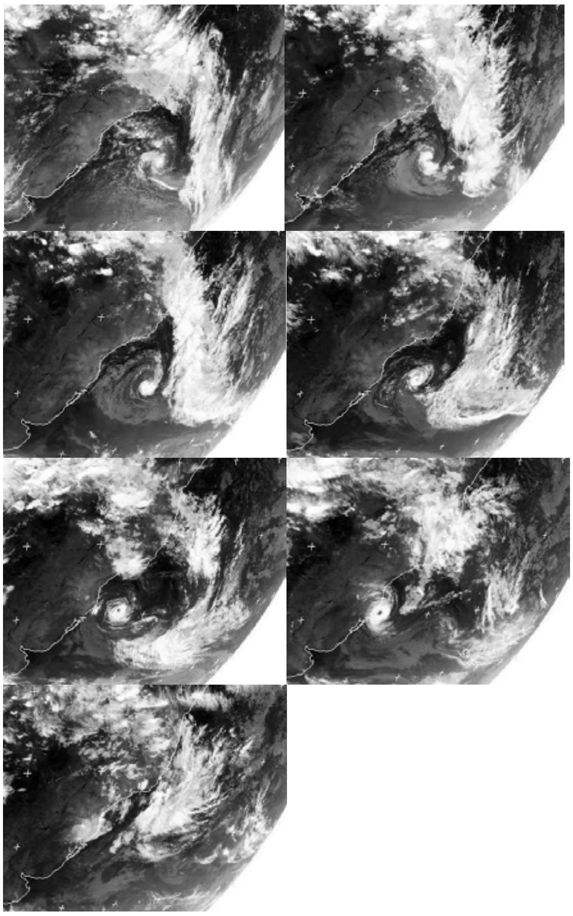


Figure 4: GOES-12 IR images at 0000 UTC from 23 to 29 March 2004. Gray scale indicates brightness temperatures from lowest (white) to highest (black).

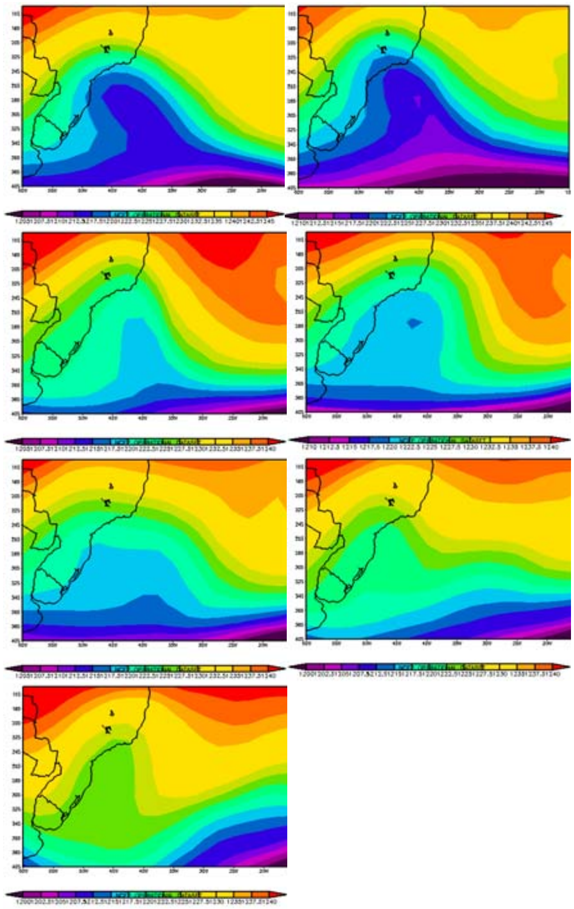


Figure 5: Daily geopotential mean at 200 hPa between 23 and 29 March 2004. Latitudes, longitudes and geographic contours are indicated as well as color scale (m). Source: NCEP.

The trough as depicted in the WV images agrees with the geopotential analysis. Catarina was initially classified as an extra-tropical circulation with non-organized convection near its center on 23 March.

Catarina evolved to a hybrid system with cyclonic rotation and deeper convection near its center on 24 March. On the next day, the system evolved to a deeper tropical storm with clouds organized in bands and estimated winds above 25 m s^{-1}. The spiraling of the system and a drier core are clearly seen in this stage.

The diameter of the eye on 26 March is 20-25 km wide. It moved westward at about 20 km hr^{-1}. The cloud bands around it were deeper and more organized. Catarina was classified as Category 1 hurricane in this stage.

The outmost cloud bands reached the continent on March 27 with strong winds and heavy rainfall. The vortex was more symmetric around the well defined cloudless and dry eye. Catarina reached its mature phase completely changed from its earlier stages.

The axisymmetric vortex core reached the coast of Brazil at 0515 UTC on 28 March as a category 2 hurricane. After landfall, friction and shear caused the occlusion of the eye and mixing that reduced moisture in its vicinity. Thus, the WV field on 29 Mach is coherent with the wind shear field (Fig. 3).

The ACQUA satellite high resolution visible image in Fig. 1 shows a deck o cirrus clouds aloft and deep clouds wrapped around the eye forming the wall cloud of hurricane Catarina. Within the eye, shallow clouds and the surface of the ocean can be seen. Shallow cumulus can be seen over the continent to the Northwest and deeper stratus over the ocean to the Southwest. Both indicate environment subsidence surrounding Catarina in the early afternoon. The red arrows in Fig. 1 indicate anti-cyclonic divergent aloft and, the blue ones, subsiding cyclonic rotation, distinctive features of a hurricane.

Fig. 7 shows satellite daily rainfall estimates between 23 and 29 March obtain with CMORPH (Joyce et al., 2004). The daily maximum precipitation associated with Catarina was fairly constant and above 100 mm day^{-1} except on 25 and 29 March. Catarina quickly dissipated on 29 March due to a significant depletion in moisture fluxes over the continent that in turn reduced the rainfall amounts.

As Catarina was organizing itself on 25 March, a tongue of colder and less humid air was brought by its circulation from higher latitudes (Fig. 6). Thus, it reduced the water contend by advection of colder and drier air. As Catarina became more symmetric, this advection from the surroundings was reduced and so the cyclonic convergence at lower levels over warm ocean waters increased the moisture contends.

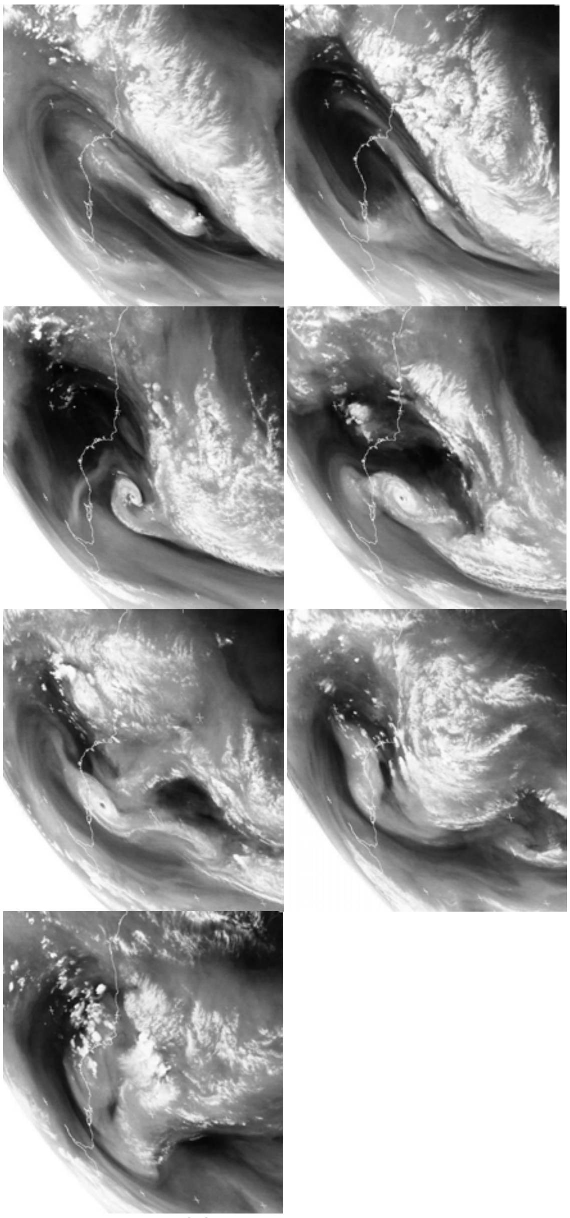


Figure 6: METEOSAT-7 water vapor channel at 1800 UTC from 23 to 29 March 2004. Gray scale indicates water vapor contend from lowest (black) to highest (white). Source: Dundee.

Hurricane Catarina produced more than 600 mm of precipitation during its life cycle in spite of its relative shallowness and lower than average sea surface temperature. Vertical profiles of heating rate by latent heat release (Barbio and Pereira Filho, 2004) indicate warming at mid and upper levels in the order of 1.0 to 2.0 K day^{-1}. Fig. 7 also shows no significant precipitation surrounding Catarina in a very larger area, especially towards the west where subsidence and higher static stability inhibited deep convection.

Fig. 8 shows estimated temperatures near the ground and approximately at 500, 350, 200 and 100 hPa at 0343 UTC on March 27 when Catarina was classified a category 1 Hurricane. Relatively warm air is found in the eye area, especially close to the ground. The estimate temperature is close to 7^{o} C in the eye and -13 o C few kilometers away. Clouds tend

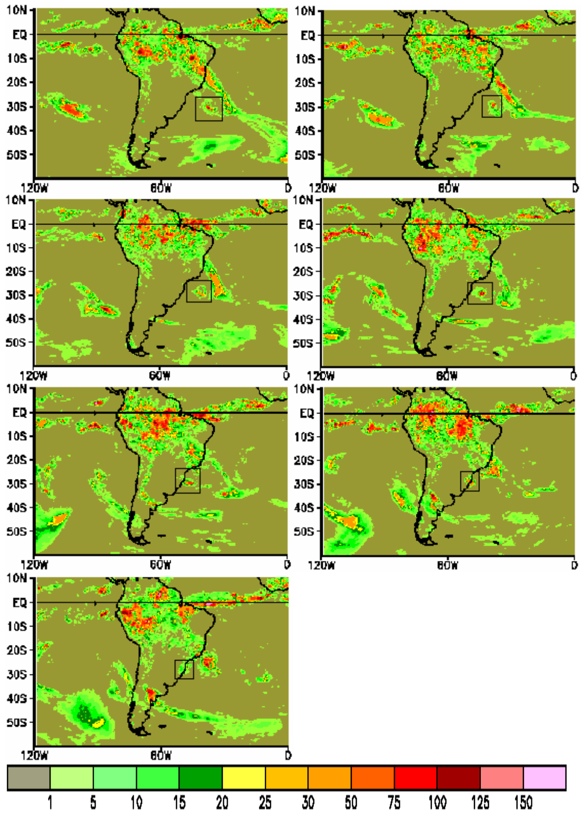


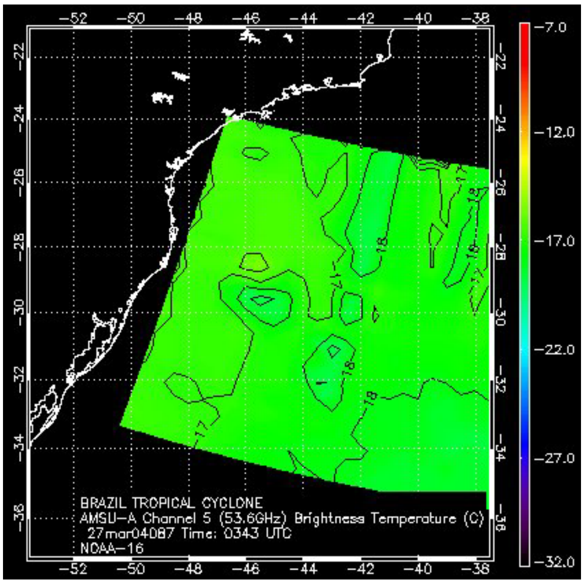
Figure 7: Daily rainfall estimation with CMORPH associated with Hurricane Catarina. Color scale in mm day^{-1}. Latitude, Longitudes and geographic contours are indicated. Source: CPC/NCEP.

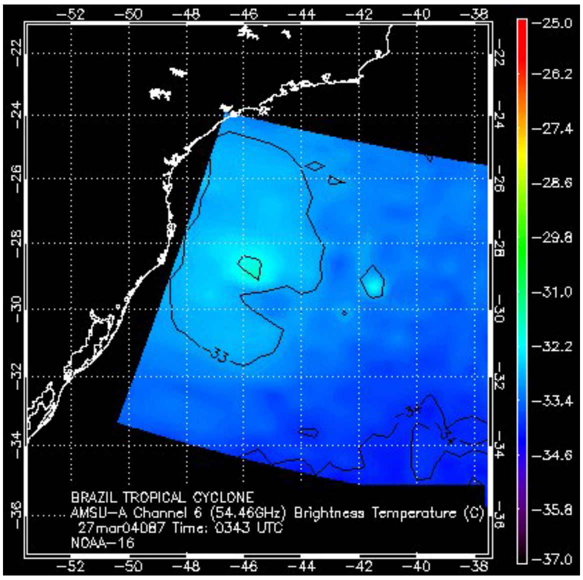
to affect temperature estimates, but, in spite of that, the vertical structure of positive temperature anomalies indicate a distinct warm core at all five microwave channels of the AMSU-A and AMSU-B sensors onboard satellite NOAA-16.

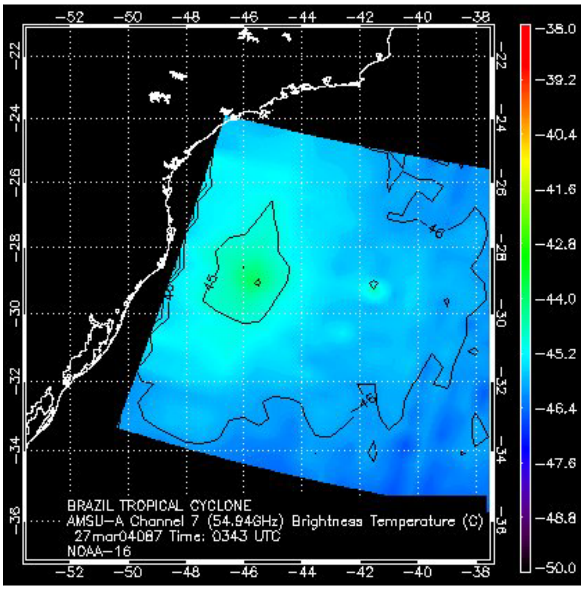
Fig. 9 shows 3D views and vertical cross-sections of rainfall rates of Hurricane Catarina on March 27 obtained by NASA with the Precipitation Radar (PR) onboard the TRMM satellite. The three vertical cross-sections clearly show a bright band which is close to the 0^{o} C isotherm where ice particles and snow melts as it falls through that level. It is about 4-km altitude and can be used as height reference.

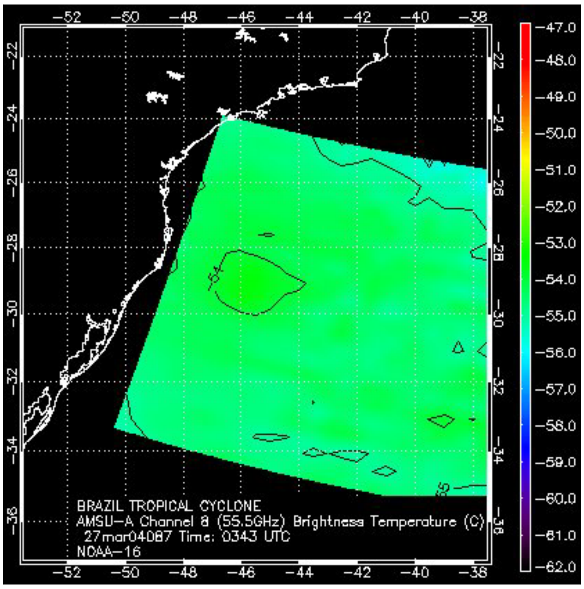
The top cross-section in Fig. 9 was taken near the eye and shows a cumulonimbus about 8-km deep to the right and deck of stratus to the left no more then about 5-km deep. This indicates cold microphysics processes present within Catarina. The horizontal cross-section shows three circular sectors of precipitation bands near the surface. They are better seen in the middle cross-section in Fig. 9 as well as cumulonimbus structures with rainfall rates ranging from 30 to more than 50 mm hr^{-1}. A very well defined bright band is apparent as well as a vigorous rainfall shaft close to the middle part of the cross-section.

The bottom cross-section in Fig. 9 shows several precipitating cells with alternating upward and downward movements associated with updrafts and compensating downdrafts as normally seen in hurricanes (Anthes, 1982). The highest cumulonimbus tops are associated with the wall cloud close to the eye.









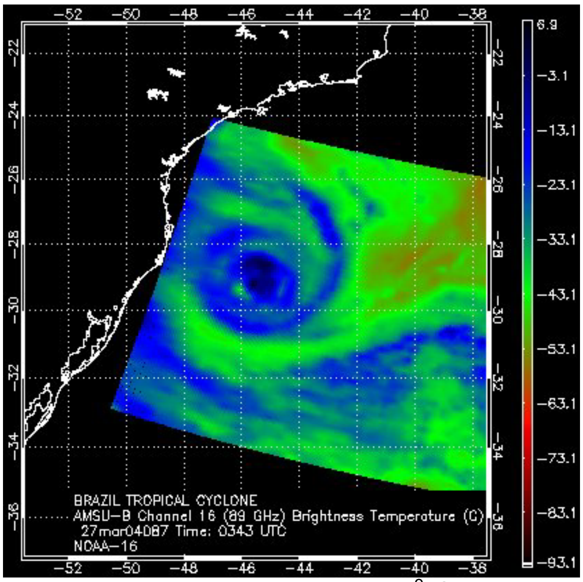


Figure 8: Brightness temperatures (° C) measured with the Advanced Microwave Sounding Unit (AMSU) onboard NOAA-16 satellite at 0343 UTC on 27 March 2004 for channels 5 (500 hPa), 6 (350 hPa), 7 (200 hPa) 8 (100 hPa) and 16 (surface). Latitudes, longitudes, geographic contours and color scale are indicated. Source: UW/CIMMS.

These deeper clouds have stronger updrafts and stronger compensating downdrafts. Given the asymmetry around the wall cloud, the effect of each downdraft is added to increase the subsidence and hydrostatic warming in the eye. This agrees with the microwave temperature estimates shown in Fig. 8.

The map of lighting strikes shown in Fig. 10 indicates the absence of electrical activity associated with Catarina particularly in the eye wall, though convective cells had a vertical structure that indicated the presence of ice crystals (Fig. 9). It might be related to the kind of cloud condensation nuclei (CCN) available over the ocean (salt). Some electrical activity was observed over the continent in association to a convective band to the Northwest of Catarina.

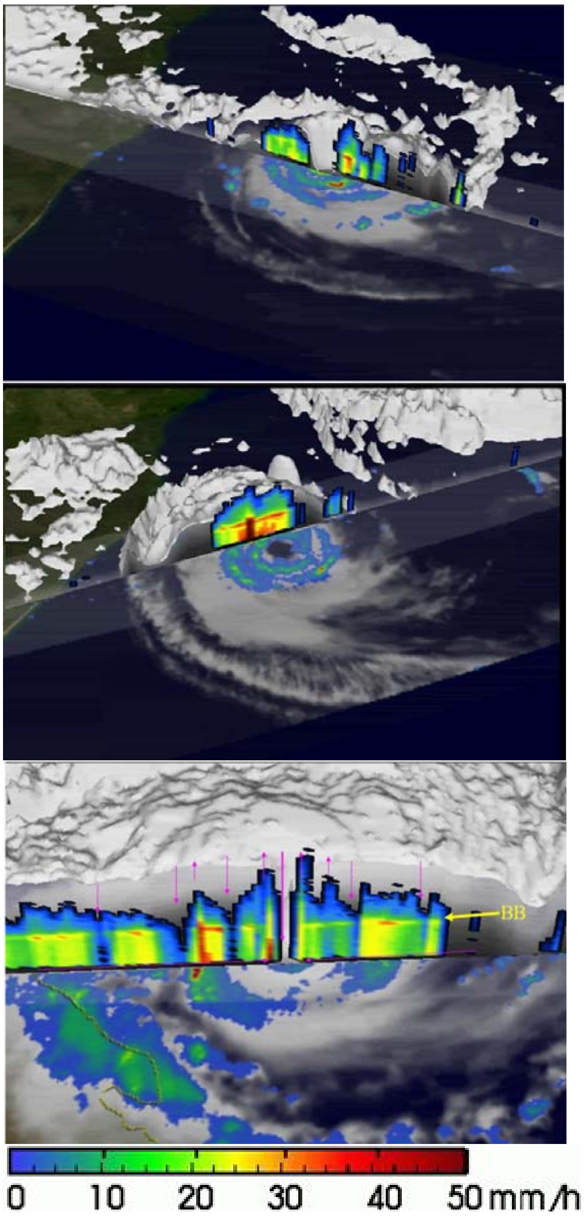


Figure 9: Rainfall rate cross-sections of Hurricane Catarina measured by TRMM/PR on 27 March 2004. Color scale indicates rainfall rates and, arrows, vertical and horizontal air motion. Source: GSFC/NASA.

The small dot over the continent in Fig. 1 shows the location of the closest surface weather station (Siderópolis City) to the path of the eye of the hurricane. Fig 11 shows the time evolution of hourly measurements of pressure, pressure change and wind between 26 and 29 March. The largest negative (-4.9 hPa) and positive (+4.8 hPa) pressure changes occurred at 0300 and 0600 UTC on 28 March as the eye of the hurricane approached the continent. The minimum surface pressure reached 973.6 hPa with maximum wind speeds of 41 m s^{-1} at 0300 UTC. These values correspond to a category 2 hurricane.

The wind and pressure are fairly symmetric about the time of minimum pressure and maximum wind speed. This symmetric as monitored with the surface weather station is consistent with the various satellite images shown in this analysis.

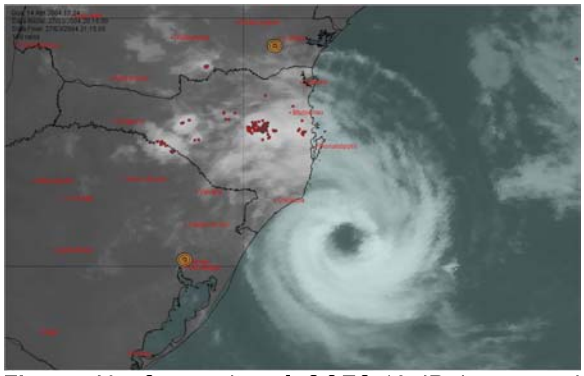


Figure 10: Composite of GOES-12 IR image and lightning activity (red dots) between 2015 and 2016 UTC on 27 March 2004. Major cities and geographic contours are indicated. Source: RINDAT/SIMEPAR.

A team of observers from the Federal University of Santa Catarina and the Civil Defense were at the place of hurricane landfall (Haas, 2004). They reported strong winds, heavy rainfall rates and cold temperatures before landfall followed by calm winds, very rapid warming and clear sky. Afterwards, a second episode of heavy rainfall, cold temperatures and strong winds occurred. The report also suggested a significant number of swirls span by strong winds.

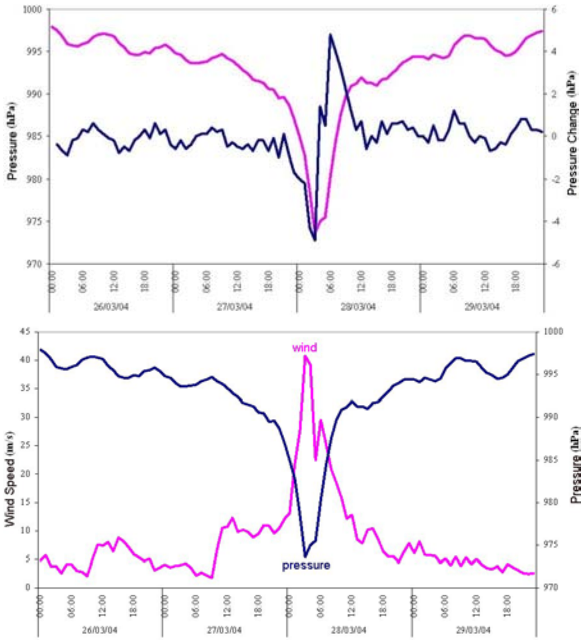


Figure 11: Time evolution of pressure (hPa), pressure change (hPa) and wind speed (m s^{-1}) measured at Siderópolis (Fig. 2).

4. CONCLUSION

Hurricane Catarina was formed in a decaying baroclinic zone with cyclonic rotation as in many other similar instances (Bosart and Bartlo, 1991). It triggered convection within this low shear circulation and organized itself into an inverted comma system or a tropical transition (Davis and Bosart, 2004).

The initial baroclinic dynamic organization was succeeded by a CISK mechanism that amplified the cluster of tropical storms as significant fluxes of sensible and latent heat (Burlaud and Viltard, 2004) were available to maintain the system long enough to generate an axisymmetric vortex.

The westward moved of Catarina indicates that it followed an optimum path given its symmetry about its eye. Northward and southward of the vortex wind shear would have destroyed its vertical structure and the system would dissipate (Nakano and Nakajima, 2004). Sea surface temperatures, on the other hand, were higher on the coast where the warm current of Brazil developed a tongue of warm waters. Thus, as the system approached the coast fluxes of heat increased and further strengthened the hurricane.

Regional models run by the weather services with horizontal resolutions between 20 and 40 km were unable to forecast the development of the vortex and its westward movement. The GFDL model (Bender and Marchock, 2004) forecasted many important features of the hurricane, including its path, with great accuracy (not shown). This specific model has a peculiar initialization scheme that places a warm anomaly in the eye of the vortex. This very interesting and "unorthodox" modeling approach can be applied to probable future events as well as in any other model to spin up the system.

Conceptual models such as the one proposed by Conway (1997), qualitatively adapted for the Southern Hemisphere, shown in Fig. 12, can be very useful in conjunction with satellite and other remote sensing data such as weather radars.

Hurricane Catarina represents a water divide in South America meteorology since it prompted the weather services to keep an open perspective on the kinds of weathers systems Earth's system can produce on a time of fast changes in climate.

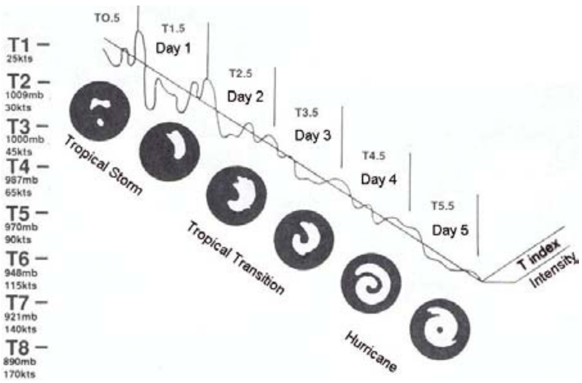


Figure 12: Conceptual model of a tropical cyclone development in South Hemisphere as observed from satellite. Adapted from Conway (1997).

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