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ON THE WESTWARD PROPAGATION OF CATARINA STORM

José Paulo Bonatti [1]

Vadlamudi Brahmanada Rao [2]

Pedro Leite da Silva Dias [3]

Abstract

An unusual cyclone formed along the coast of Southern Brazil at the end of March 2004. The cyclone eventually acquired the structure of a hurricane and was named Catarina, as the first system of this type to hit the Brazilian southern coast (State of Santa Catarina). The cyclone actually has hybrid characteristics of subtropical and tropical types. During the period of 20 to 23 March 2004 there was a cold front crossing that region that lead to the formation of an inverted comma cloud system below the upper level cold low. From 23 to 29 March the comma cloud system slowly propagated westward, contrary to the normal behavior and acquired characteristics of a hurricane and hit the coast of Santa Catarina State with winds in excess of 100 m/s and with very heavy precipitation. A case study of the Catarina storm is performed during the period 20 to 29 March 2004 in this paper. The methodology used for the observational part is the conservation of properties like vorticity, thermodynamic energy and specific humidity. Several simulations of the system are presented, based on the CPTEC global model for operational resolution (T126L28, at that time) and for higher resolutions (T170L42, T254L64 and T511L64). The results show that the primary factor responsible for the westward propagation was the relative vorticity stretching and secondarily is the planetary vorticity stretching. The planetary vorticity advection does not contribute significantly in this case. The high resolution global model does not give better simulation intensity for the surface pressure and winds, because the model simulates the maximum heating source too high in vertical. However, the model simulates the main characteristics of the phenomenon and the high resolution is essential to better define the precipitation fields, due to the better representation of topography.

[1] Centro de Previsão de Tempo e Estudos Climáticos – CPTEC/DMD, Rodovia Presidente Dutra, km 40 CEP 12630-000, Cachoeira Paulista – SP, Fone: (12) 3186-8421, Fax: (12) 3101-2835, e-mail: bonatti@cptec.inpe.br

[2] Instituto Nacional de Pesquisas Espaciais – INPE/CPTEC, Avenida dos Astronautas. 1758, Jd. Da Granja CEP 12227-010, São José dos Campos – SP, Fone: (12) 3945-6649, Fax: (12) 3945-6666, e-mail: vbrao@cptec.inpe.br

[3] Instituto Astronômico e Geofísico – DCA – IAG/USP, Rua do Matão, 1226, Cidade Universitária, CEP 05508-990, São Paulo – SP, Fone: (11) 3091.4713, Fax: (11) 3091.5034, e-mail: pldsdias@model.iag.usp.br

1. INTRODUCTION

Between days 20 and 30 of March of 2004 have been occurred a spectacular phenomenon in the coast of Santa Catarina State and adjacent ocean. The phenomenon started with an intense cold front followed by the formation of a mesoscale system with cloud associated inverted comma cloud. This type of event occurs more frequently in the intermediate seasons (Bonatti and Rao, 1987), and the comma cloud at the mature stage acquires characteristics of a cold front. However, in the cited event, the development after the mature period of the comma cloud a new mesoscale system with visual hurricane characteristics was generated. A careful detailed analysis of the vertical structure of the storm, called Catarina, shows that the associated heat source is confined below 200 hPa level and the vorticity field has barotropic characteristics, not changing sign until high levels. Although these characteristics are not of a hurricane it was decided in an international meeting held at CPTEC to classify the phenomenon as a hurricane. But it seems like a hybrid case with some characteristics of hurricane and others of extratropical cyclone; even in its origin it has some characteristics similar with polar lows. Therefore, in this work it will be called of Catarina storm.

2. METHODOLOGY

An interesting form to understand some observational aspects of the Catarina storm is an analysis of the conservation of vorticity, thermodynamic energy and specific humidity including the calculation of the residues of the respective equations (Borges Mendonça, 2000).

The vorticity equation can be written as:

$$\frac{\partial \varsigma}{\partial t} + \frac{u}{a\cos\varphi}\frac{\partial \varsigma}{\partial \lambda} + \frac{v}{a}\frac{\partial \varsigma}{\partial \varphi} + \omega\frac{\partial \varsigma}{\partial p} + \beta v + (\varsigma + f)\delta - \left(\frac{1}{a}\frac{\partial \omega}{\partial \varphi}\frac{\partial u}{\partial p} - \frac{1}{a\cos\varphi}\frac{\partial \omega}{\partial \lambda}\frac{\partial v}{\partial p}\right) = F_\varsigma$$

the thermodynamic energy equation is given by:

$$\frac{\partial T}{\partial t} + \frac{u}{a\cos\varphi}\frac{\partial T}{\partial \lambda} + \frac{v}{a}\frac{\partial T}{\partial \varphi} + \omega\frac{\partial T}{\partial p} + \frac{\omega}{C_P}\frac{\partial \phi}{\partial p} = \frac{\dot{Q}}{C_P}$$

and the conservation of specific humidity equation can be written as:

$$\frac{\partial q}{\partial t} + \frac{u}{a\cos\varphi}\frac{\partial q}{\partial \lambda} + \frac{v}{a}\frac{\partial q}{\partial \varphi} + \omega\frac{\partial q}{\partial p} = F_q\,.$$

The symbols in the previous equations have the usual meteorological meaning and all of them are written in vertical pressure coordinate. In the conservation equations the first term represents the local variation, the second and third is the horizontal advection and the fourth the vertical advection. The terms on the left side are the residues. The residue of the equation of the thermodynamics is known as Q_1 and of the equation of humidity conservation as Q_2. In the vorticity equation the fifth term is the advection of planetary vorticity, sixth is the stretching of absolute vorticity, which can be separated into stretching of relative vorticity and planetary vorticity, respectively, and the seventh is a twist of relative vorticity. In the thermodynamic energy equation the fifth term represents the vertical advection of thickness.

It is also interesting to test the capability of the operational CPTEC global model (T126L28, corresponding to 91 km in the region of the phenomenon - 30^{O}S) and in high resolution (T170L42, T254L64 and T511L64, corresponding to 68 km, 45 km and 23 km in the region of the phenomenon, respectively) in simulating the main characteristics of the Catarina storm. Integrations beginning at day 26/03/2004, 00 UTC, have been carried through when the phenomenon already was established until day 29/03/2004, 00 UTC, for the cited resolutions. All the cases have been run using Kuo type convection scheme and sea surface temperature from NCEP. The initial conditions have been generated from analyses T254L64, also from NCEP, interpolated for the resolution in question and always using the topography adjusted for the new resolution. A brief description of the CPTEC global model is given now and more details can be found in Kinter et al (1996) and Bonatti (1996). The CPTEC global model has its origin in the National Centers for Environmental Prediction (NCEP/USA) and was modified by the Center for Ocean-Land-

Atmosphere Studies (COLA/USA) during the decades 80 and 90. It is spectral and has horizontal spherical coordinates and in vertical is sigma (pressure of the level normalized by the pressure of surface in the considered point). It has triangular truncation and the vertical boundary conditions are vertical sigma velocity null at the top and at the surface. It uses spectrally truncated topography, zonal average ozone and the seasonal climatological values are interpolated for each instant of time. The carbon dioxide is constant and sea surface temperature and sea ice are fixed. Also climatological fields of soil moisture and snow are used as initial condition.
The dynamic part of the model uses the primitive spectral equations in divergence form and vorticity, virtual temperature, specific humidity and natural logarithms of the surface pressure. It has nonlinear normal mode diabatic initialization and uses finite differences in the vertical line and semi-implicit time integration scheme has Asselin filter.

The physical processes considered will now be described. At the surface on the land has a biological simplified model and on the ocean an aerodynamic bulk type scheme is used. The planetary boundary layer is parameterized with a scheme of turbulent vertical second order closure diffusion considering also the effect of gravity waves drag. The solar radiation is activated each hour of integration and the long wave radiation is activated each 3 hours. The deep convection is Kuo type modified by Anthes and has an option for a Relaxed the Arakawa-Schubert scheme. The shallow convection is an additional diffusion following Tiedke scheme. The model has procedures of adjustments for the large scale precipitation and horizontal bi-harmonica diffusion and has another additional diffusion to control the computational instability that follows the ECMWF scheme.

3. RESULTS

A section at 30^{O}S of the field of pressure in the region of occurrence of the Catarina storm during the period of 20 to 30 of March of 2004 is presented in figure 1. It shows eastward propagation of the comma cloud system approximately between the longitudes of 45^{O}W and 35^{O}W until day 23 and then a clear Catarina storm westward propagation approximately between longitudes 35^{O}W and 55^{O}W with velocity of approximately 20º in 6 days or about 15 km/h (4 m/s).

Figure 2 shows the pressure field in the beginning of the westward propagation of the Catarina storm. Initially there is a deepening of the low reaching 1007 hPa. In figure 3 hPa has the corresponding fields of vorticity for 1000 and clearly it is verified the moment when the low associated to the Catarina storm separates from (day 23 at 06 UTC) the comma cloud system which already has characteristics of a cold front (figure 3.A) and the westward movement starts.

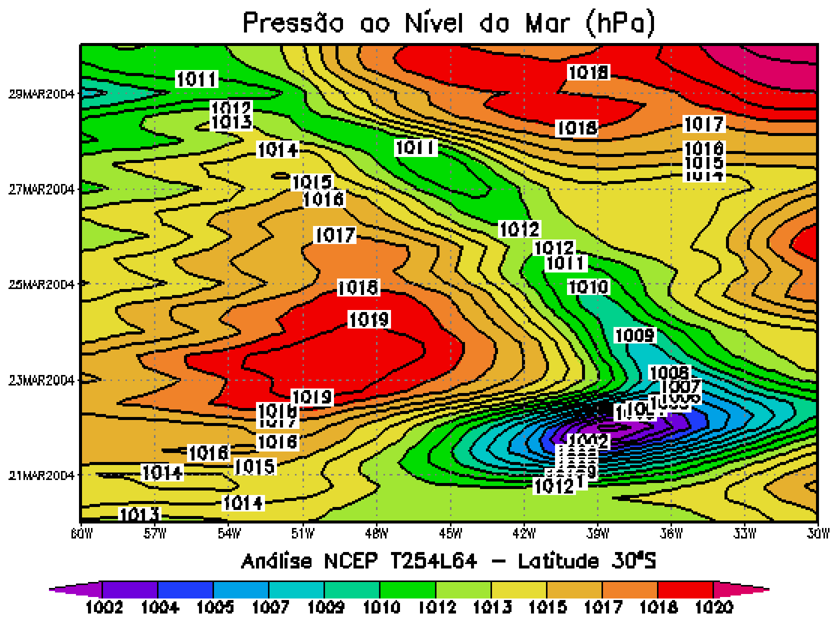


Figure 1 – Surface pressure section at 30^{O}S.

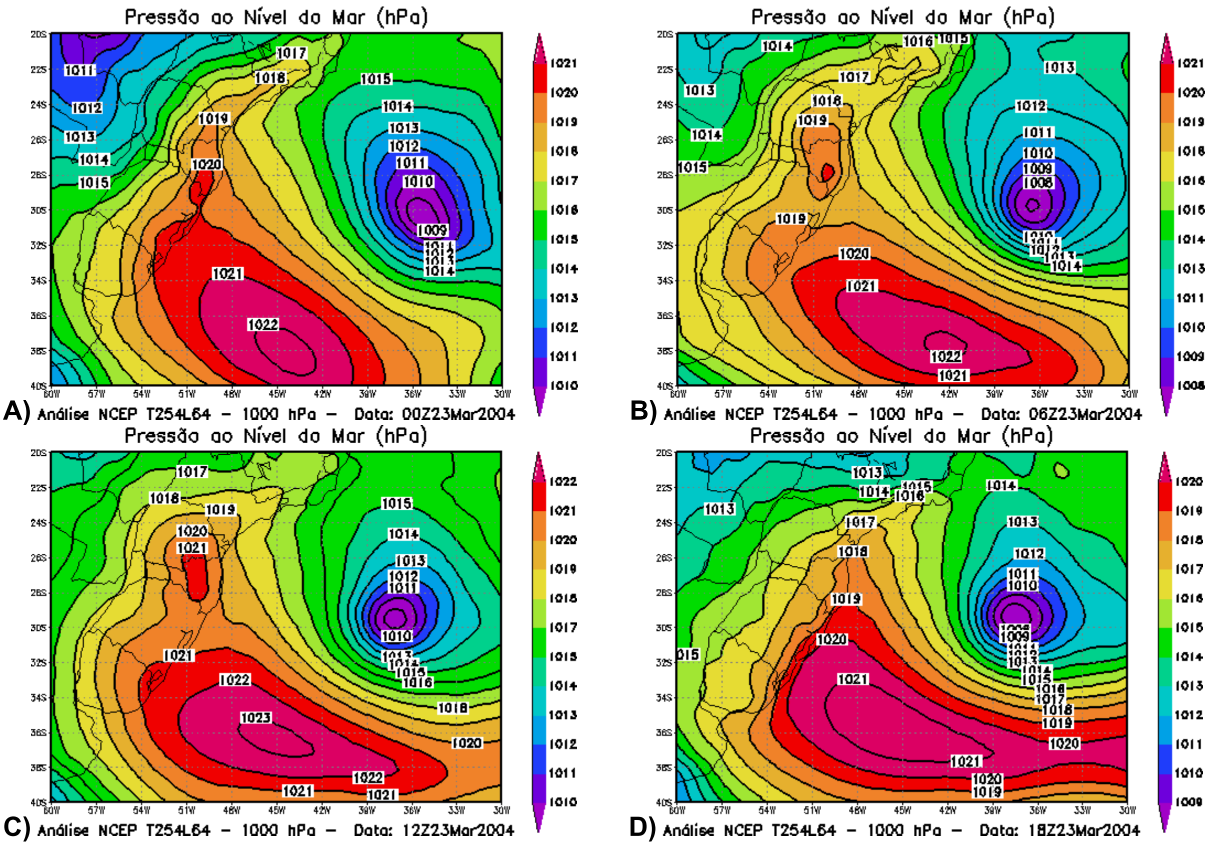


Figure 2 – Sea level pressure (hPa) at the beginning of westward propagation.

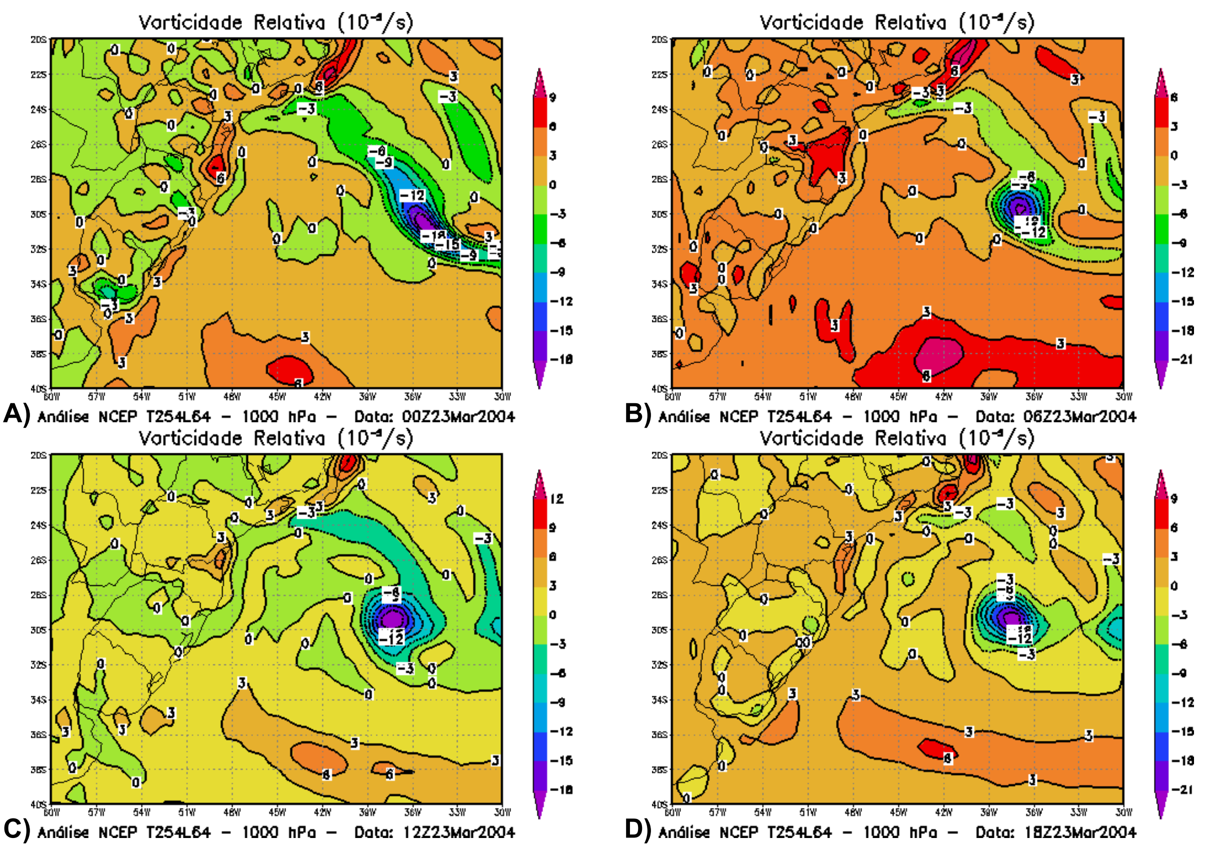


Figure 3 – Relative vorticity (10^{-5} s^{-1}) on 1000 hPa at the beginning of westward propagation.

In figure 4 the vorticity tendency is shown. It shows that in the west side of the negative vorticity center (figure 3) the tendency is negative and in the east side it is positive, characterizing the propagation of the system to west. Figure 5 shows the horizontal advection of relative vorticity with positive values in the region of the center of negative vorticity, characterizing propagation to east due to this process. Figure 6 shows the horizontal advection of planetary vorticity, characterizing propagation to east, however with no significant values. Figure 7 shows the vertical advection, with in generally very small values on the ocean having not significant contribution for the balance of vorticity in this case. Figure 8 shows the stretching of relative vorticity with relatively high positive values on the region of negative vorticity, causing through this process the westward displacement of the system. In figure 9 the stretching of planetary vorticity agrees to the previous case of figure 8 with very similar characteristics, however with lesser values. Figure 10 presents the vorticity twist and similar to the vertical advection does not have significant contribution. Figure 11 shows the residue of the vorticity conservation, showing high positive values in the region of the center of negative vorticity, showing that dissipation processes also have importance in the determination of the vorticity tendency.

Then the westward propagation of the Catarina storm must be mainly due to nonlinear effects of the relative vorticity stretching process. However the linear process of planetary vorticity stretching and dissipation also contribute significantly. The process of stretching of absolute vorticity has importance until about 800 hPa (figure not shown); however it is this process that determines the westward propagation of the system as a whole.

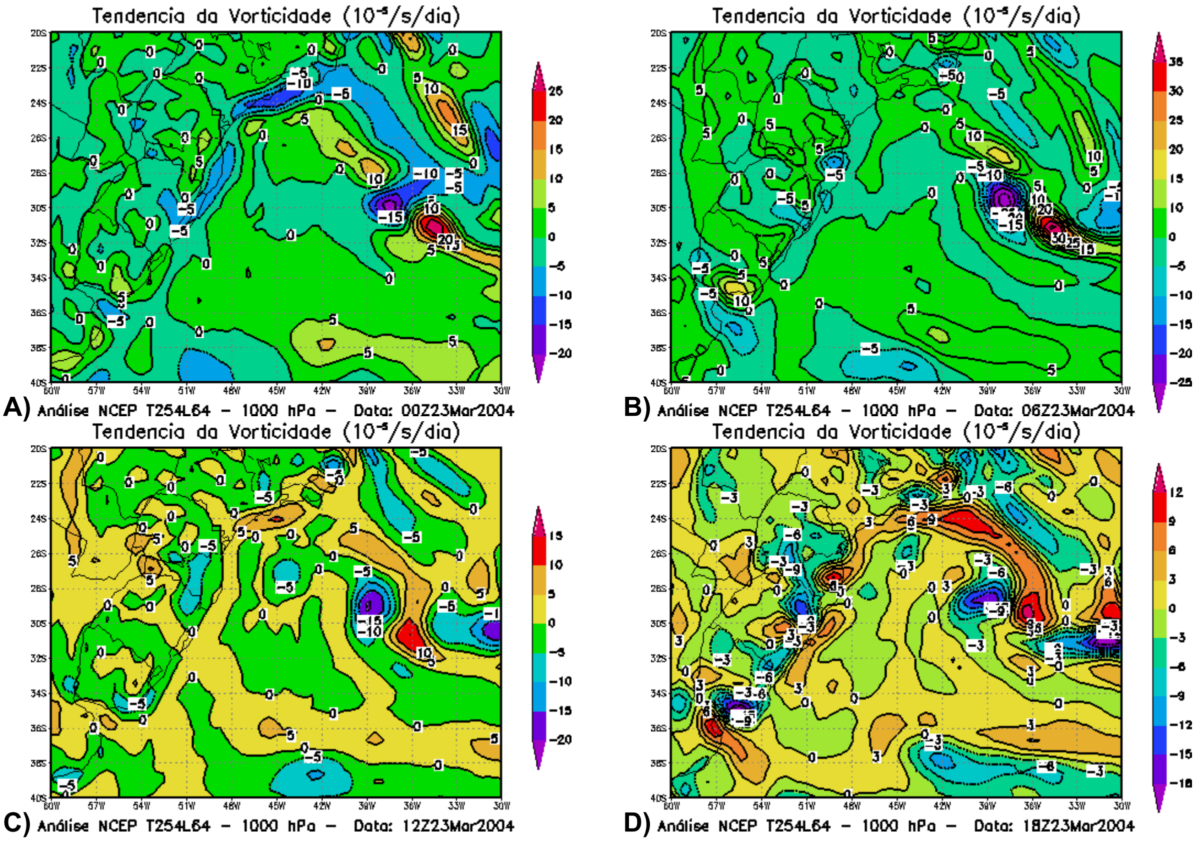


Figure 4 – Vorticity tendency (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

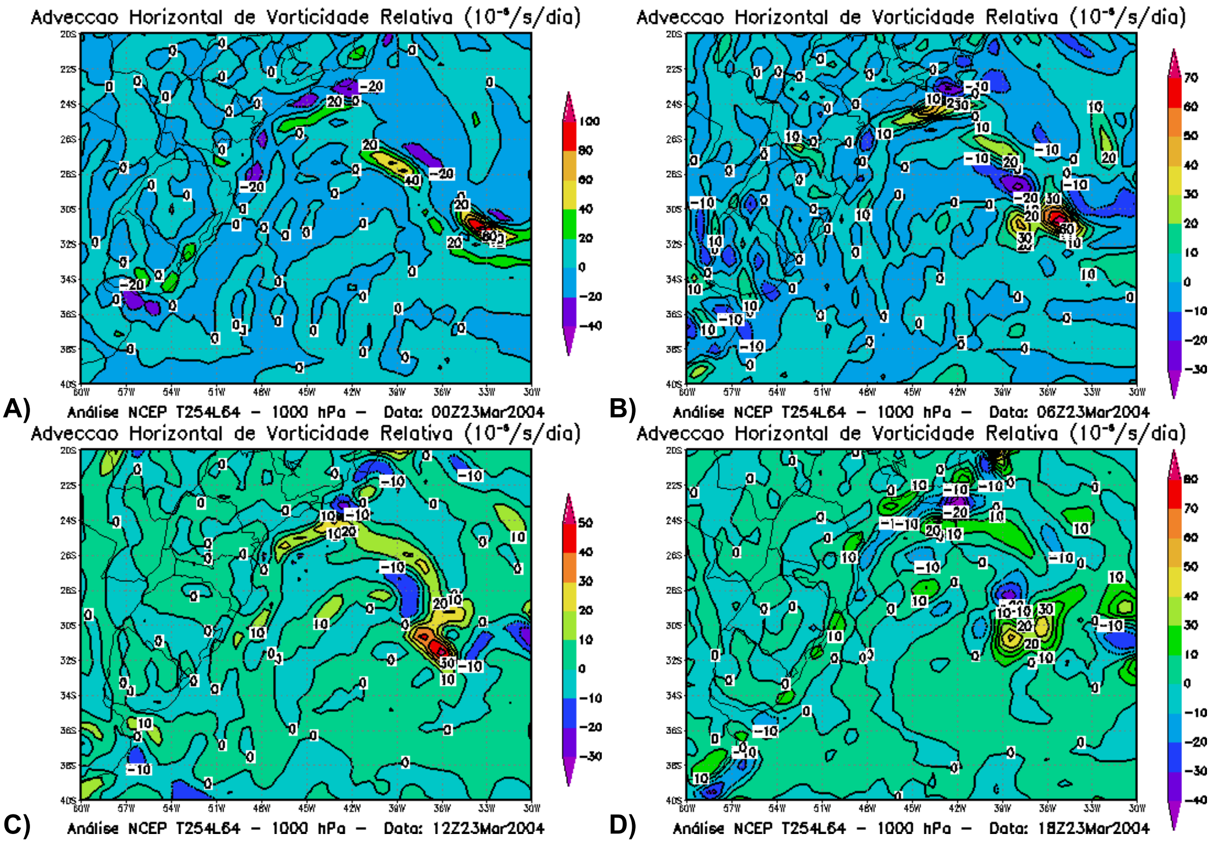


Figure 5 –Horizontal relative vorticity advection (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

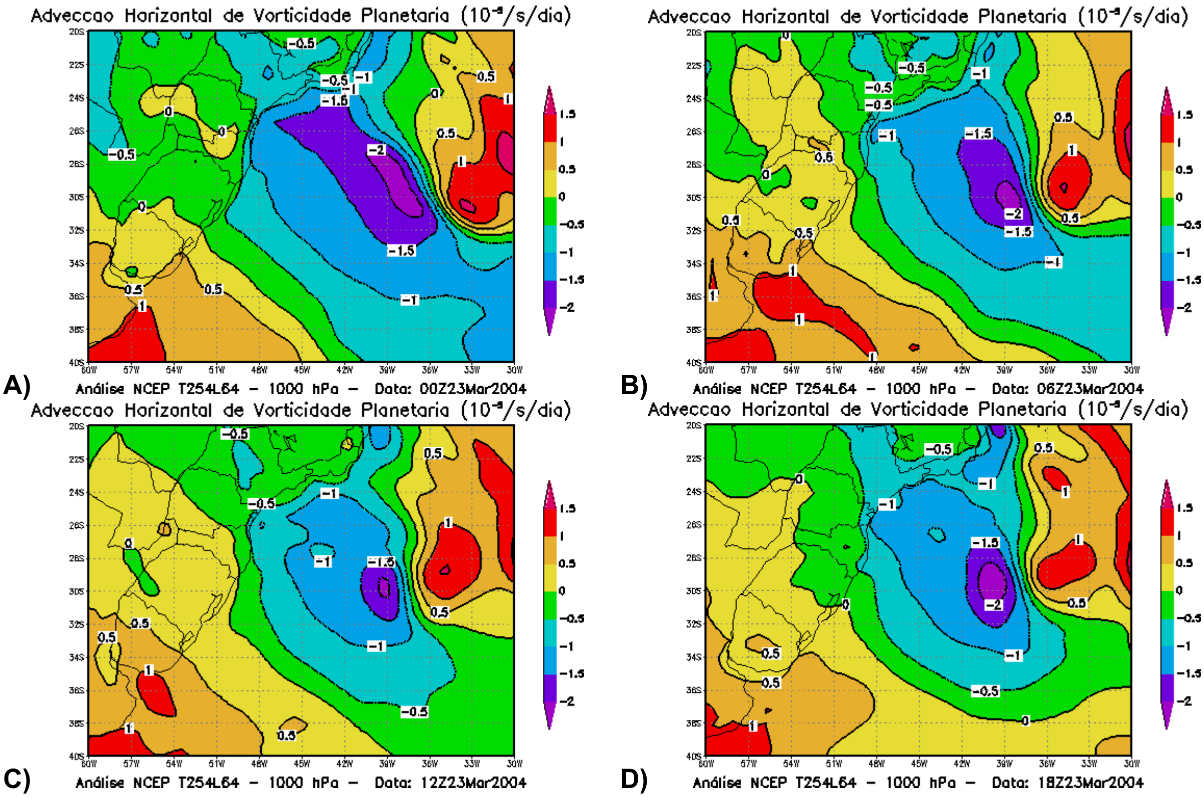


Figure 6 – Horizontal planetary vorticity advection (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

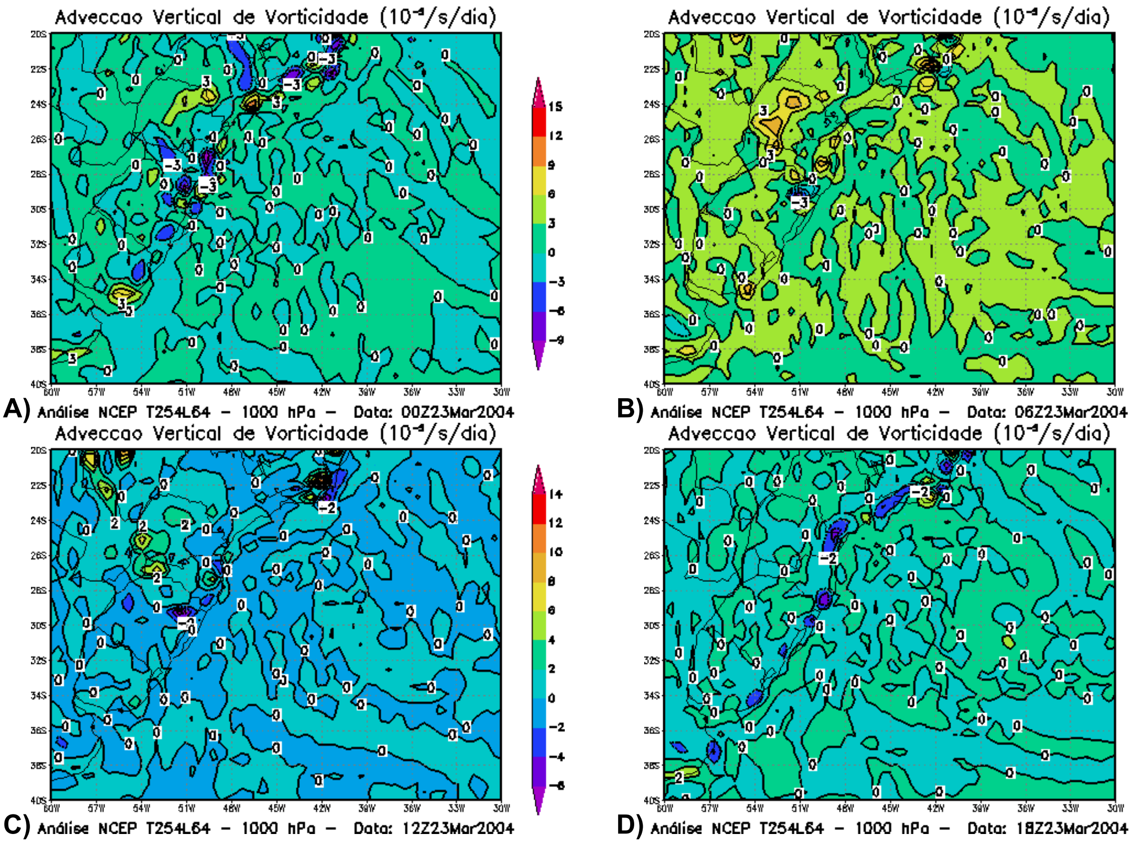


Figure 7 – Vertical relative vorticity advection (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

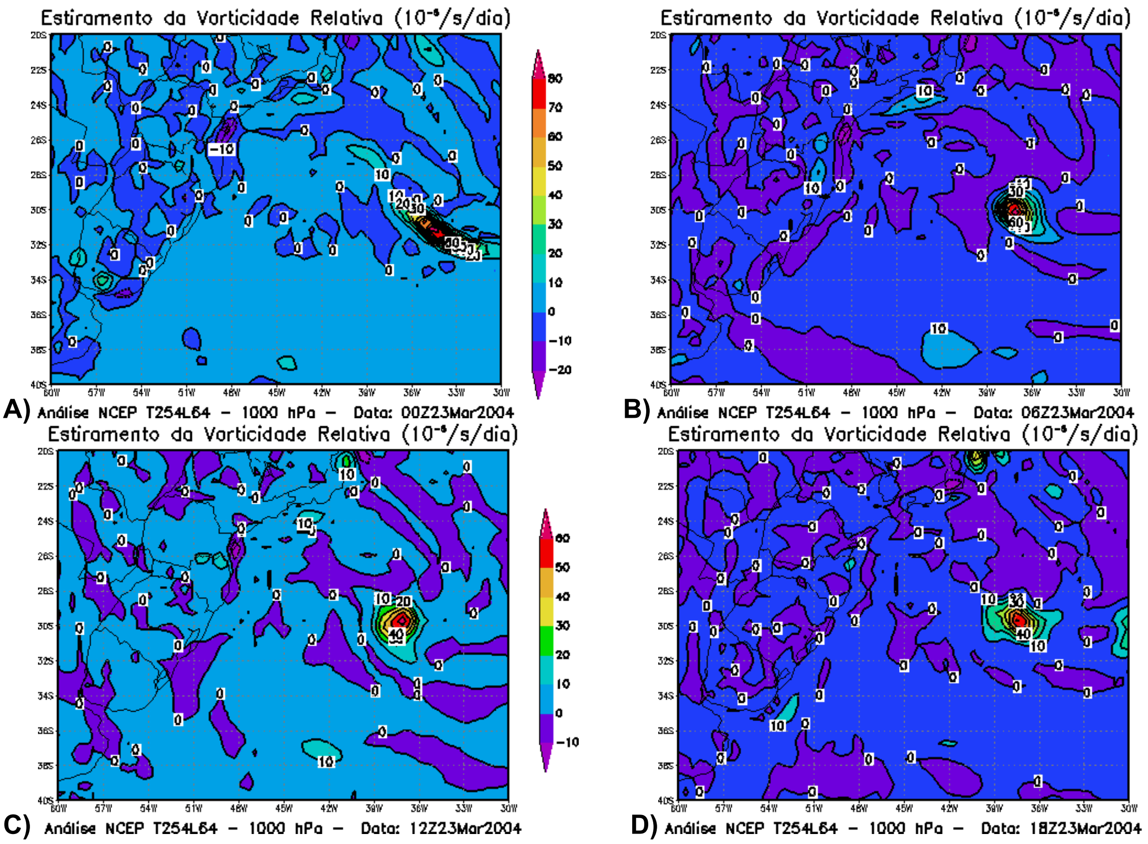


Figure 8 – Relative vorticity stretching (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

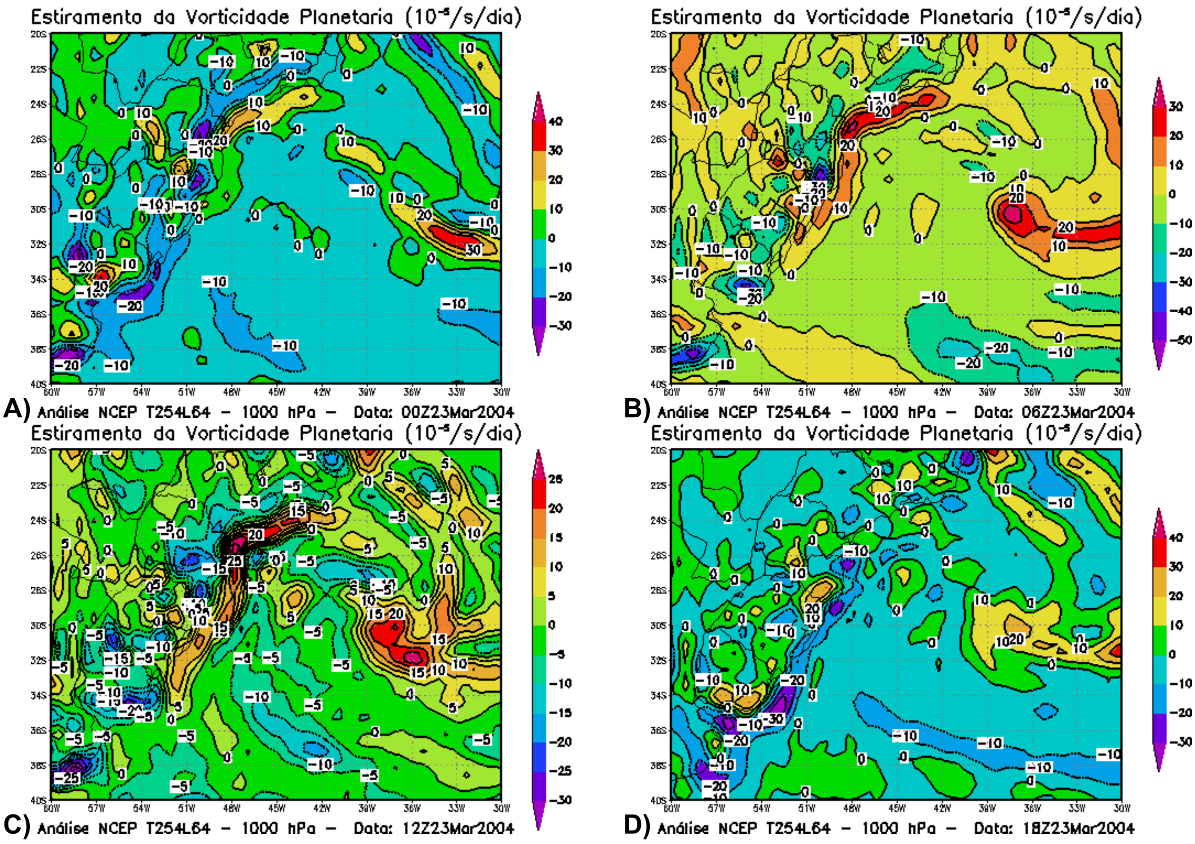


Figure 9 – Planetary vorticity stretching (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

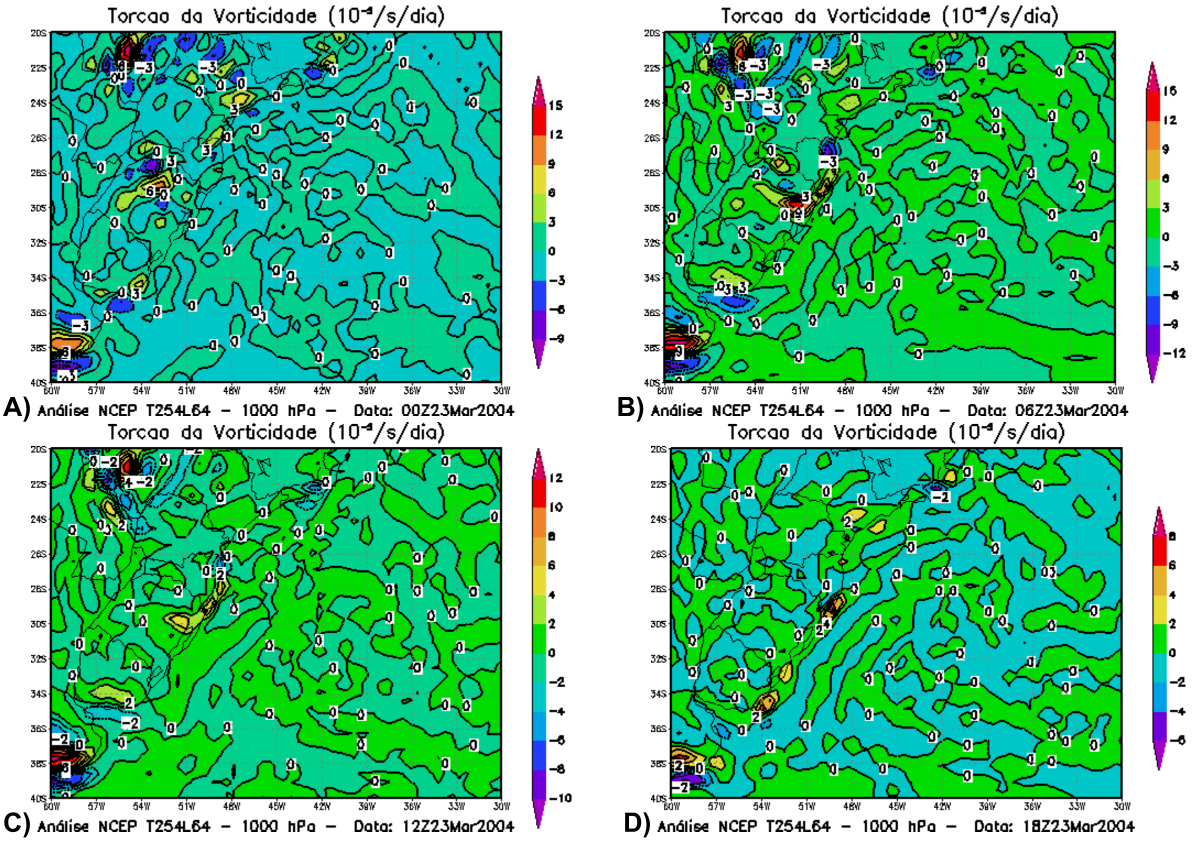


Figure 10 – Relative vorticity twist (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

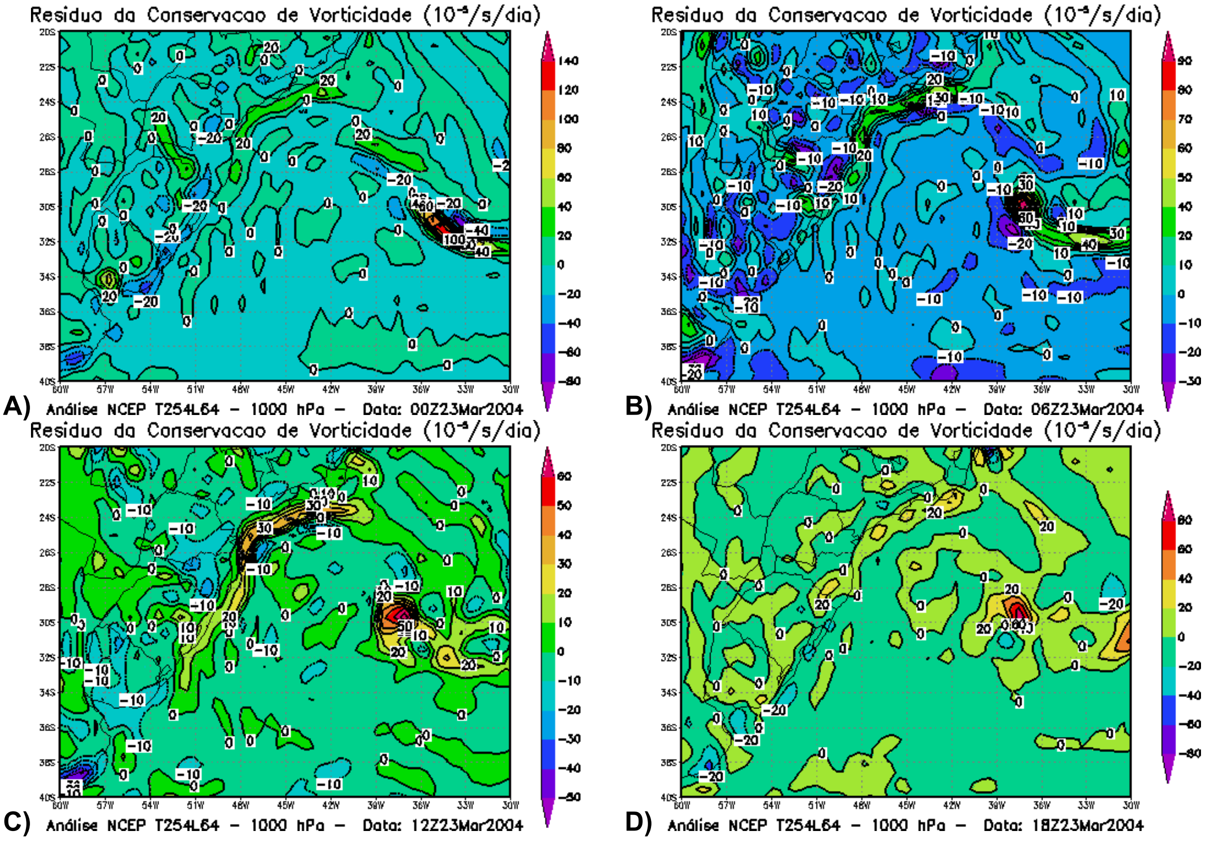


Figure 11 – Residue of the vorticity conservation (10^{-5} $s^{-1}day^{-1}$) on 1000 hPa.

Following Charney (1973) A possible theoretical explanation on the westward propagation of the Catarina storm can be given through the equation of conservation of the quasi-geostrophic potential vorticity (Q) linearized over a basic state with zonal wind (U) and temperature dependent of the pressure only. Therefore, the static stability (σ) is also function of the pressure only. Considering the disturbance of the stream function as ψ', this equation can be written as:

$$\frac{\partial Q'}{\partial t} + U\frac{\partial Q'}{\partial x} + \frac{\partial \overline{Q}}{\partial y}\frac{\partial \psi'}{\partial x} = 0,$$

where

$$Q' = \nabla^2 \psi' + f_o^2 \frac{\partial}{\partial p}\left(\frac{1}{\sigma}\frac{\partial \psi'}{\partial p}\right),$$

$$\frac{\partial \overline{Q}}{\partial y} = \beta - f_o^2 \frac{d}{dp}\left(\frac{1}{\sigma}\frac{dU}{dp}\right),$$

with $\beta = d\,f/dy)_{y=y_o}$ and f_o is the Coriolis parameter at $y = y_o$. Considering now that U and σ are constants the solution would be:

$$\psi'(x,y,p,t) = \mathrm{Re}\{\Psi(p)\exp[ik(x-ct)]\sin(\ell y)\}$$

At this equation $k = 2\pi/L$ is the zonal wavenumber, L is the wavelength, $\ell = \pi/D$ is the meridional wavenumber, D is the half width of the canal and c is the phase velocity. As the variation with y is function of the sine only is not considered propagation of phase in this direction however propagation of energy can occur. The equation for the amplitude of the disturbance which is function alone of the pressure is then, given by:

$$\frac{d^2\Psi}{dp^2} - \frac{\sigma}{f_o^2}\left[\frac{\beta}{c-U} + k^2 + \ell^2\right]\Psi = 0 .$$

For this equation be valid c must be different of U. Considering null vertical speed at the top and at the surface it can be shown that:

$$\left.\frac{d\Psi}{dp}\right)_{p=p_s, p_t} = 0 .$$

If the term inside brackets amplitude equation will be null ($c = c_o = U - \beta/[k^2 + \ell^2]$), the variation of the amplitude would be linear with the pressure and using the boundary conditions its value would be constant. This is the non-divergent barotropic classic case studied by Rossby. If $c < c_o$ or $c > U$, the term inside brackets will be positive and the solution will be exponential type. In this in case there is also a barotropic solution. These solutions have no interest in this case where the divergence term has the basic role. However, if $c_o < c < U$ the term inside brackets will be negative and the solution will be of the form:

$$\Psi(p) = \mathrm{Re}\{\hat{\Psi}\exp[im(p - p_t)]\}$$

where $m = 2\pi/(p_s - p_t)$ and the amplitude will be real having no the phase propagation in the vertical direction however has energy propagation. The phase and group velocities in the directions zonal (c_{gx}), meridional (c_{gy}) and vertical line (c_{gz}) are then given respectively by:

$$c = U - \frac{\beta}{k^2 + \ell^2 + (f_o^2/\sigma)m^2}$$

$$c_{gx} = \frac{\partial(k\,c)}{\partial k} = U + \frac{\beta\,[k^2 - \ell^2 - (f_o^2/\sigma)m^2]}{[k^2 + \ell^2 + (f_o^2/\sigma)m^2]^2}$$

$$c_{gy} = \frac{\partial(k\,c)}{\partial \ell} = \frac{2\,\beta\,k\,\ell}{[k^2 + \ell^2 + (f_o^2/\sigma)m^2]^2}$$

and

$$c_{gz} = \frac{\partial(k\,c)}{\partial m} = \frac{2\,\beta\,k\,(f_o^2/\sigma)m}{[k^2 + \ell^2 + (f_o^2/\sigma)m^2]^2} .$$

It can be noted that the phase velocity is negative in relation to the basic state leading to westward propagation. The effect of the divergence is to introduce a new term in the denominator in relation to the non-divergent barotropic case that is equivalent to an acceleration of the system as a whole. The southern and vertical group velocities are positive however for the case of the Catarina where $k \approx \ell$ the zonal group velocity is also negative in contrast of non-divergent the barotropic case that is always positive. Therefore, the effect of the divergence in a quasi-geostrophic system when $k \approx \ell$ is to allow westward energy propagation. This characteristic is in accordance with the observations of the Catarina storm. It has evidences through calculations based on observations in the high troposphere that the phase and of group velocities can in the same directions (Chang and Yu, 1996).

The vertical structure of the Catarina storm is important for its classification. Figure 12 shows vertical cross sections in 28.3^{O}S for 26 March, 12 UTC, for relevant fields for the classification of the Catarina storm at the moment it reaches its half life. In the figure 12.A the sections of vorticity and vertical speed it is noted that the system has negative vorticity in all its vertical extension and confined until 200 hPa. In the figure 12.B gives sections of relative humidity and potential temperature where also it is noted that the extension of the humidity is confined where the phenomenon is hotter over the region of the low surface center (white vertical line), however at the moment of its generation (day 23, 06 UTC) this does not occur. The figure 12.C presents the heat source of Q1 and the figure 11.D the apparent source of humidity Q2; one also note that in both the cases there is confinement below 200 hPa.

After this observational analysis based on data from NCEP in resolution T254L64 it will be shown some relevant results of modeling of the Catarina storm with operational resolution and in high resolution of the CPTEC global model. In all the cases the initial condition is for day 26/03/2004, 00 UTC. Figure 13 shows the used topography spectrally truncated and smoothed (to minimize Gibbs effect) for each resolution of the model. It shows that the mountain at the State of Santa Catarina coast is only well represented in the T511 resolution and the difference among the resolutions is notable. The figure 14 presents the field of observed surface pressure and it shows small differences between the resolutions with the biggest differences where the topography is high at the States of Santa Catarina and Paraná. The minimum in the center of the low is around 1008.5 hPa in 44.2^{O}W and 28.5^{O}S. The figure 15 brings the surface pressure simulated by the model in their various resolutions. In all the cases the simulation shows a center of low pressure located at 46^{O}W and 27.5^{O}S, with values of approximately 1012 hPa for T126L28 and T170L42 and 1013 hPa for T511L64. Therefore, all the model resolution resolutions was not enable to locate the center of low surface pressure in the observed place and have higher values of about 3,.5 hPa, although the pattern is very similar to the observed one.

Figure 16 shows the accumulated precipitation fields at the last 6 hours valid for 27 March 2004, 00UTC. It is noted the great impact of the topography (figure 13) in these simulation fields. In resolution T126L28 the precipitation center maximum is around 27 mm/day and is on the ocean. The same occurs for T170L42 however there is some penetration of the maximum in the south coast of Santa Catarina. The model with resolutions T254L64 and T511L64 obtains the maximum approximately locate on the south coast of Santa Catarina with values of 36 and 63 mm/day, respectively. It can be seeing, however, that the concentration of rain on the south coast and the increase of its intensity approaches more to the observed one in resolution T511L64. This indicates that the resolution increase is crucial to get better simulated rain in this case.

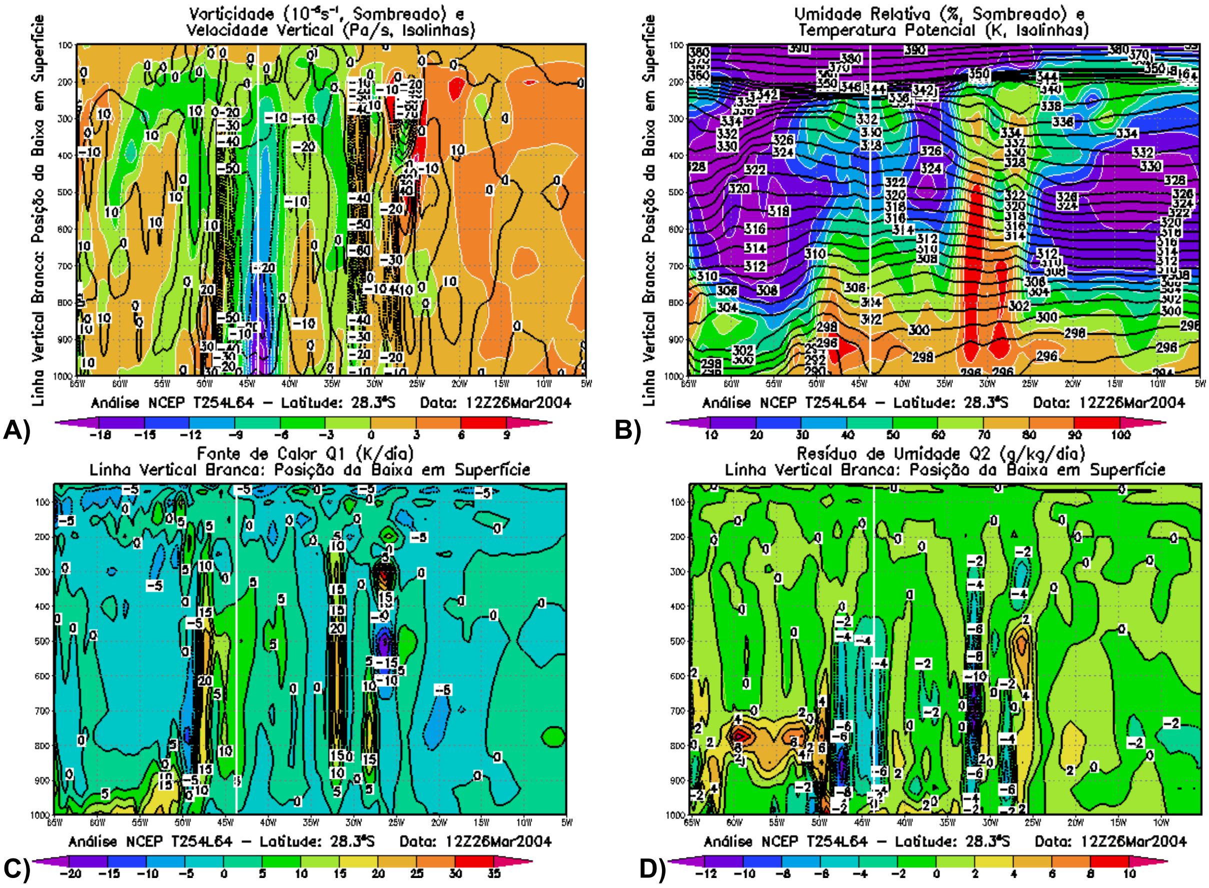


Figure 12 – Vertical cross section at 28.3^{O}S for 26 March 2004, 12 UTC.

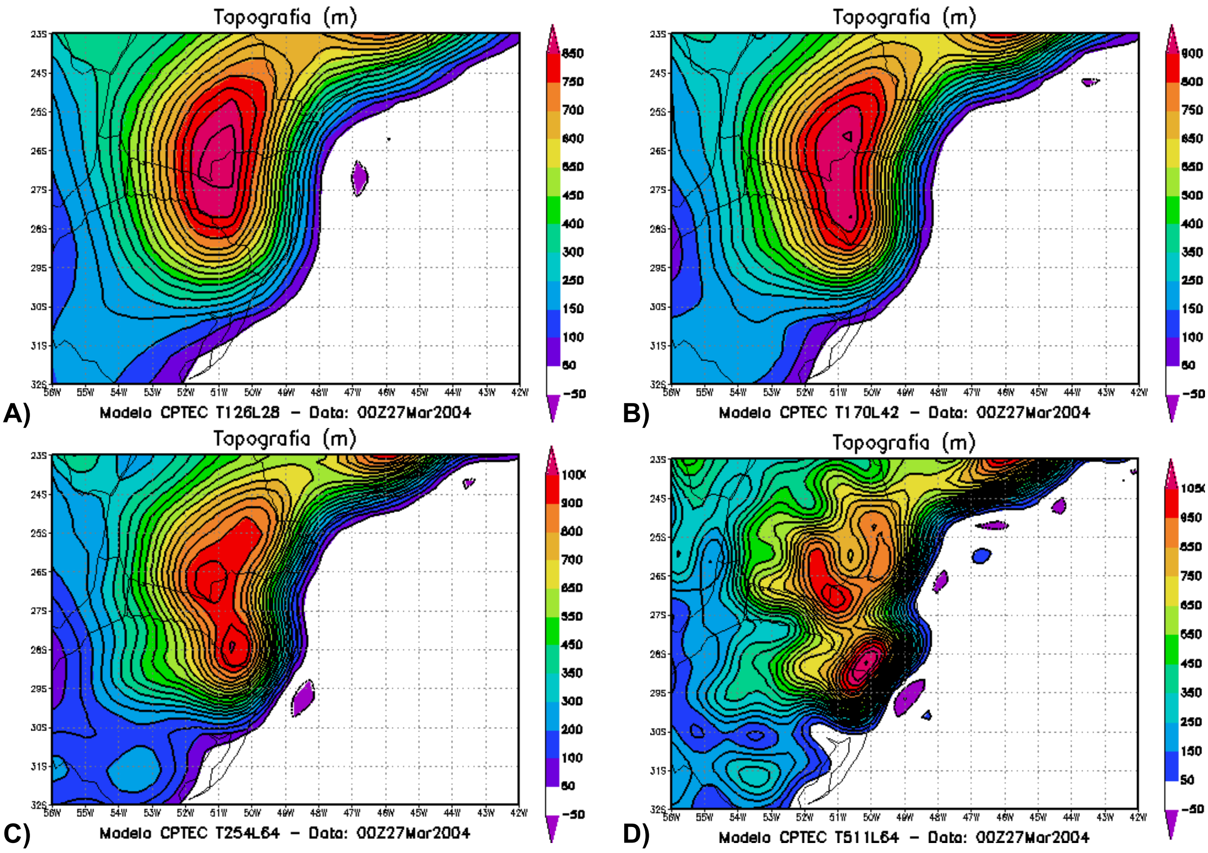


Figure 13 – Topography (m) at the region of Santa Catarina State for each used resolution.

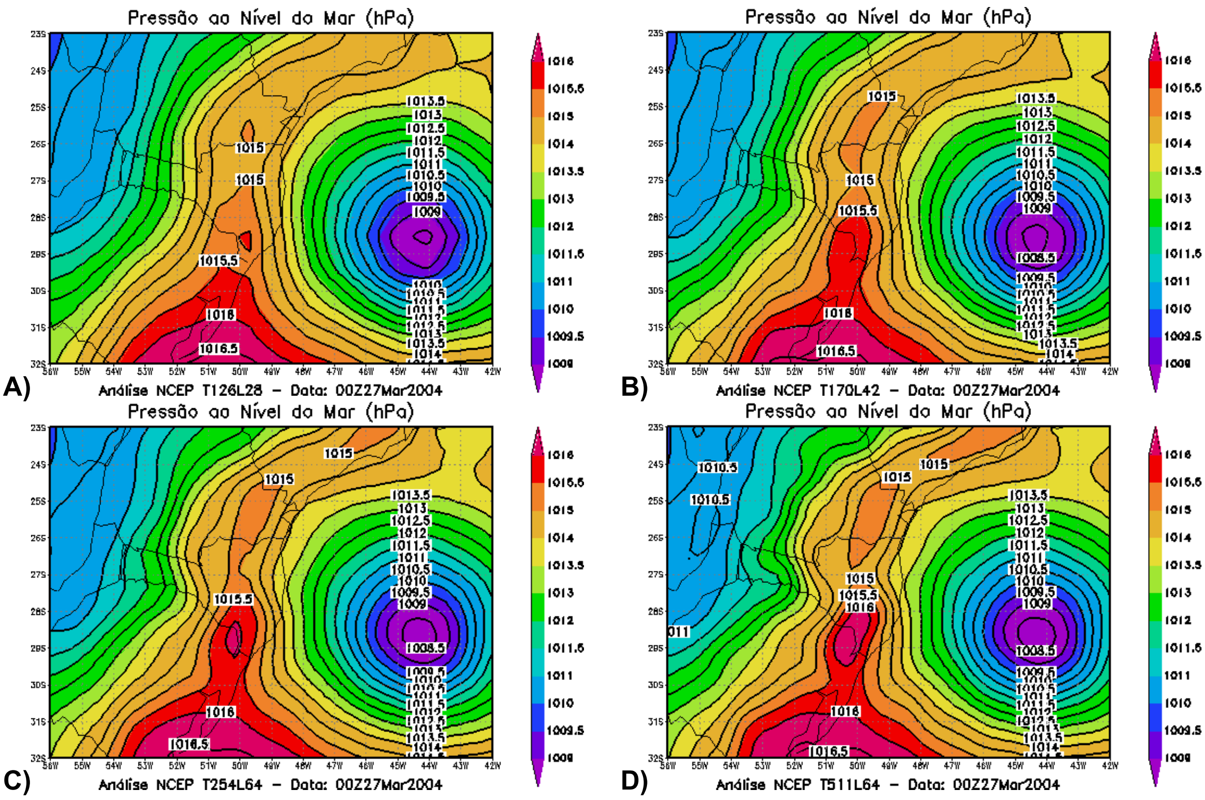


Figure 14 – Observed surface pressure for 27 March 2004, 00UTC.

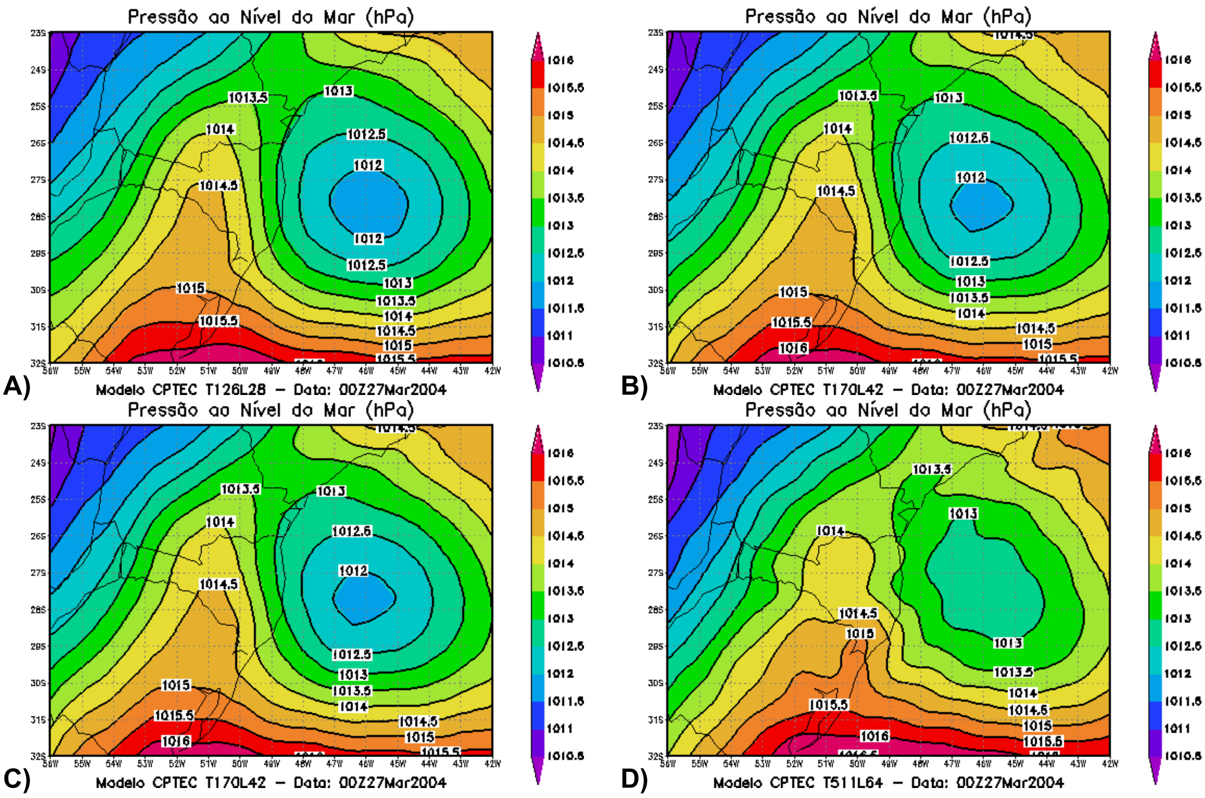


Figure 15 – Simulated surface pressure for 27 March 2004, 00UTC.

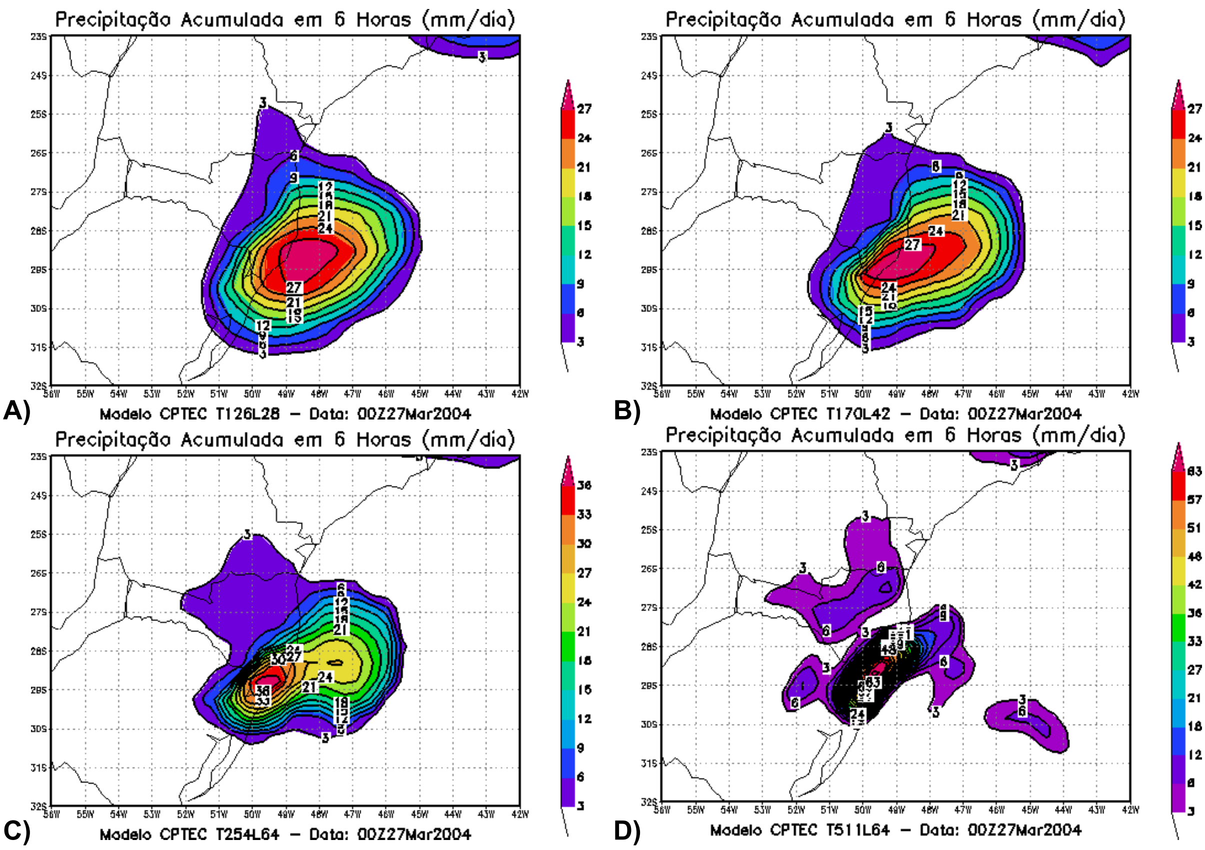


Figure 16 – Accumulated precipitation at the last 6 hours as simulated for 27/03/2004, 00UTC.

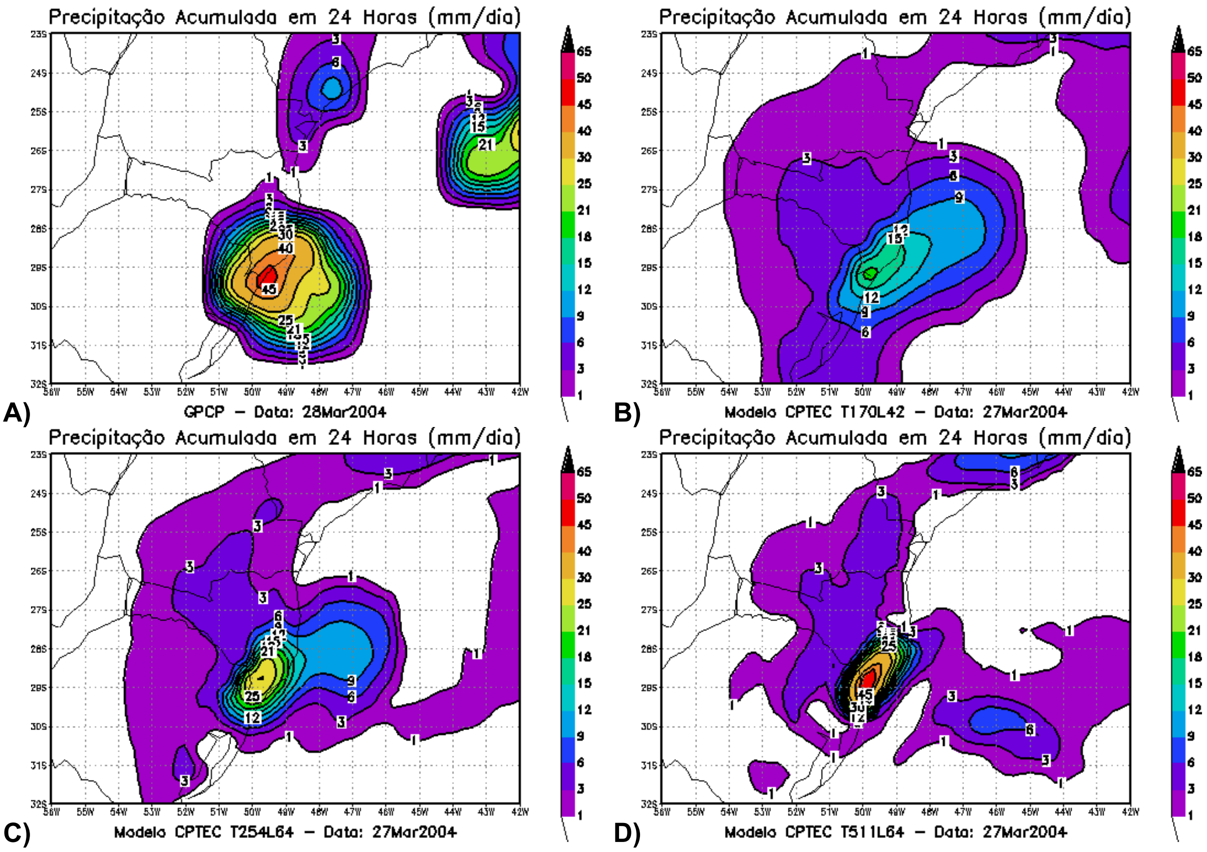
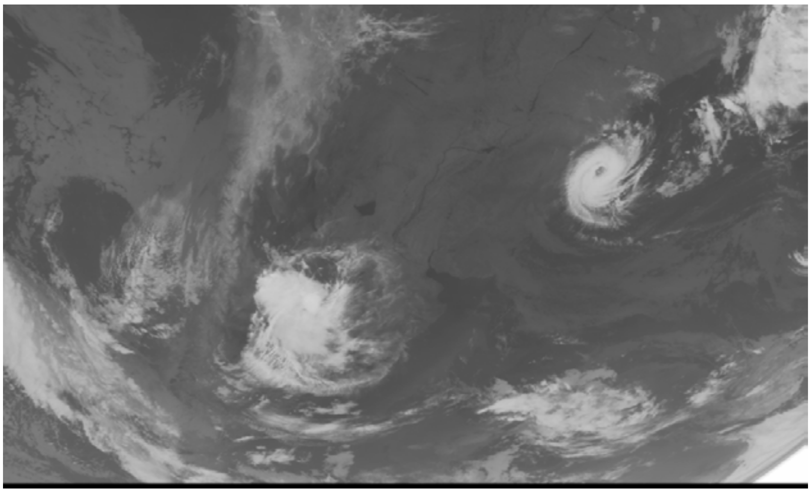
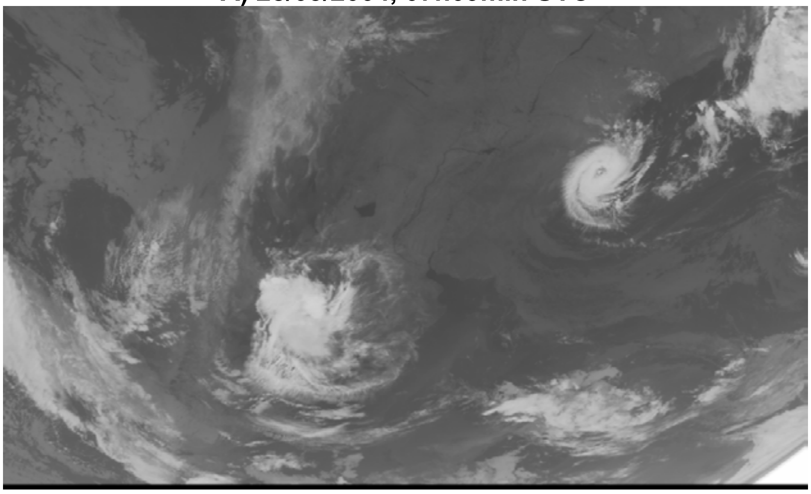


Figure 17 – Accumulated precipitation at the last 24 hours: observed and simulated for 27/03/2004.

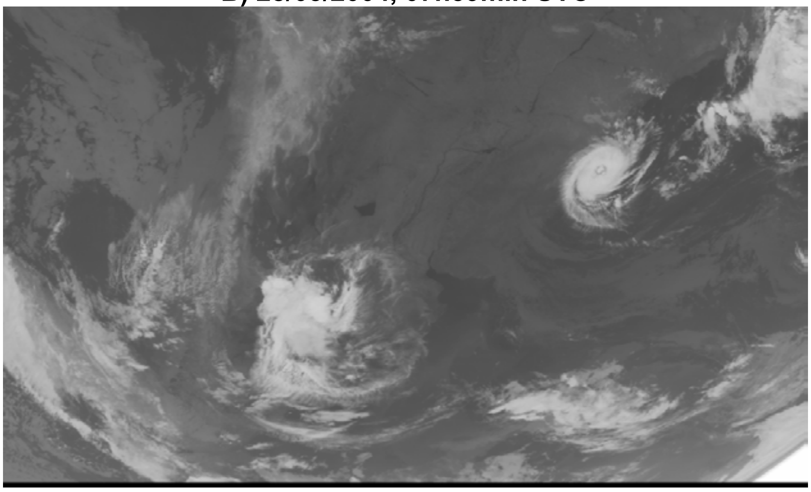
In figure 17A it is given the observed accumulated precipitation in 24 hours getting from the Global Precipitation Climatology Center (http://precip.gsfc.nasa.gov/pub/1dd/, CPCP) which is calculated from daily information to each 3 hours initiating in 00 UTC. Therefore, it must be considered that the data are valid from 22:30 UTC of the previous day. The figures 17B, 17C and 17D bring the accumulated precipitation in 24 hours, from the 18:00 hours of the previous day, simulated for the global model with resolutions T170L42, T254L64 and T511L64, respectively. All the simulations gives a good location of the maximum rain on the south coast of Santa Catarina (about 45 mm/day in the observations), however in resolution T170L42 this maximum very is underestimated (18 mm/day), in resolution T254L64. Although it is also underestimated (30 mm/day) the value approaches more and the shape of the field is most similar to the observed ones. For resolution T511L64 the maximum is very well simulated (45 mm/day) however the shape of the field is more concentrated than the observed one. This confirms that the high resolution is necessary for better reproduction of shapes and intensities among simulation and observed precipitation.



A) 28/03/2004, 07h09min UTC



B) 28/03/2004, 07h39min UTC



C) 28/03/2004, 08h09min UTC

Figure 18 – High resolution satellite imageries of Catarina storm reaching the coast.

4. DISCUSSION AND CONCLUSIONS

A preliminary study of the Catarina storm was carried out for the period of 20 to 29 March 2004. The methodology used for the observational part is the conservation of properties such as vorticity, thermodynamic energy and specific humidity. Simulations are also carried out using the operational CPTEC global model (T126L28) and higher resolutions (T170L42, T254L64 and T511L64). A process that normally causes westward propagation is the advection of planetary vorticity (beta effect). However, based on the theory of Rossby this would occur for very long waves which it is not the case of Catarina storm. Another process that can generate propagation for west is the stretching of absolute vorticity, that can be separate in stretching of planetary vorticity (linear) and stretching of relative vorticity (nonlinear). The results have shown that the major factor of the westward propagation was the stretching of relative vorticity and with secondary contribution of the stretching of planetary vorticity and dissipation. This fact points out the role of the nonlinear effect for this westward propagation. The advection of planetary vorticity has no significant contribution in this case and the stretching of absolute vorticity has effect until about 80 hPa. The vertical sections at the mature stage show a barotropic character of the vorticity, in the sense that there is no signal change in the vertical until about 200 hPa. The same occurs for the diabatic heating. However, the system at this stage has hot core and when it reaches the continent acquires destructive characteristics like a hurricane. This shows the hybrid character of the Catarina storm.

In relation to the simulation experiments, the high resolution of the global model did not improve surface winds and the intensity of the simulation of low the pressure which remains 4 hPa above observations, showing the necessity of use of mesoscales models may be non-hydrostatic and cloud microphysics and higher resolution. The scale of the eye of the Catarina storm in the order of 80 km and at the moment where it arrived at the continent have appeared two nuclei of intense precipitation one in the Southeastern edge of the eye, responsible for intense rains and winds in the coast, and another one in the center of the eye, responsible for intense rains and winds in the eastern part of Santa Catarina. These two nuclei joined covering the eye with cloudiness, as shown in figure 18. Certainly the simulation of these processes does not obey the hydrostatic approach and its scale demands cloud microphysics for an adjusted simulation. However, the global model captured the main characteristics of the phenomenon and the resolution increase is essential to better define the precipitation field, due to a better definition of the topography.

The theoretical discussion using the linearized equation of the quasi-geostrophic potential vorticity, shows that the westward propagation due to the stretching of vorticity (divergence term) based in observations is compatible with the relations of the group and phase velocity when applied to the case of the Catarina storm giving westward propagation of phase and energy in relation to the basic state.

More detailed studies must be carried through to better characterize the phenomenon, mainly in the energetic point of view and simulation with models that has more appropriate parameterizations for the scale and intensity of the phenomenon.

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