Rainstorms during spring in Sao Paulo State, Brazil: A Case Study of 27-28 September 2015.

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Abstract
Rainstorms were observed in Sao Paulo State, Brazil (53°W-44°W; 20°S-25°S) during 27-28 September 2015. This was the second event of simultaneous strong storms in September 2015, but with smaller scope compared to that in 7-8 September 2015. Even thus, the impact was harmful in many regions of Sao Paulo State. In this paper the atmospheric conditions responsible for the intense rainfall and their social consequences were analyzed. The results showed that the storms affected most of Sao Paulo State causing floods and threw down trees, affecting the distribution of electric energy. The cause of the intense rainfall was a strong squall line moving from Parana State to Sao Paulo State. Strong divergence at high levels over the region of the squall line was responsible for the severe weather conditions.
The WRF model was used to simulate the severe weather conditions on 27-28 September 2015. The results showed that model simulations and observations are in a good agreement indicating that the model may be an important tool to be used to forecast severe weather events in future. The use of WRF model for theses purposes forms part of a co-operative project between National Institute for Space Research (INPE) institution and Energisa Power Company aimed to mitigate the effects of adverse weather conditions.

1. Introduction

September 2015 was an atypical rainy month. Intense rainfall with strong winds affected practically all the regions of Sao Paulo State (53°W-44°W; 20°S-25°S) provoking harmful economic and social impacts (http://sao-paulo.estadao.com.br/noticias/geral,capital-paulista-registra-osetembro-mais-chuvoso-desde-1993,1770753). Events of severe weather cause the damage of hundreds of residences and put in risk people life. They affect the transmission and distribution of electric energy and the agricultural activities. The impact on system of electric energy is highly preoccupying since Sao Paulo State supplies the national electric energy power. In this paper we analyze the atmospheric conditions which caused the rainstorms occurred in 27-28 September 2015 as well as their social and economic consequences. This was the second event of simultaneous strong storms in September 2015, but with smaller scope compared to that in 7-8 September 2015 (Franchito, 2016). Even thus, the impact was intense in many regions of Sao Paulo State (http://sao-paulo.estadao.com.br/noticias/geral,temporais-deixam-500-mil-sem-luz-no-litoral-e-estragos-no-interior-,1770337). We use a numerical model to simulate the synoptic system which provokes the severe weather conditions in 27-28 September 2015. The simulations can be useful to understand the evolution the weather systems and give information to forecast future synoptic systems which can produce similar harmful effects. Section 2 shows the Data and Methodology used in this study. The synoptic analysis of the event is presented in Section 3; Section 4 shows the social impacts. Section 5 presents the model simulation and the Summary is shown in Section 6.

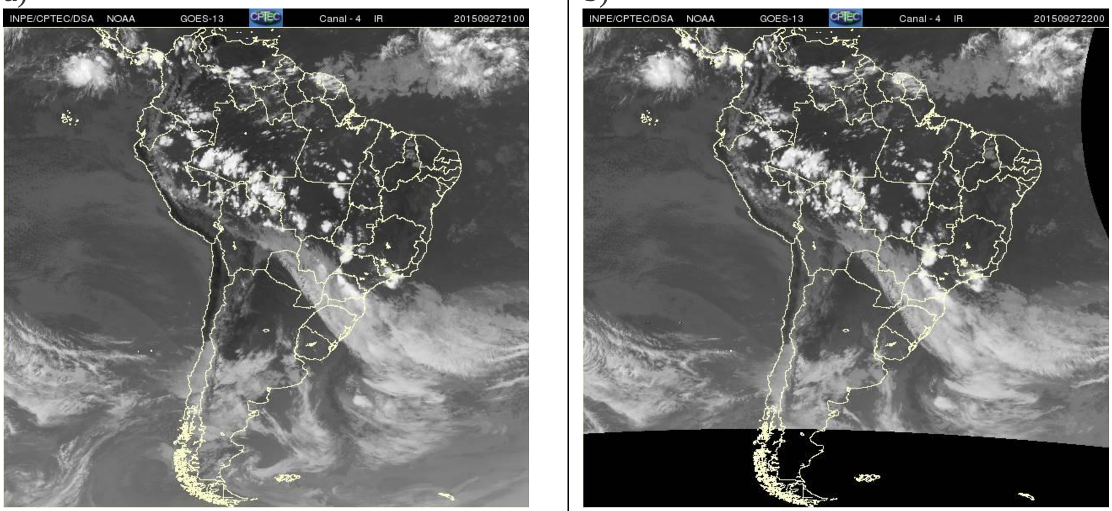
2. Data and methodology

Satellite images are used to identify the atmospheric conditions on 27-28 September 2016 (http://satelite.cptec.inpe.br/home/novoSite/index.jsp). Data of surface pressure, vertical velocity, divergence in high levels from Climate Forecast System Reanalysis (CFSR) are used for analyzing the synoptic systems on 27-28 September 2015. CAPE (Convective Available Potential Energy, Betts, 1974) was calculated using data from GFS (http://nomads.ncdc.noaa.gov/data/gfsanl). The numerical model used is the Weather Research and Forecasting-Nonhydrostatic Mesoscale Model (WRF-NMM) (Janjic, 2003). Information of news agencies is used to illustrate the destroying effects of the rainstorms on 27-28 September 2015.

3. Synoptic analysis

A strong squall line moving from Parana State to Sao Paulo State was responsible for the rainstorms that occurred from the night of 27 September to the dawn of 28 September 2015. The squall line was active in many regions of Sao Paulo State. As shown in Fig. 1 a band of nebulosity extended from the south of the Amazon region towards the Atlantic ocean, passing by the south of the Center-West region, south Brazil and Sao Paulo State. On day 27 September at 2100 UTC the squall line was formed in the north part of this band of nebulosity over Parana State and a cluster of cumulonimbus was developed between the states of Sao Paulo and Mato Grosso do Sul (Fig. 1a-d). These two mesoscale systems developed and propagated towards the east provoking strong convective activity over most of Sao Paulo State (Fig. 1e-f).

a) b)



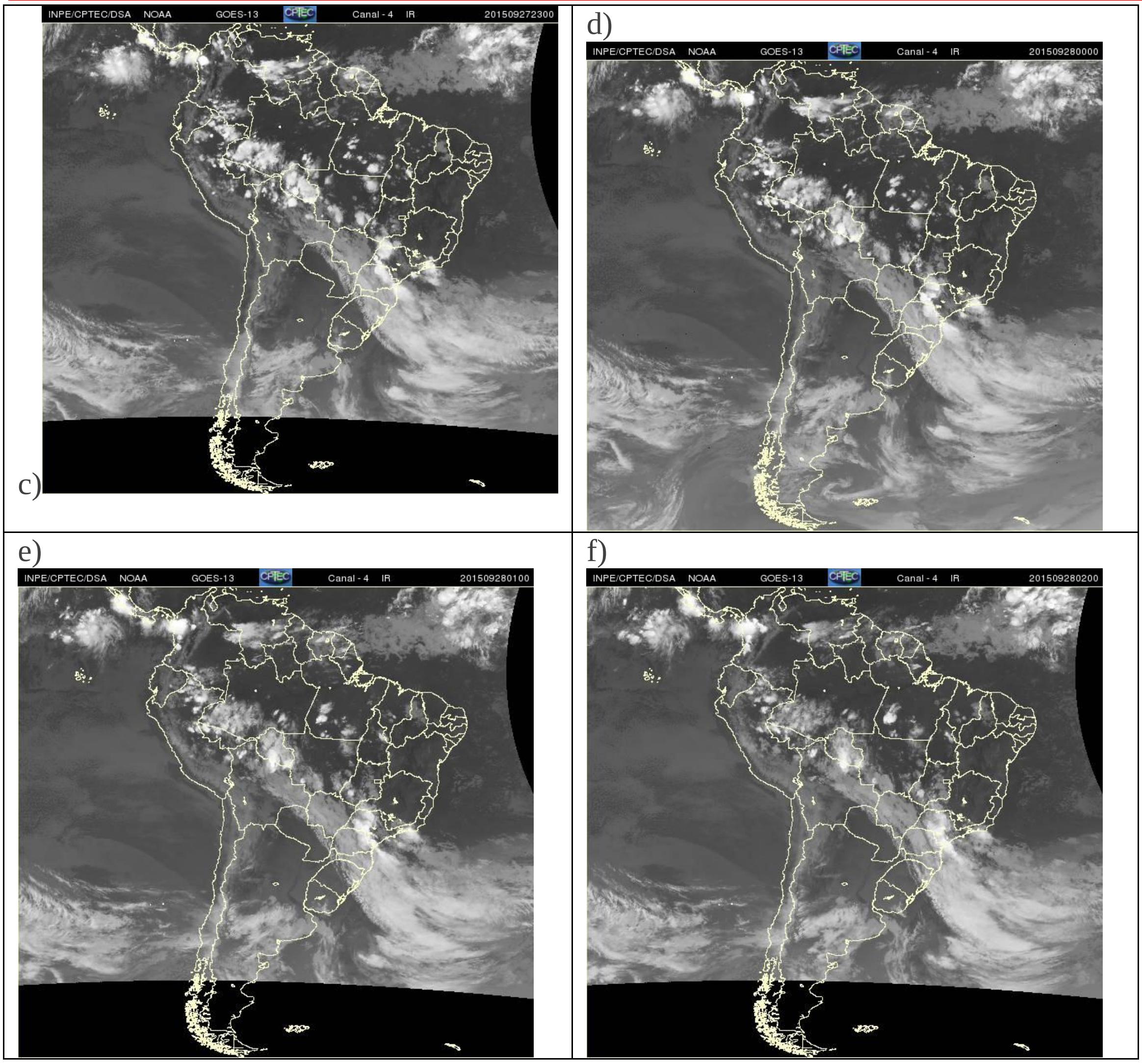


Fig. 1: Satellite images for day 27 September 2015 at 2100 UTC and for day 28 September 2015 at 0200 UTC. Interval of 1h between the images (Source: http://satelite.cptec.inpe.br/home/novoSite/index.jsp).

The surface pressure field shows that the band of nebulosity passing through the continent was associated to a cold front (Fig. 2). The squall line was formed in the warm sector of the cold front, very close to this system. However, the presence of a cold front does not explain entirely the developing of the squall line. From the analysis of the fields of winds at 850 hPa for days 27 and 28 September (Fig. 3) it can be noted that southerlies behind the cold front converged with strong northwesterly winds coming from the Amazon region. When these warm and moist winds reached the cold winds associated to the cold front they ascended forming large vertical extension clouds (cumulonimbus). Also, it is noted that the region where the southerlies reached the northwesterly winds coincided with the region where the squall line is found.

The fields of winds and divergence at high levels (250 hPa) show a cyclonic circulation associated to the wave trough which gives dynamical support to the cold front (Fig. 4). Also, it can be seen a strong divergence over the region where it is found the squall line responsible for the severe weather conditions in many areas of the Sao Paulo State.

An indicator of atmospheric instability is the CAPE. High atmospheric instability are associated with high values of CAPE. The field of CAPE for day 27 September is shown in

Fig. 5. As can be seen, at 1800 UTC there was a region of high values of CAPE along the cold front. The higher values of CAPE were observed between the states of Parana and Sao Paulo indicating that in that region there was conditions for the occurrence of strong rainstorms. The impact on the cities in many areas of Sao Paulo State was strongly destructive, as will show in the next section.

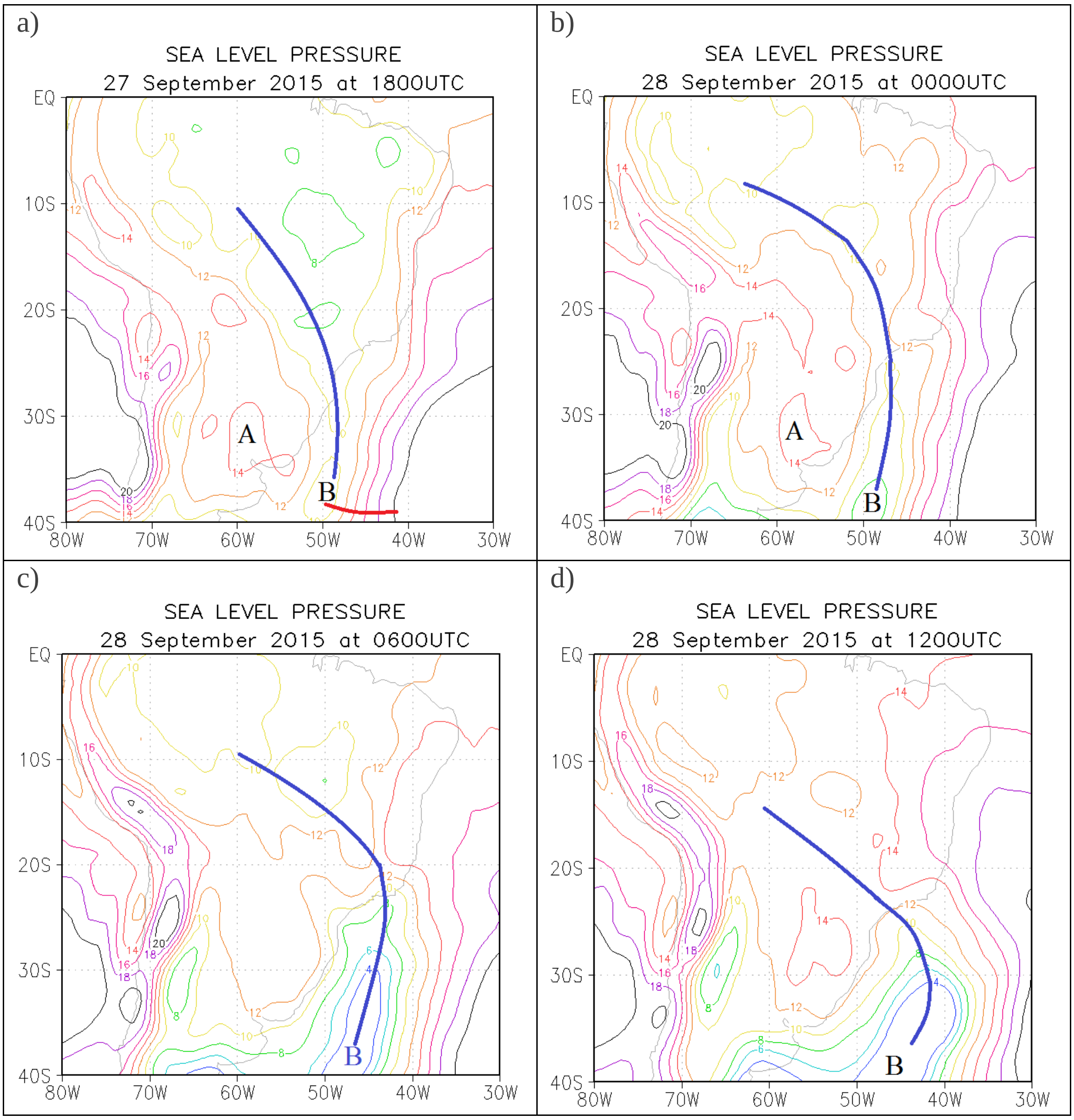


Fig. 2: Sea level pressure: a) for day 27 September 2015 at 1800 UTC, and for day 28 September 2015 at: 0000 UTC, c) 0600 UTC and d) 1200 UTC. Units, hPa. Source: http://nomads.ncdc.noaa.gov/data/gfsanl.

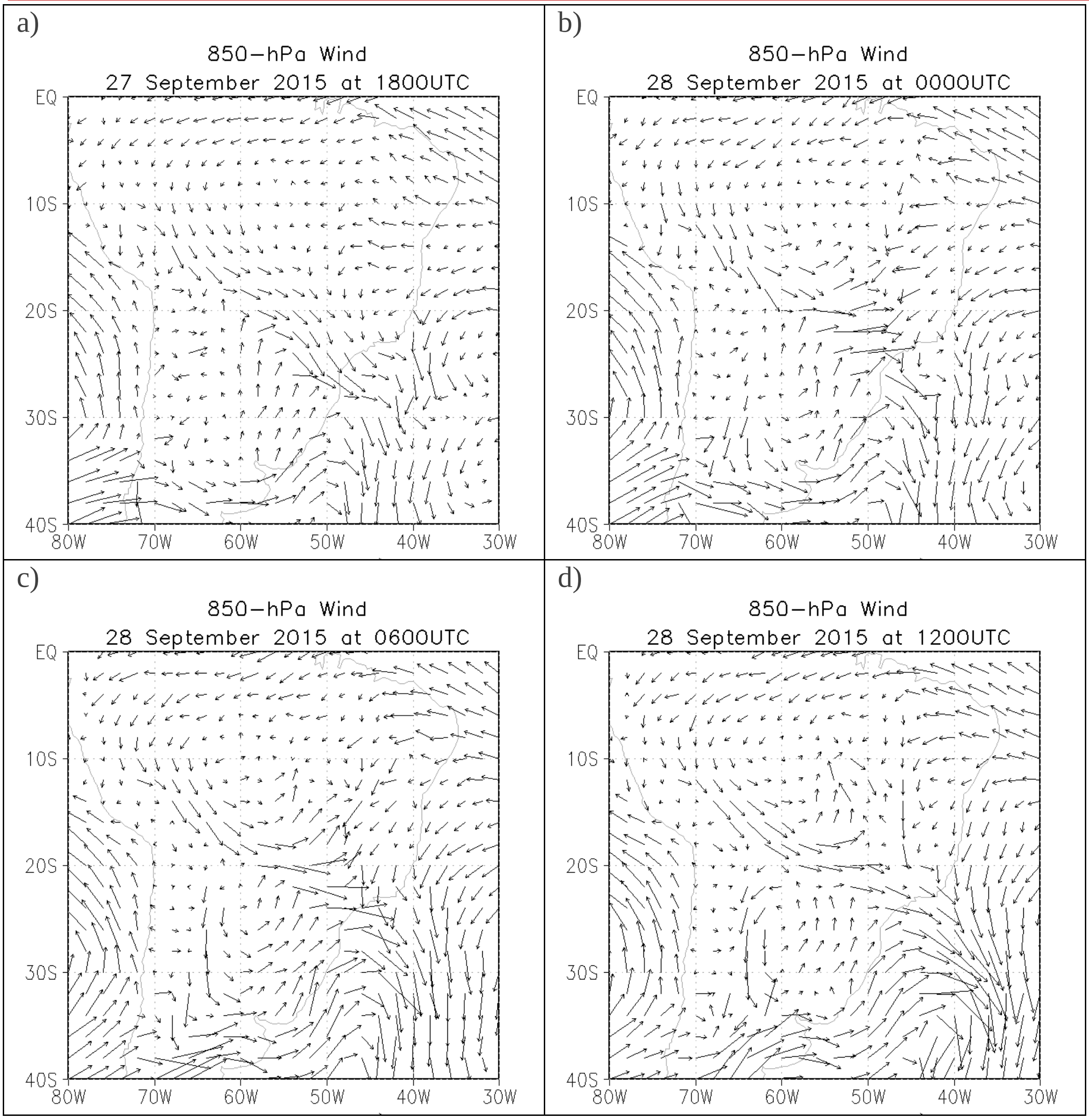


Fig. 3: Legend similar to Fig.2, but for the wind field at 850 hPa. Units, m s^{-1}.

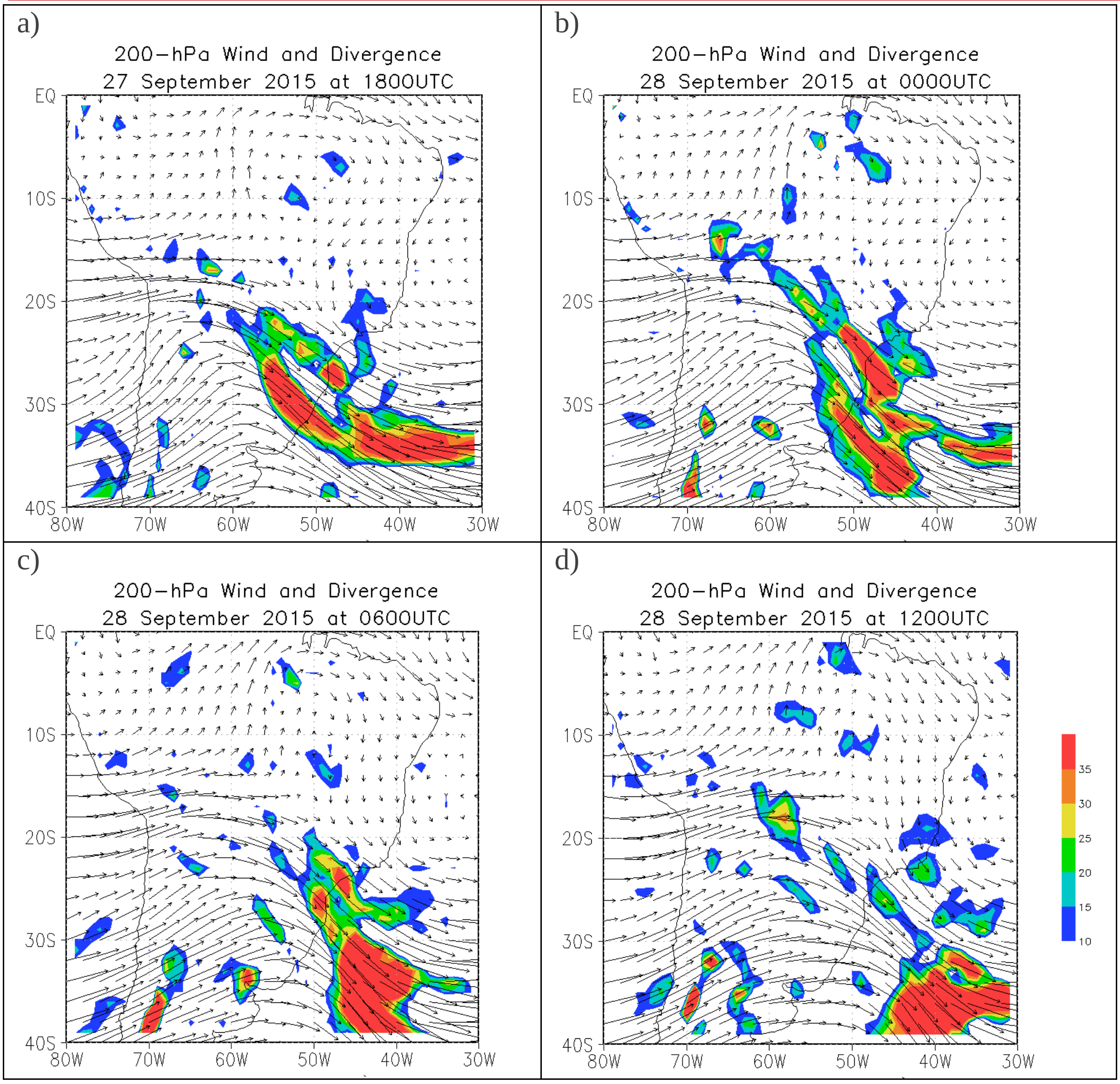


Fig. 4: Legend similar to Fig.2, but for the divergence (s^{-1}) and wind field at 250 hPa. (m s^{-1}).

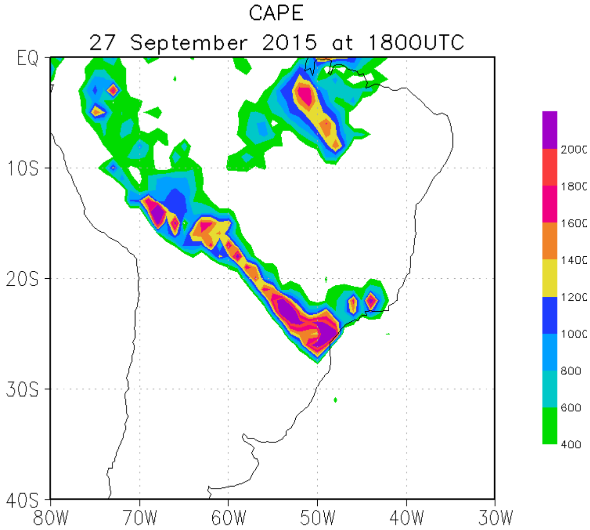


Fig. 5: Values of CAPE for day 27 September 2015 at 1800 UTC. Source: http://nomads.ncdc.noaa.gov/data/gfsanl.

4. Social impacts

The rainstorms that occurred on days 27-28 September 2015 caused harmful effects in many cities of Parana and Sao Paulo States. In the Parana State the storms were accompanied by gust winds higher than 70 km h^{-1} causing damage in many residences. The impact of the rainstorms was higher in the city of Ponta Grossa where more than 600 people were affected (http://www.iguaimix.com/v3/2015/09/28/temporais-causam-transtornos-em-sao-paulo-e-parana-previsao-e-de-tempestades-severas-para-a-primavera/). In Presidente Prudente, located in the west region of the Sao Paulo State (see Fig. 6), wind gusts of 86 km h^{-1} occurred in the evening of day 27 September. The strong winds unroofed residences, threw down trees, turned street lamps out causing damage for the people (http://g1.globo.com/sp/presidente-prudente-regiao/noticia/2015/09/vendaval-causa-destelhamentos-e-prejudica-fornecimento-de-energia.html). There was also impact on the distribution of electric energy. Seven towers of electric energy transmission fell down during the storm on day 27 September. As a consequence eight cities in the region remained without electric energy from the evening of day 27 to the dawn of day 28. Figs. 7a illustrates the fall of electric energy towers in this region.

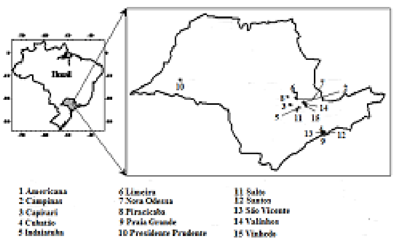


Fig. 6: Location of some cities located in Sao Paulo State which were attained by the strong rainstorms on days 27-28 September 2015.

Fig. 7: Impacts of the rainstorms on Sao Paulo State: a) fall of electric energy towers in in the evening of 27 September 2015 in the region of Presidente Prudente; b) Impacts of the storms on the down day 28 September 2015: b) Salto, c) Campinas. Source: (http://g1.globo.com/sao-paulo/sorocaba-jundiai/noticia/2015/09/tempestade-derruba-roda-gigante-e-arranca-mais-de-200-arvores-em-salto.html); http://g1.globo.com/sp/presidente-prudente-regiao/noticia/2015/09/vendaval-causa-destelhamentos-e-prejudica-fornecimento-de-energia.html http://g1.globo.com/sp/campinas-regiao/noticia/2015/09/temporal-tem-ventos-ate-1425-kmh-na-regiao-de-campinas-diz-cepagri.html.

Torrential rainfall with wind gusts provoked damage in the interior and litoral of Sao Paulo State in the dawn of 28 September. Around 500 thousands of residents in the Baixada Santista (litoral) retained without electric energy due the storm. The rainfall associated to strong winds threw down trees and unroofed residences. The cities of Santos, Sao Vicente, Praia Grande and Cubatao (see Fig. 6) were the most affected (http://www.iguaimix.com/v3/2015/09/28/temporais-causam-transtornos-em-sao-paulo-e-parana-previsao-e-de-tempestades-severas-para-a-primavera/). In the interior of Sao Paulo State several harmful consequences occurred. In the region of Salto more than 200 trees fell down, the traffic in many streets was interrupted and 18 thousands of home stayed without electric energy due to gust winds of 100 km h^{-1} (http://g1.globo.com/sao-paulo/sorocaba-jundiai/noticia/2015/09/tempestade-derruba-roda-gigante-e-arranca-mais-de-200-arvores-em-salto.html). Strong winds reaching 142.5 km h^{-1} occurred in the region of Campinas (center of the state) (Fig. 6). As a consequence 52 thousands domiciles remained with a lack of electric energy. In the city of Campinas 31 mm of precipitation was registered according to the civil defense. In cities of the region, like Vinhedo, Valinhos, Indaituba and Americana, damages also occurred such as fall down trees and dropped conducting wires affecting the transmission and distribution of electric energy. In cities of the center-eastern of state, as Piracicaba, Nova Odessa, Capivari and Limeira, the harmful impact of the storms was also observed (http://g1.globo.com/sp/campinas-regiao/noticia/2015/09/temporal-tem-ventos-ate-1425-kmh-na-regiao-de-campinas-diz-cepagri.html). For the locations of the cities see Fig. 6.

Figs. 7b-c illustrates the damages in Salto and Campinas, respectively, caused by the rainstorms during 27-28 September.

5. Numerical simulation

In this section the fields of some meteorological variables during the rainstorms of 27-28 September were simulated using the WRF model. These simulated fields are compared with those obtained in the synoptic analysis (Section 3). The objective of this simulation is to examine if the model is able to capture the behaviour of the atmospheric conditions during the rainstorms. The use of the WRF model to simulate several weather conditions makes part of a co-operative project between National Institute for Space Research (INPE) institution and Energisa Power Company, which is in progress, aimed to mitigate the effects of adverse weather conditions as in the case of the rainstorm that occurred on 27-28 September 2015 (see Franchito et al., 2016).

We run the WRF-NMM model version 3.6.1 using a 9 km resolution grid with 615 rows, 1392 columns, and 38 vertical layers. The modeling domain covers the South America continent. The domain is centered at geographical coordinate (19.5◦ S, 59.0◦ W). The NMM core is also a fully compressible, non-hydrostatic mesoscale model with a hydrostatic option (Janjic et al. 2001, Janjic 2003). It consists of a hybrid sigma-pressure, terrain following vertical coordinate, Arakawa E-grid, a forward-backward time integration scheme, a second order advection option in the horizontal and vertical, and conservation of energy and enstrophy (Janjic 1984). The time step is 24 sec.

WRF physical parameterizations (see Table 1) include a modified Betts–Miller cumulus parameterization (Betts 1986; Betts and Miller 1986; Janic 1994) and Kain and Fritsch (1993) scheme, a gridscale cloud water/ice prediction scheme (Ferrier et al., 2002), planetary boundary layer: Mellor-Yamada-Janjic Turbulent Kinetic Energy scheme (TKE-MYJ, Janjic, 1996, 2002), surface layer: Janjic Similarity (Janjic, 1996, 2002), the Geophysical Fluid Dynamics Laboratory (GFDL) radiation scheme with predicted cloud interaction (Lacis and Hansen 1974; Fels and Schwarztkopf 1975), and a four-layer soil land surface package (Chen and Dudhia, 2001). The analyses and forecasts from the Global Forecasting System (GFS) from the US National Centers for Environmental Predictions (NCEP), were used to initialize the model and to specify the lateral boundary conditions, updated each 3 h.

Table 1: WRF-NMM model configuration.

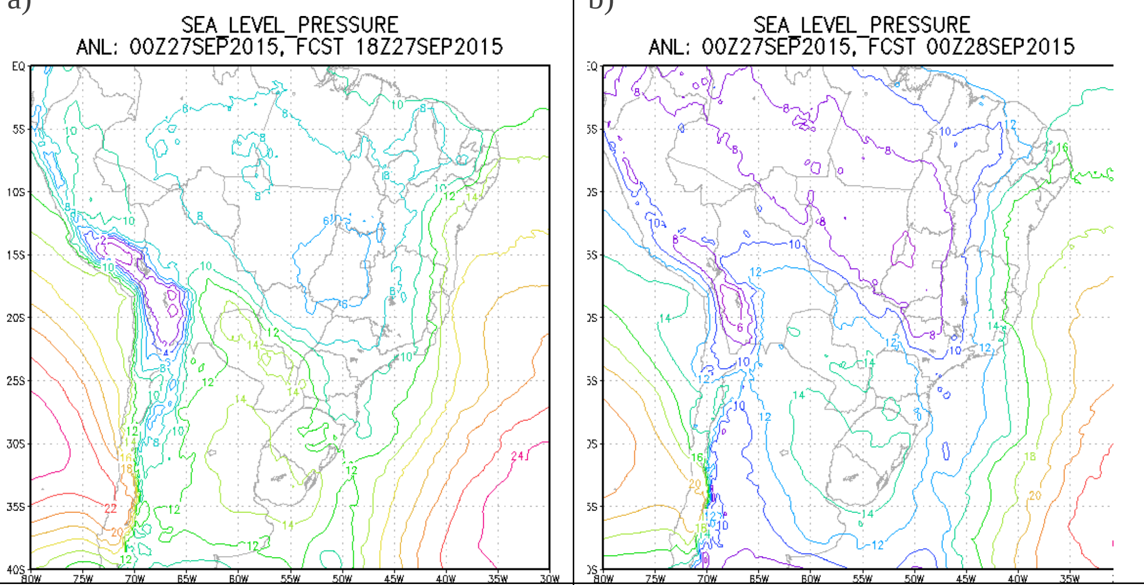
Model	WRF-NMM
Dynamics	Nonhydrostatic
Horizontal resolution	9 km
Gridpoints (west-east by north-south)	990x1000
Forecast length	72/84 hrs
Map projection	Rotated latitude and Longitude
Domain	South America
Horizontal grid system	Arakawa E-grid
Vertical coordinate	Hybrid sigma to pressure vertical coordinate (38levels)
Radiation	GFDL/GFDL
Surface layer	Janjic scheme

Land surfasse	Noah land surfasse scheme
Cumulus	Betts-Miller-Janjic
PBL parameterization	Mellor-Yamada-Janjic
Microphysics	Ferrier (new eta) scheme

Figures 8a-d show the sea-level pressure field simulated by the model. As can be seen, there is a good agreement with the observed one. The low pressure associated to the cold front in the simulation matches well with that in the observation (point B in Figs. 2a-d). The squall line is formed in the warm sector of the cold front. The comparison between Figs. 9a-d and 3a-d shows that the model is able to simulate the region of convergence of the southerlies associate to the cold front and the strong northwesterly winds coming from the Amazon region. This region coincides with the region where the squall line is found (Figs. 8a-d and 2a-d). From Figs 10a-d and 4a-d it can be seen that the model simulates the cyclonic circulation at high levels associated to the wave trough which gives dynamical support to the cold front. Although the model simulates reasonably well the strong divergence at high levels in the south Brazil it does not capture the other region of divergence where the squall line responsible for the severe weather conditions in many areas of the Sao Paulo State is found. This may due to the resolution used in the model run (9 km). Since the divergence is calculated using the values of winds in adjacent points, the increase of the grid spacing may adjust the correct position of the region of divergence.

The results above indicate that the model used in the present study may be an important tool to forecast future synoptic systems that provoke strong rainstorms and thus may be used to mitigate the adverse weather conditions. However, many other tests must be done to have more clear conclusions.

a) b)



c) d)

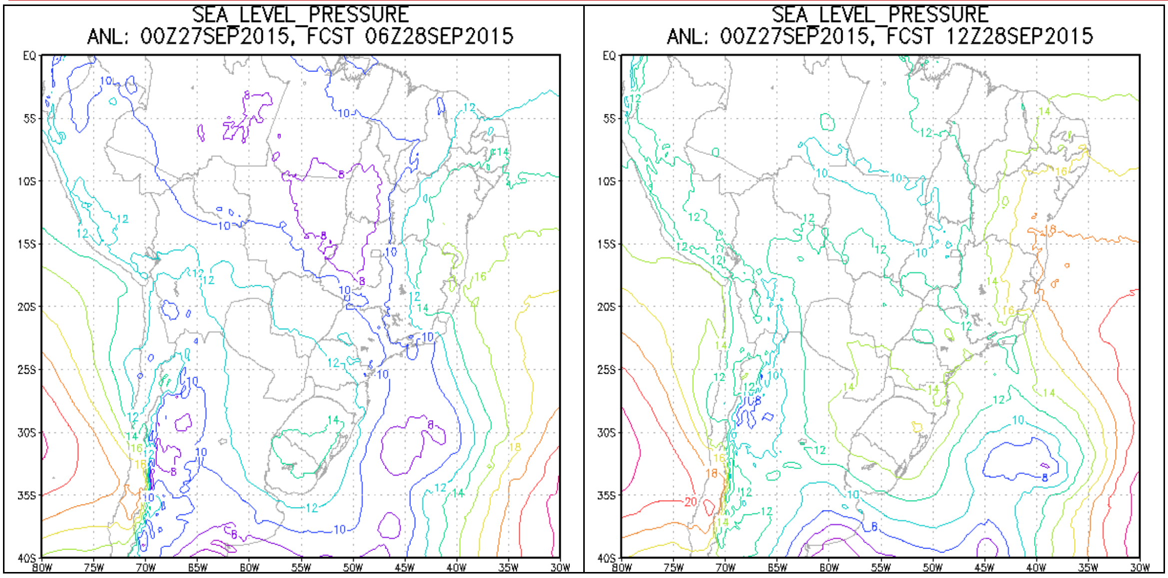
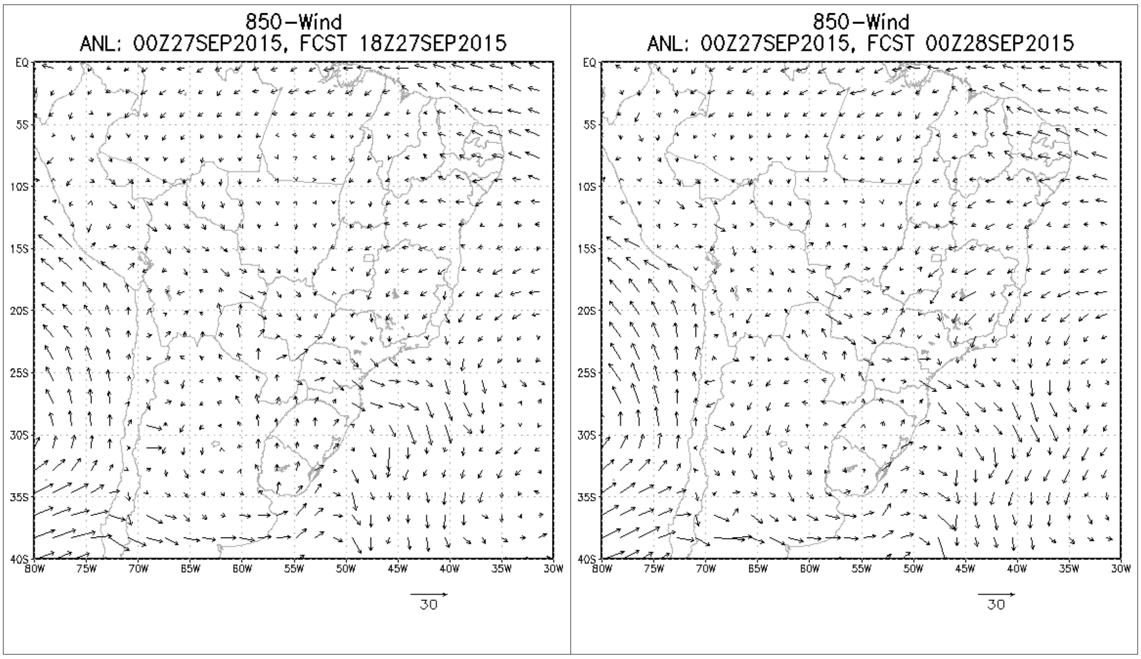


Fig.8: Simulated sea-level pressure: a) for day 27 September 2015 at 1800 UTC, and for day 28 September 2015 at: 0000 UTC, c) 0600 UTC and d) 1200 UTC. Units, hPa.



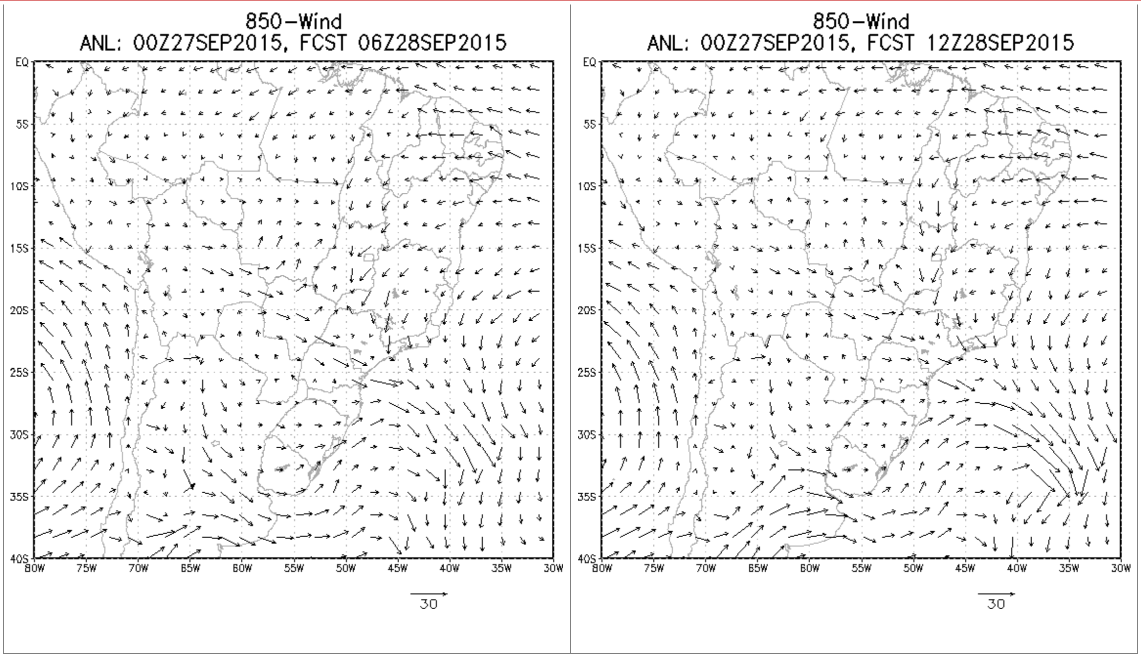
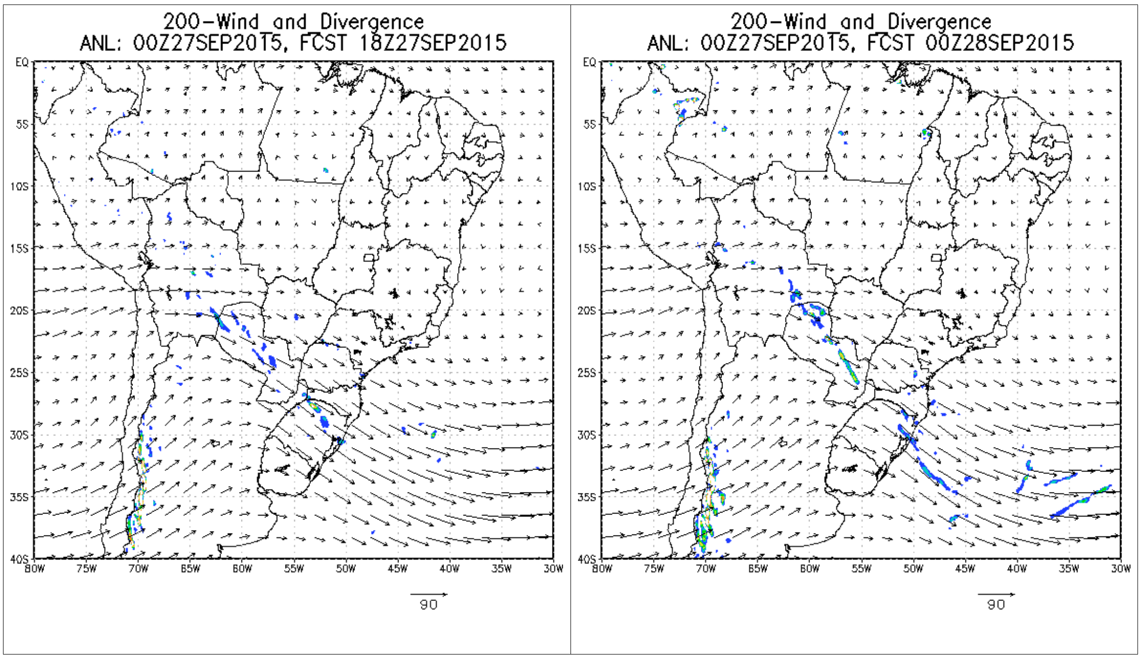


Fig.9: Legend similar to Fig.2, but for the wind field at 850 hPa. Units, m s^{-1}.



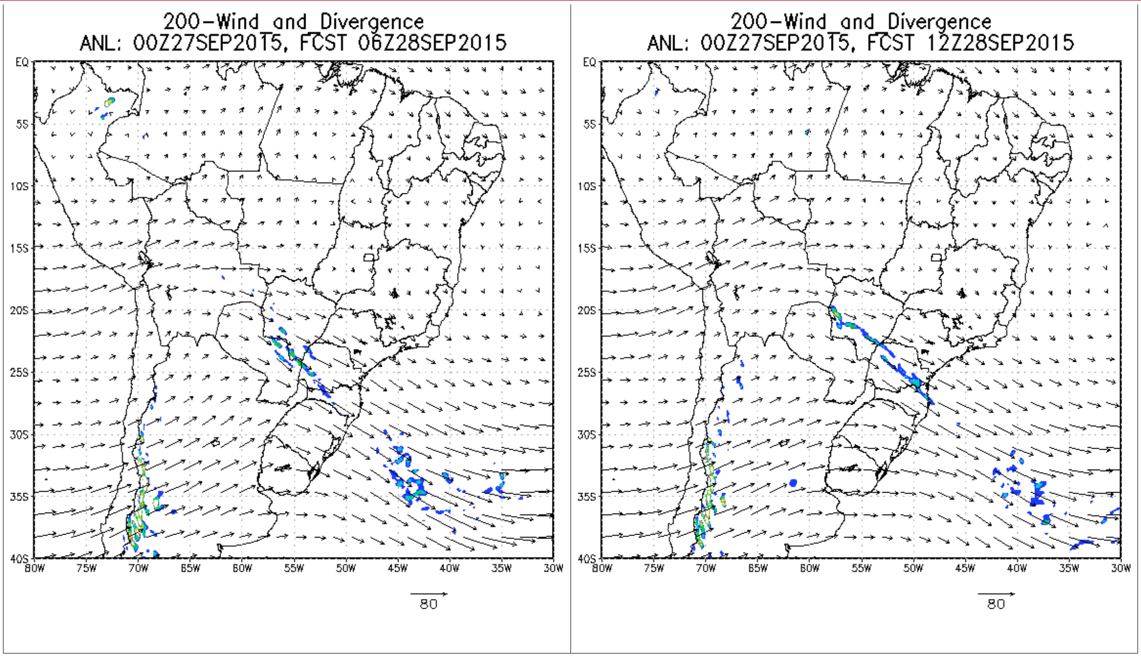


Fig. 10: Legend similar to Fig.2, but for the divergence (s^{-1}) and wind field at 250 hPa. ($m\ s^{-1}$).

6. Summary

In this paper the atmospheric conditions during the rainstorms occurred in 27-28 September 2015 were analyzed. This was the second event of simultaneous strong storms in September 2015, but with smaller scope compared to that in 7-8 September 2015. Even thus, the impact was harmful in many regions of Sao Paulo State. The rainstorms occurred from the night of 27 September to the dawn of 28 September 2015. The intense rainfall was caused by a strong squall line moving from Parana State to Sao Paulo State. Strong divergence at high levels over the region of the squall line was responsible for the severe weather conditions.

The WRF model was used to simulate the event of 27-28 September 2015. Some meteorological variables such as sea-level pressure, winds at 850 hPa and 250 hPa showed good agreement with the observations. This indicates the model may be an important tool to be used to forecast severe weather events. The use of the WRF model to simulate several weather conditions makes part of a co-operative project between National Institute for Space Research (INPE) institution and Energisa Power Company aimed to mitigate the effects of adverse weather conditions. The project is in progress and the results are expected to be useful for the national economy and the people welfare.

Acknowledgements
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