Improving the CPTEC ensemble forecasting for the hurricane Catarina using extra EOF initial perturbations

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Abstract

Hurricane Catarina, occurred in March 2004, represented the first confirmed hurricane over South Atlantic Ocean. Typically, Brazilian operational forecasts at time of Catarina failed in predicting its development. In this paper we show that the method for producing perturbed initial conditions based on empirical orthogonal functions (EOF method) could be used to perturb the extratropics and to compute perturbations for a target area over South America in order to improve the performance of the ensemble prediction system of the Center for Weather Prediction and Climate Studies (CPTEC) for predicting the intensity and the trajectory of the hurricane Catarina.

1. Introduction

Hurricane Catarina developed over an area where is not common to observe such intense tropical system. It initiated over South Atlantic Ocean near the Brazilian coast around 20 March 2004 as an extratropical cyclone. It started moving toward the continent after a tropical transition two days later its origin, making landfall around 28 March (Pezza and Simmonds, 2005). Climatologically, the region where Catarina formed presents high wind shear and relatively cold sea surface temperature which is not ideal conditions for tropical cyclone developments (McTaggart-Cowan et al., 2006). In general, numerical predictions of Catarina evolution produced by the Brazilian meteorological operational centers underestimated its intensity and indicated conflicting information concerning the trajectory (Silva Dias et al., 2004). Particularly, the weather forecasts based on the ensemble prediction system (EPS) of the Center for Weather Prediction and Climate Studies (CPTEC) which was operational in that period did not present satisfactory performance in simulate the system.

The EPS-CPTEC at time of Catarina occurrence was a perfect model approach with perturbation on initial conditions applied to temperature and wind fields on a latitude belt 45°S-30°N (Mendonça and Bonatti, 2006). The initial perturbations were computed using the Empirical Orthogonal Function method (EOF method) developed by Zhang and Krishnamurti (1999) (hereinafter ZK1999). ZK1999 demonstrated that EOF method produce suitable perturbations for hurricane predictions when the hurricane initial position is perturbed and the EOF initial perturbations are computed in the vicinity of the tropical system. Coutinho (1999) adapted the EOF method to the CPTEC Atmospheric General Circulation Model (CPTEC-AGCM) in order to produce ensemble predictions mainly over South America. For this purpose, perturbations were applied for temperature and wind analysis fields over a broad area 45°S-30°N, since the restriction of the perturbation for a more limited area had affected the perturbation growth in regions relevant to the development of the synoptic systems.

Accurate forecasts of intensity and trajectory of a severe system like the hurricane Catarina may represent a lesser amount of loss of human lives and a reduction of damages caused by the associated strong winds and heavy rain. We suppose that the EOF perturbations could represent better the uncertainty associated to Catarina event if the method would be adjusted to incorporate new elements in the perturbed initial conditions such as perturbations on surface pressure (P) and specific humidity (Q) fields, extratropical perturbations and the computation of initial perturbations on a target area in the vicinity of the system. The influence that these new elements have on the CPTEC-EPS is investigated analyzing how the trajectory and the cyclone central pressure is simulated when these new elements are incorporated individually or combined in the CPTEC-EPS perturbed initial perturbations.

Descriptions of initial conditions, CPTEC-AGCM, EOF method and detail of the experiments performed in this study are described in section 2. A synoptic view of Hurricane Catarina and the results are discussed in section 3. In section 4 is presented the conclusions.

2. Data and methodology

2.1. Initial conditions and CPTEC atmospheric general circulation model

The initial conditions (control analyses) used in this study are the spectral analyses generated by the National Center for Environmental Prediction (NCEP) and kindly provided for the CPTEC producing operational ensemble weather forecasts. The current resolution used for ensemble forecasts are approximately 0.975° longitude x latitude in grid space and 28 sigma layers in the vertical. The 0000 UTC and 1200 UTC analyses of the period surrounding Hurricane Catarina (20 March 2004 through 28 March 2004) are considered for CPTEC-EPS simulations and forecast evaluations.

The model used in this study is the CPTEC-AGCM at the same resolution as the analyses. Briefly, the CPTEC-AGCM is based on the spectral solution of the primitive dynamic equations in the form of divergence and vorticity, virtual temperature, specific humidity and logarithm of the surface pressure, and includes sub-grid processes through physical parameterizations. Details of the model can be obtained in Kinter et al. (1997).

2.2. The operational CPTEC-EPS

The procedure employed to generate the perturbed atmospheric initial conditions is based on the method developed by ZK1999, originally proposed for hurricane forecasting using the Florida State University (FSU) AGCM. This method, called *EOF-based perturbation*, was developed in view of the fact that during the first few days of model integration, perturbations grow linearly. The procedure for producing perturbed analyses is outlined in the following steps:

a) *n* random small perturbations are added to the control analysis;

b) the resulting *n* random perturbed analysis and the control analysis are used to integrate the model for 36 h (optimal interval) saving results every 3 h;

c) *n* temporal series of difference field forecasts are constructed by subtracting the control forecast from the perturbed forecasts at each time increment of 3 h;

d) an EOF analysis of the temporal series is performed on a domain of interest in order to obtain the fastest-growing perturbations (considered as the eigenmodes associated with the largest eigenvalues). These modes are called *optimal perturbations*. More details of the EOF computation can be found in ZK1999;

e) the *optimal perturbations* are rescaled in order to make their standard deviation of the same order as the initial perturbations;

f) adding (subtracting) these rescaled *optimal perturbations* to (from) the control analysis produces an ensemble of *2n* initial perturbed states.

For each CPTEC-EPS simulation, seven EOF-based perturbations are generated and added (subtracted) to (from) the control analysis, creating a set of fourteen perturbed initial conditions. Each ensemble member represents an integration of the CPTEC-AGCM up to 15 days lead time from a perturbed initial condition or from the control analysis. The result obtained from each EPS simulation is an ensemble of 15 members for each forecast range.

2.3. Experimental design

While the perturbation growth over midlatitudes is mainly caused by dynamic instability (according to linear perturbation theory), in the tropics the perturbations are strongly influenced by physical processes at smaller scales than those resolved by models and exhibit a growth rate much smaller than that over the extratropics (Zhang, 1997; Reynolds et al., 1994). Therefore, it is more reasonable to generate perturbations over extratropics and tropics separately. Special treatment of perturbations over the tropics was inserted at the European Centre for Mediun-Range Weather Forecasts (ECMWF) EPS through the computation of tropical singular vectors over target areas

(Barkmeijer et al., 2001; Puri et al., 2001). At NCEP, a regional rescaling, based on analysis uncertainties, contributed to the enhancement of the ensemble mean skill over the tropics and the Southern Hemisphere (Toth and Kalnay, 1997). In those experiments in which EOF-based perturbations are extended to midlatitudes, we consider it is more suitable to calculate the perturbations for the tropics and extratropics separately. In an attempt to obtain better-adjusted EOF-based perturbations for South America, regional perturbations are computed over two almost homogeneous areas with respect to the influence of meteorological systems: a sector with tropical regime, strongly influenced by convective systems (Northern South America: 100W-10W; 20S-20N); and a region influenced by baroclinic systems (Southern South America: 110W-20W, 60S-20S). Overall, six regions are considered in the computation of EOF-based perturbations, depending on the configuration used for each experiment (to be described later):

- Northern Hemisphere (NH): 0-360W; 20N-90N;
- Southern Hemisphere (SH): 0-360W; 20S-90S;
- Tropics (TR): 0-360W; 20S-20N;
- Extended Tropics (ETR): 0-360W; 45S-30N;
- Northern South America (NSA): 100W-10W; 20S-20N;
- Southern South America (SSA): 110W-20W; 60S-20S.

Another source of initial uncertainties is the two analysis fields that are not perturbed in the operational EOF method configuration: surface pressure and specific humidity fields. Initial EOF perturbations for both fields are proposed in an attempt to introduce more diversity to CPTEC-EPS perturbed initial conditions.

In order to evaluate the impacts that the proposed modifications in the operational CPTEC-EPS perturbation scheme have on the ensemble forecast, five experiments are carried out: Experiment OPER--considered as a reference for other experiments--represents the operational configuration used currently at CPTEC, in this case, the zonal and meridional wind components (U,V) and temperature (T) fields are perturbed over an extended tropical region (TRE); in the second experiment (EXT1), perturbations are computed for three global regions, Northern Hemisphere (NH), Southern Hemisphere (SH) and tropics (TR), and the perturbed fields are again U, V and T; in the third experiment, defined as TROP the perturbed region is the same as the operational version (OPER), but includes perturbations to surface pressure (P) and specific humidity (Q) fields (which were not perturbed in the former experiment); in the fourth experiment (EXT2), perturbations in three global regions NH, SH and TR are combined with additional perturbations to P and Q fields; in the fifth experiment, ETSA, besides perturbations in midlatitudes (NH and SH) and the tropics (TR), additional perturbations for two different sectors of South America (Northern South America--NSA and Southern South America--SSA) are computed, and the perturbed fields are P,T,Q,U and V. A list of the experiments and their respective characteristics is presented in Table 1.

3. Results

3.1. Description of Catarina according to analyses

The selected meteorological event, called Catarina, occurred in March 2004 near the Brazilian coast. It was characterized in its mature phase by an eye (Fig. 1), typical of intense tropical systems such as hurricanes, with strong winds and westward displacement. More detailed analyses indicate that Catarina began as an extratropical cyclone embedded in a frontal system and underwent a tropical transition two days later under low vertical wind shear over near-average sea surface temperatures (Pezza and Simmonds, 2005). Satellite estimates indicated that the cyclone's central pressure was about 970-975 hPa, with sustained winds of up to 35 m/s (Silva Dias et al., 2004).

Figure 2 shows the representation of Catarina by NCEP initial conditions at 1200 UTC 24 March 2004 as seen by msl pressure and wind intensity fields, at the horizontal resolution used in this study. It can be verified that the analysis significantly overestimates the cyclone central pressure (underestimates its intensity). For this situation, the analysed pressure value inside the center of the system is around 1008 hPa. The wind magnitude on the cyclone boundaries is relatively smaller than those estimated by satellite. According to the analysis, the largest wind speed - around 14 m/s - occurs in the southern part of the system. Part of the underestimation of the cyclone intensity by the analysis may be associated to the relatively low resolution used in this study. The inadequate representation of the system by the initial conditions makes difficult the simulation of the event by numerical models. Zhu and Thorpe (2006) found that an accurate representation of the initial conditions for extratropical cyclones is essential for predicting the development of these systems with some skill.

The trajectory of Catarina, as represented by the NCEP analyses, is given in Fig. 3. The space between two points represents the displacement of the system over a period of 12 hours. The initial point of the trajectory (northernmost point) indicates the position of the system at 1200 UTC 20 March 2004. The last point, when the center of the system had already reached the continent, was 1200 UTC 28 March 2004. Initially, the system moved southeastward. Then, after a change in its dynamic structure from extratropical cyclone to tropical cyclone, it turned westward, moving toward the continent. Despite the low resolution of the analyses used in this study, the trajectory shown in Fig. 3 is similar to that obtained from ECMWF high-resolution analyses by Pezza and Simmonds (2005).

3.2. Results from ensemble simulation experiments

The prediction of Catarina event is carried out in order to investigate the influence that the modifications in the procedure of producing perturbed analyses suggested in this study have on the performance of the CPTEC-EPS. In general, prediction of severe events by numerical models is difficult, especially at the low resolution (about 100 Km) used here. Nevertheless, we try here to assess whether such modifications add useful information to CPTEC ensemble weather forecasts. This study aims to assess mainly the ensemble prediction of the cyclone trajectory and the value of the central pressure. The information about the trajectory and intensity of the cyclone is valuable for an analysis of the risk of damage if the system should strike.

For each experiment, ensemble simulation started at 1200 UTC 24 March 2004. In Fig. 4a, it is clearly noticed that the model is deficient in simulating the evolution of the system. The control prediction (dashed lines) is able to simulate the system only up to forecast hour 48. From 1200 UTC 24 March until 0000 UTC 26 March, Catarina moved northwest, then, it turned westward. The cyclone trajectory predicted by the control forecast shows a more northward displacement than was observed. The ensemble members (dots) of the operational configuration (experiment OPER) present a large spread in forecasts of the cyclone position. Some members are able to simulate the system up to forecast hour 72 and are able to simulate the change in the system's direction of motion. However, in general, the ensemble members also indicate trajectories to the north of those observed. The results of other experiments (Figs. 4b-g) indicate that those experiments with extratropical perturbations and perturbations on P and Q fields applied simultaneously (EXT2 and ETSA) present greater spreads in the predicted trajectories, enhancing the overlap with the analyzed track. The inclusion of perturbations to surface pressure and specific humidity fields (experiments TROP, EXT2 and ETSA) causes an increased dispersion of the cyclone initial position when compared with the experiments without these perturbations (experiments OPER and EXT1). This result suggests that perturbations, mainly to surface pressure, can produce an effect similar to those applied to cyclone position by Zhang (1997).

Figure 5 shows the results of central pressure predictions. It is observed that the cyclone central pressure value is overestimated by the control prediction (dashed line). This result was also obtained by Bonatti et al. (2006) in a simulation of the Catarina episode, using a high resolution (T511L64, about 22 Km) version of CPTEC-AGCM model. The overestimate of the cyclone central pressure is due in part to the position at which the model locates the maximum heating source--around 500hPa--whereas it was observed at around 850hPa in the analyses.

For experiment OPER (Fig. 5a), it is verified that the forecasted values of msl pressure (dots) are higher than those observed at all forecast lead times. Although the ensemble mean (dotted line) was able to maintain the cyclone 12 hours longer than the control forecast did, it shows values very close to that of the control. The application of perturbations in the extratropics in experiment EXT1 (Fig. 5c) produces a small growth in the ensemble spread and slightly improves the ensemble mean prediction. However, the predicted pressure values are higher than those observed. With additional perturbations to surface pressure and specific humidity fields in experiment TROP (Fig. 5b), the ensemble mean maintains the cyclone out to forecast hour 84, although the ensemble mean values are still very close to the control values at the first few forecast lead times. The inclusion of additional perturbations in the extratropics and on P and Q fields in experiment EXT2 increases the spread and simulates central pressure values, as seen in the ensemble mean, closer to the analyzed values. Moreover, at forecast hour 12 the ensemble members capture the value verified in the analysis. The impact of regional perturbations over South America on the performance of ensemble forecasts can be assessed through the results of experiment ETSA (Fig. 5e). It is evident that such perturbations contribute to produce forecasted values of central pressure lower than those obtained in the control experiment (OPER). The ensemble mean values are closer to the observed values.

Generally, the results indicate that the experiment ETSA improves the forecast performance more than do the other experiments. This effect is associated with the application of regional perturbations to the region of South America surrounding Catarina's position. This result is in agreement with those of Puri et al. (2001) who found that reasonable spreads in the tracks for tropical cyclone (TC) prediction are only obtained if a target area around the TC, or in the particular region of the TC, is used in the derivation of the singular vectors.

4. Conclusion

The effect of using the EOF method to insert extra initial perturbations to the extratropics and to surface pressure and specific humidity fields in the CPTEC Ensemble Prediction System is addressed in this study. Also, the computation of regional perturbations over South America is tested. Under the perfect-model hypothesis, five experiments were performed by modifying the regions used to compute the initial perturbations and applying perturbations to P and Q fields. The impacts of such changes were assessed through the reults of the experiments for the particularly intense cyclone Catarina that occurred over South Atlantic in March 2004.

The results revealed that cyclone intensity is underestimated by initial conditions, i.e., the minimum central pressure is higher and the wind on the cyclone periphery is weaker than value estimated from satellite information. Operational ensemble forecasts overestimate the analysed central pressure values and do not indicate a well-configured cyclone after 60 hours forecast lead time. Additional perturbations in the extratropics and to P and Q fields extend that range for an extra 24 hours, and also improve forecasts of cyclone central pressure. The best results were obtained when additional regional perturbations over South America are computed: the number of ensemble members capturing the cyclone track was increased and values of central pressure closer to the analysed values were forecasted.

The results of this study encourage an operational implementation of additional EOF-based perturbations in the extratropics and on P and Q fields, as well as, regional perturbations over South America at CPTEC-EPS in order to improve the quality of CPTEC ensemble forecasts.

References

Barkmeijer J, Buizza R, Palmer TN, Puri K, Mahfouf J-F. 2001. Tropical singular vectors computed with linearized diabatic physics. Quarterly Journal of the Royal Meteorological Society 127 : 685-708.

Bonatti JP, Rao VB, Silva Dias PL. 2006. On the westward propagation of Catarina storm. Proceedings of 8th International Conference on Southern Hemisphere Meteorology and Oceanography, 24-28 April 2006, Foz do Iguaçu, PR, Brazil.

Coutinho MM. 1999. Previsão por conjuntos utilizando perturbações baseadas em componentes principais. (Ensemble prediction using principal-component-based perturbations). M. Sc. Dissertation, INPE, São José dos Campos, SP, Brazil, 136 pp.

Kinter JL, DeWitt D, Dirmeyer PA, Fennessy MJ, Kirtman BP, Marx L, Schneider EK, Shukla J, Straus DM. 1997. The COLA atmosphere-biosphere general circulation model. Volume 1: Formulation. Center for Ocean-Land-Atmosphere Studies. Calverton, MD, COLA Staff, Report N.o 51.

McTaggart-Cowan R, Bosart LF, Davis CA, Atallah EH, Gyakum JR, Emanuel KA. 2006. Analysis of Hurricane Catarina (2004). Monthly Weather Review 134 : 3029-3053.

Mendonça AM, Bonatti JP. 2006. Experiments with EOF-based perturbation method to ensemble weather forecasting in midlatitudes. Proceedings of 8th International Conference on Southern Hemisphere Meteorology and Oceanography, 24-28 April 2006, Foz do Iguaçu, PR, Brazil.

Pezza AB, Simmonds I. 2005. The first South Atlantic hurricane: Unprecedented blocking, low shear and climate change. Geophysical Research Letters 32 : L15712. DOI:10.1029/2005GL023390.

Puri K, Barkmeijer J, Palmer TN. 2001. Ensemble Prediction of tropical cyclones using targeted diabatic singular vectors. Quarterly Journal of the Royal Meteorological Society 127 : 709-731.

Reynolds CA, Webster PJ, Kalnay E. 1994. Random error growth in NMC´s global forecasts. Monthly Weather Review 122 : 1281-1305.

Silva Dias PL, Silva Dias MAF, Seluchi M, Diniz FA. 2004. O ciclone Catarina: Análise preliminar da estrutura, dinâmica e previsibilidade (in Portuguese). XIII Brazilian Meteorological Conference, Brazilian Meteorological Society, 29 August-3 September 2004, Fortaleza, CE, Brazil.

Toth Z, Kalnay E. 1997. Ensemble forecasting at NCEP and the breeding method. Monthly Weather Review 125 : 3297-3319.

Zhang Z. 1997. Hurricane ensemble prediction using EOF-based perturbations. PhD Dissertation, Florida State University, Florida,173 pp.

Zhang Z, Krishnamurti TN. 1999. A perturbation method for hurricane ensemble predictions. Monthly Weather Review 127 : 447-469.

Zhu H, Thorpe A. 2006. Predictability of extratropical cyclones: the influence of initial condition and model uncertainties. Journal of the Atmospheric Science 63 : 1483-1497.

Figure Legends

Fig. 1. Satellite image from GOES-12 Infrared channel at 1339 UTC 26 March 2004. Hurricane Catarina's well-configured eye near the Brazilian Coast can be seen. From: Environmental Satellite Division - Center for Environmental Prediction - National Institute for Space Research (DSA/CPTEC/INPE).

Fig. 2. Mean sea level pressure (hPa) (contours) and wind speed (m/s) (shaded) fields over Catarina region for the CPTEC-AGCM initial condition at 1200 UTC 24 March 2004. The cyclone central pressure is about 1008 hPa and highest wind speed in the neighborhood of the system is about 14 m/s.

Fig. 3. Cyclone Catarina's track as seen by NCEP analyses at T126L28 resolution. The cyclone position is plotted for each 12 hours. The most northern point represents the beginning of the trajectory at 1200 UTC 20 March 2004 and the last point (over the continent) corresponds to the final position at 1200 UTC 28 March 2004.

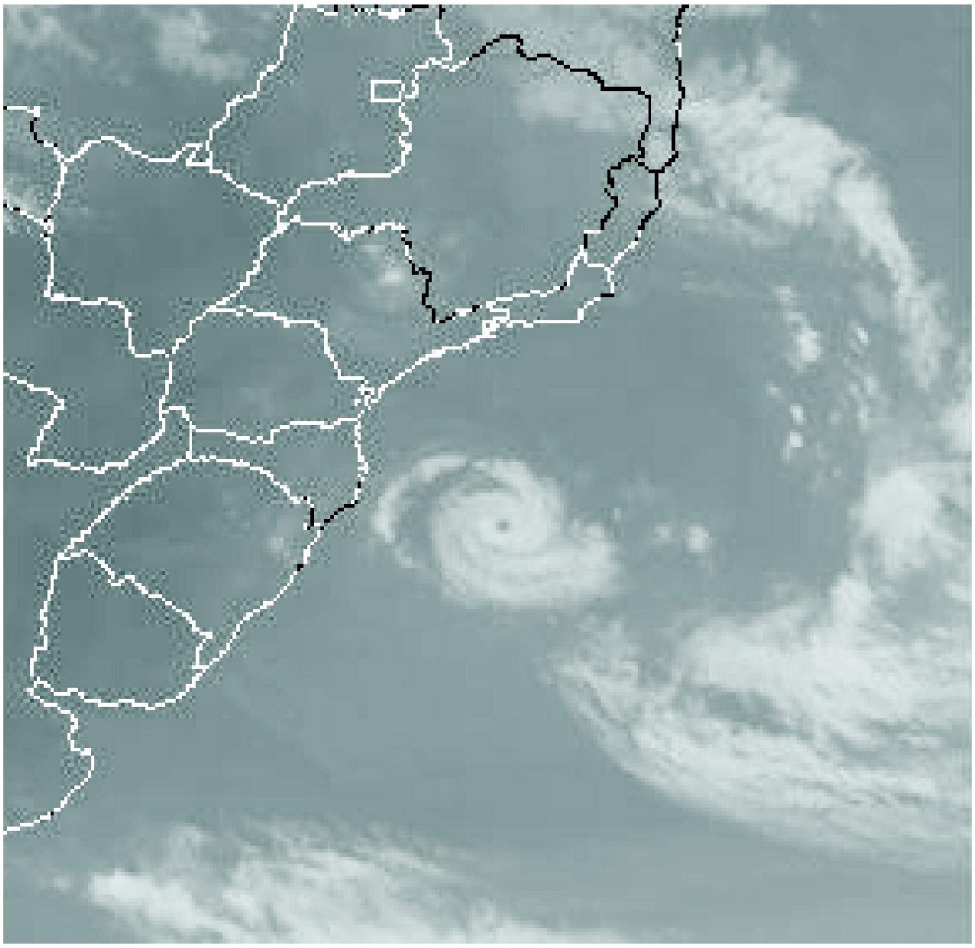
Fig.4. Catarina track prediction, starting from 1200 UTC 24 March 2004. The tracks are over four days and positions are plotted for each 12 hours. Trajectories is based on NCEP analyses (solid lines), control forecast (dashed lines), ensemble mean (dotted lines) and individual ensemble members (dots). The panels refer to experiments (a) OPER, (b) TROP, (c) EXT1, (d) EXT2 and (e) ETSA.

Fig.5. Catarina central pressure, starting from 1200 UTC 24 March 2004, as a function of time (in hours) based on NCEP analyses (solid lines), control forecast (dashed lines), ensemble mean (dotted lines) and individual ensemble members (dots). The panels refer to experiments (a) OPER, (b) TROP, (c) EXT1, (d) EXT2 and (e) ETSA.

Table 1

List of experiments and the main characteristics of the ensemble prediction system (EPS) configurations for each.

Experiment	***Regions used to compute perturbations***	***Perturbed fields***
OPER	TRE	T,U,V
EXT1	NH,SH,TR	T,U,V
TROP	TRE	P,T,Q,U,V
EXT2	NH,SH,TR	P,T,Q,U,V
ETSA	NH,SH,TR,NSA,SSA	P,T,Q,U,V



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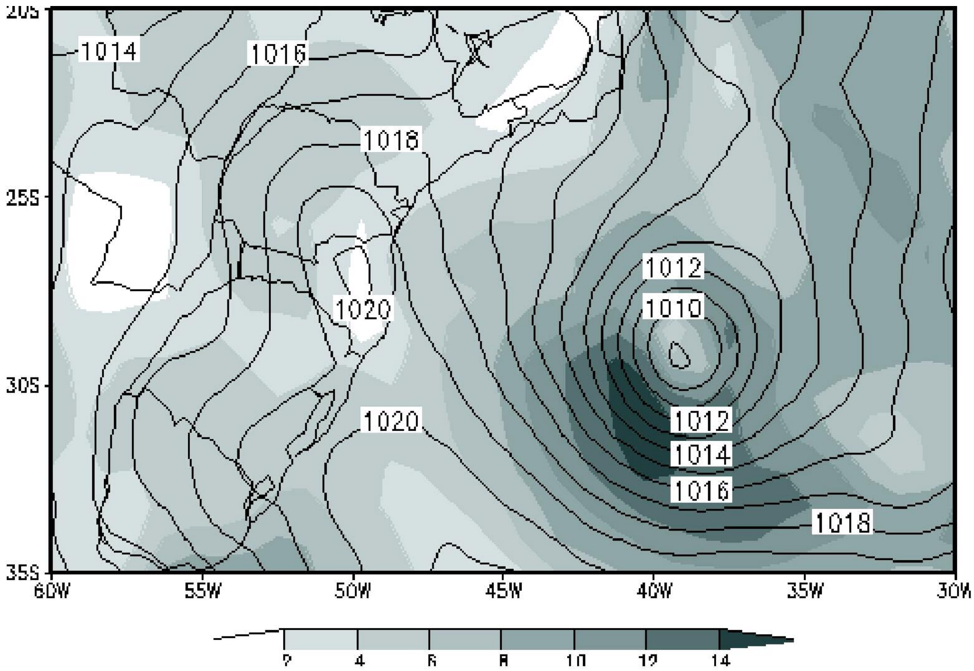

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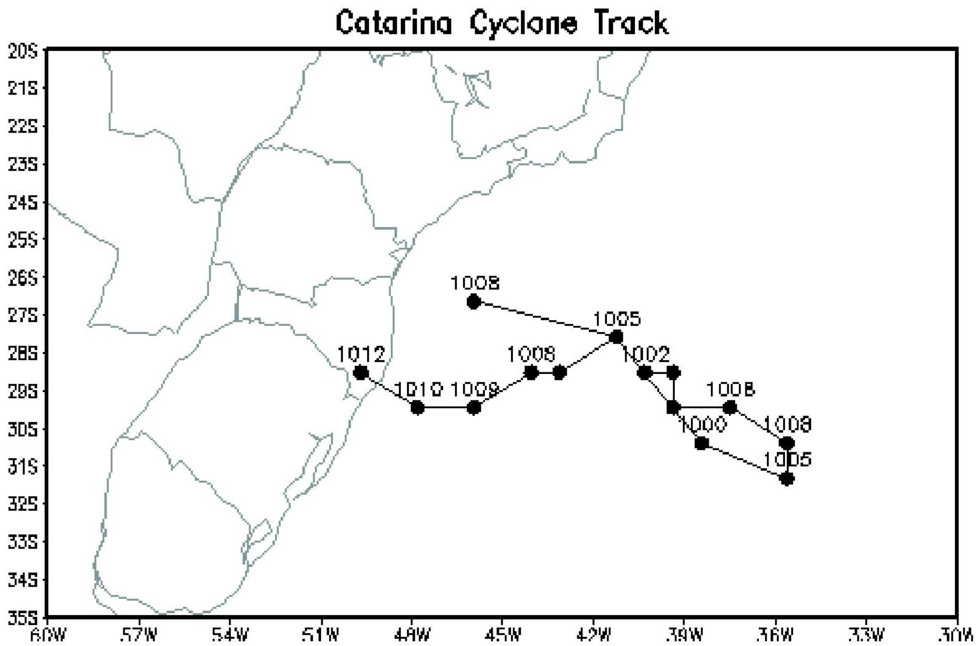
129x91mm (600 x 600 DPI)



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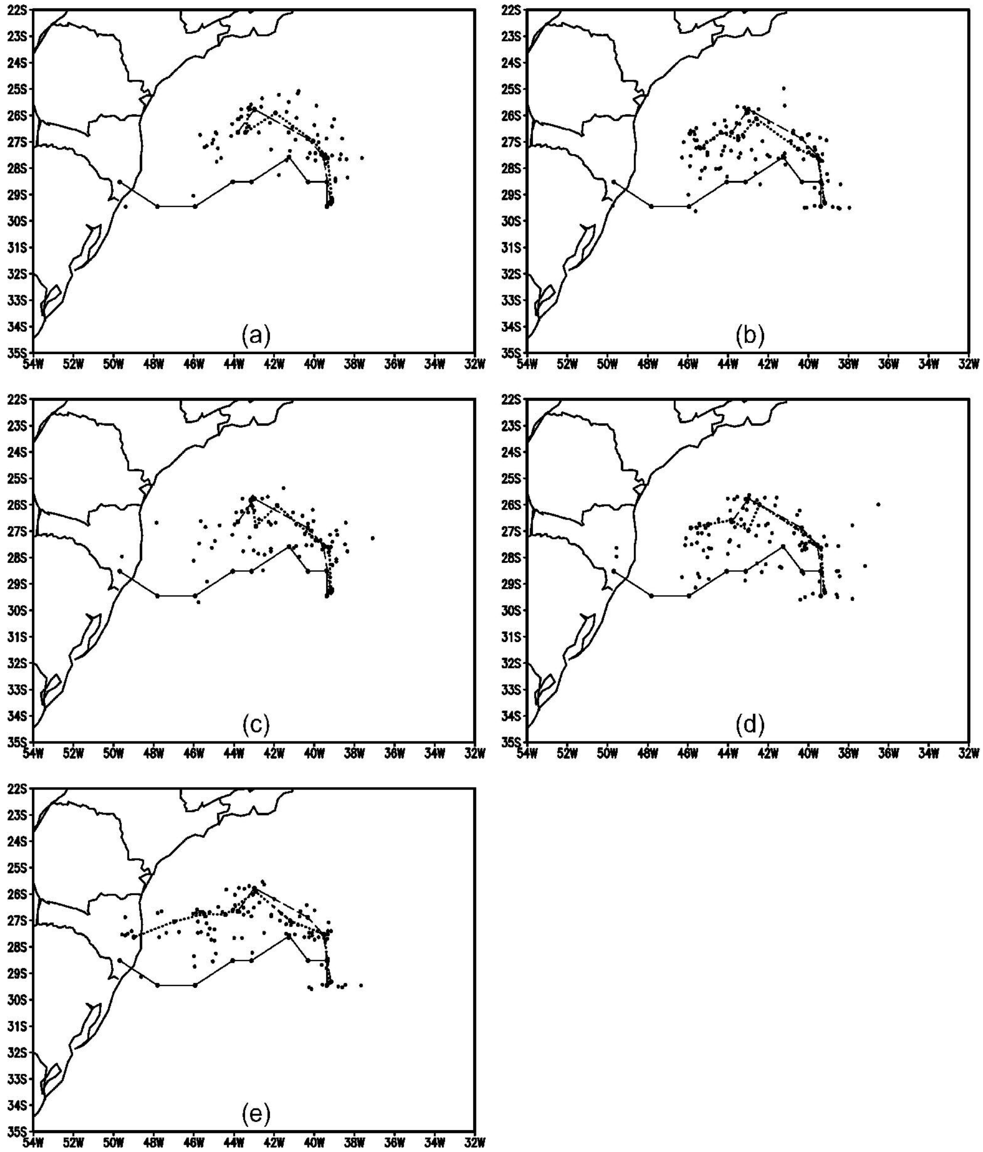
128x86mm (600 x 600 DPI)



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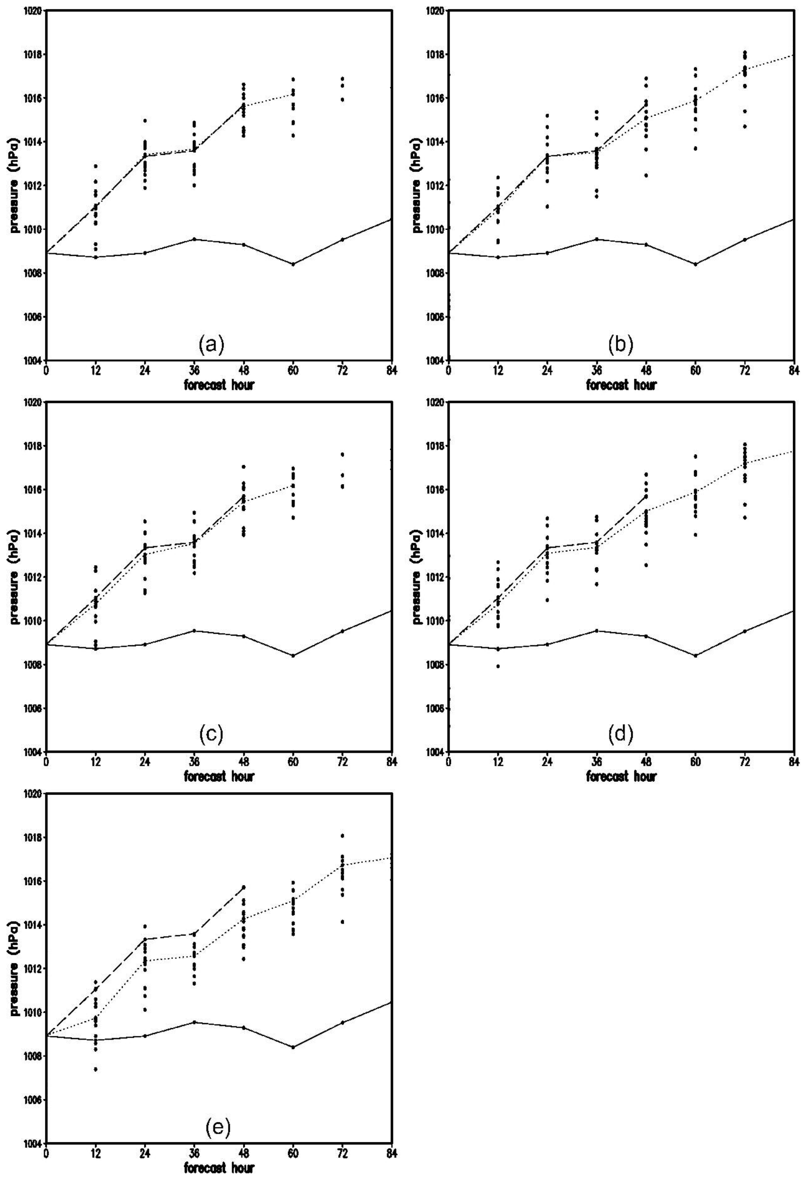
170x200mm (600 x 600 DPI)



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170x250mm (600 x 600 DPI)