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Special Edition

Assessment of 3DVAR assimilation on the Yakecan subtropical cyclone

Impacto da assimiliação 3DVAR no ciclone subtrofical Yakecan

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ABSTRACT

In the present work, the impact of the assimilation of AMSU-A satellite data, performed through the three-dimensional variational system of the WRF weather forecast model, is evaluated. The Yakecan cyclone, a system that have caused socioeconomic damage in southern Brazil on May 17, 2022, is emulated. Extratropical systems are quite common in the region, however systems such as the Yakecan, which have hybrid characteristics are especially interesting for research purposes. The simulations performed by the WRF model capture the propagation and development of the system. However, the initial condition generated by the variational technique showed a more accurate positioning of the system than the simulation without data assimilation. This difference is fundamental for weather forecasting in southern Brazil, as the correct positioning of the system determines whether the consequences of the cyclone affect densely populated areas on the coast of the country or are limited to the adjacent ocean.

Keywords: Cyclone; Subtropical; Yakecan; Assimilation

RESUMO

No presente trabalho, avalia-se o impacto da assimilação dos dados do satélite AMSU-A realizada através do sistema variacional tridimensional do modelo de previsão de tempo WRF. Estuda-se o caso do ciclone Yakecan, que causou prejuízos socioeconômicos no sul do Brasil no dia 17 de maio de 2022. Sistemas extratropicais são bastante comuns na região de estudo, entretanto sistemas como o Yakecan, que possuem características mistas entre ciclone tropical e extratropical são de particular interesse. As simulações realizadas pelo modelo WRF captaram a propagação e desenvolvimento do sistema. Entretanto, a condição inicial gerada com dados de satélite mostrou um posicionamento do sistema de maneira mais precisa do que a simulação sem assimilação de dados. Essa diferença é fundamental para a previsão de tempo no sul do Brasil, uma vez que o correto posicionamento do sistema define se as consequências do ciclone atingem áreas densamente povoadas no litoral do país ou limita-se a atingir o oceano adjacente.

Palavras-chave: Ciclone; Subtropical; Yakecan; Assimilação

1 INTRODUCTION

Cyclones are systems of low atmospheric pressure, which the directions of the pressure gradient are in opposite direction to their core. In these air masses, winds rotate inward in a counter-clockwise direction in the northern hemisphere and clockwise direction in the southern hemisphere, from the surface to high levels of the atmosphere.

In southern Brazil, the forecasting of the cyclones, since its genesis (formation) up to occlusion (phase in which the cyclone decreases in intensity and disappears) has particular importance for weather forecasting, as they are usually associated with cold fronts, storm surges, strong winds and extreme precipitation index along its trajectory (Holton, 2004). Cyclones are classified into three types: Extratropical, Tropical and subtropical.

Extratropical cyclones have a cold core at high levels of atmosphere and are associated with cold fronts. The east side of Andes Mountain, located in the southern region of the Brazil, is a region propitious to the formation and intensification of cyclones and presents great amplitude (spatial and temporal) of meteorological variables, such as pressure, temperature, humidity and winds. Searching through 17 years of data for the entire Southern Hemisphere, Sinclair (1995) found some cyclogenetic regions in South America (SA). Particularly, two centers of maximum occurrence during the year were found in the southern region of Brazil, one near Uruguay (maximum in winter) and another near the Argentina (maximum in summer). In Gan and Rao (1991) the higher frequency observed over Uruguay is associated to baroclinic instability and the effect of the mountain. While the maximum in Argentina was related to the process of baroclinic instability in the westerly Wind current, intensified by the continent-ocean contrast. A special case of cyclogenesis, known as explosive cyclogenesis or bomb cyclone, occurs IF the central pressure decreases by 24 millibars or more in 24 hours (Sanders; Gyakum, 1980). Tropical cyclones have a warm core at low atmospheric levels. Subtropical cyclones are hybrid systems, that is, with a warm core at low levels and a cold one at high levels of the atmosphere, occurring more frequently over the ocean. These characteristics may be characteristic of their Genesis or occur during the transition from extratropical to subtropical or from tropical to subtropical.

On May 17, 2022, a subtropical cyclone formed in southern Brazil called the Yakecan storm, whose position was poorly represented by numerical weather forecast models. Therefore, the objective in this work is to verify if the Weather Forecasting Model (WRF), through three-dimensional variational data assimilation technique (WRF3DVAR) simulated the meteorological system and if the ingestion of the satellite radiances corrected the position and propagation of the subtropical Yakecan cyclone.

Data Assimilation (DA) combines a background field, usually a numerical model, with collected data (in the case of this work, radiances satellite), taking into account the statistical knowledge of both observation and modelling errors. DA can be understood as an Inverse Problem, within a broader theory, the Estimation Theory (Harter; Velho, 2008). The method three-dimensional variational assimilation is especially suitable for operational weather forecasting, because it has a lower computational cost than other variational methods, such as variational four-dimensional data assimilation and sequential methods, such as Kalman filters (Harter; Yamasaki; Beck, 2015). This work uses the implementation developed by Barker *et al*. (2004) and Barker *et al*. (2012).

2 FRAMEWORKS

This section provides a brief introduction to WRF numerical modeling, the three-dimensional variational assimilation technique, initial conditions for integrating WRF and

AMSU radiances ingested during the assimilating process. A further section discusses some numerical results and the final section adds some comments and remarks.

2.1 Radiances Ingested by 3DVAR, Initial and Boundary Conditions

In this work, radiances obtained from polar orbit satellites were assimilated, which have been used in the Global Data Assimilation System (GDAS) of the National Centers for Environmental Prediction (NCEP), specifically data from the Advanced Microwave Sounding Unit-A (AMSU-A) sensor. The Initial and Boundary Conditions were provided by the GFS Model (Global Forecast System), a global numerical weather forecast model, with a resolution of 0.25 degrees.

2.2 The Weather Research and Forecasting Model (WRF)

WRF is a primitive equation model developed by the National Center for Atmospheric Research (NCAR) in collaboration with the National Centers for Environmental Prediction/National Oceanic and Atmospheric Administration (NCEP/NOAA) and the Forecast Systems Laboratory (FSL). The assimilation system, composed of the model, assimilation method, and other utilities, results in a state-of-the-art numerical time prediction system that can be implemented on several computer architectures supporting different parallelism and compiler directives. The WRF used in this research was compiled on a personal computer with 4 dual-core processors and 8 GB of RAM, running on the Linux64 operating system and compiled with Message Passing Interface (MPI) directives. The simulation domain chosen for this study includes the south-central region of South America. The model is integrated in non-hydrostatic mode with a 9 km resolution, 60-second time step, 40 vertical levels using hybrid Eta/Sigma coordinates and Lambert projection. The model was integrated for a 72-hour forecast period, starting at 00 UTC on August 20, 2020.

2.3 Three-Dimensional Variational Approach

In a variational approach, a mathematical formulation of 3D-Var can be introduced by defining a cost function ($J_0(W)$), which is proportional to the square of the difference between the analysis and both the background and the observations. The analysis is obtained by minimizing this cost function

$$J_o(W) = \frac{1}{2}\{[y_o - H(W)]^T \mathbf{R}^{-1}[y_o - H(W)] + (W - W_b)^T \mathbf{B}^{-1}(W - W_b)\} \quad (1)$$

Wherere W=W(X,Y,Z) presents the model state, W_b is a background model state, y_o is the observation vector, *H* represents observation operator (projects the state matrix onto the observations vector space), *B* is the covariance matrix of the background errors (i.e., modeling errors) and *R* is the covariance matrix of observation errors. For practical reasons, a change of variables is made so that the minimization of the cost function is calculated in physical space rather than model space. This is because numerical weather forecast models have 10^{12}-10^{14} degrees of freedom, which is several orders of magnitude greater than the number of assimilated observations. The cost function *J* measures:

1- The distance of a Field *W* to the observations (first term)

2 - The distance to the background W_b (second term).

The distances are scaled by the observation error covariance *R* and by the background error covariance *B*, respectively. The minimum of the cost function is obtained for *W* = *Wa*, which is defined as the analysis. In WRF 3D-Var, an iterative optimization algorithm is used for finding a local minimum of the differentiable cost function.

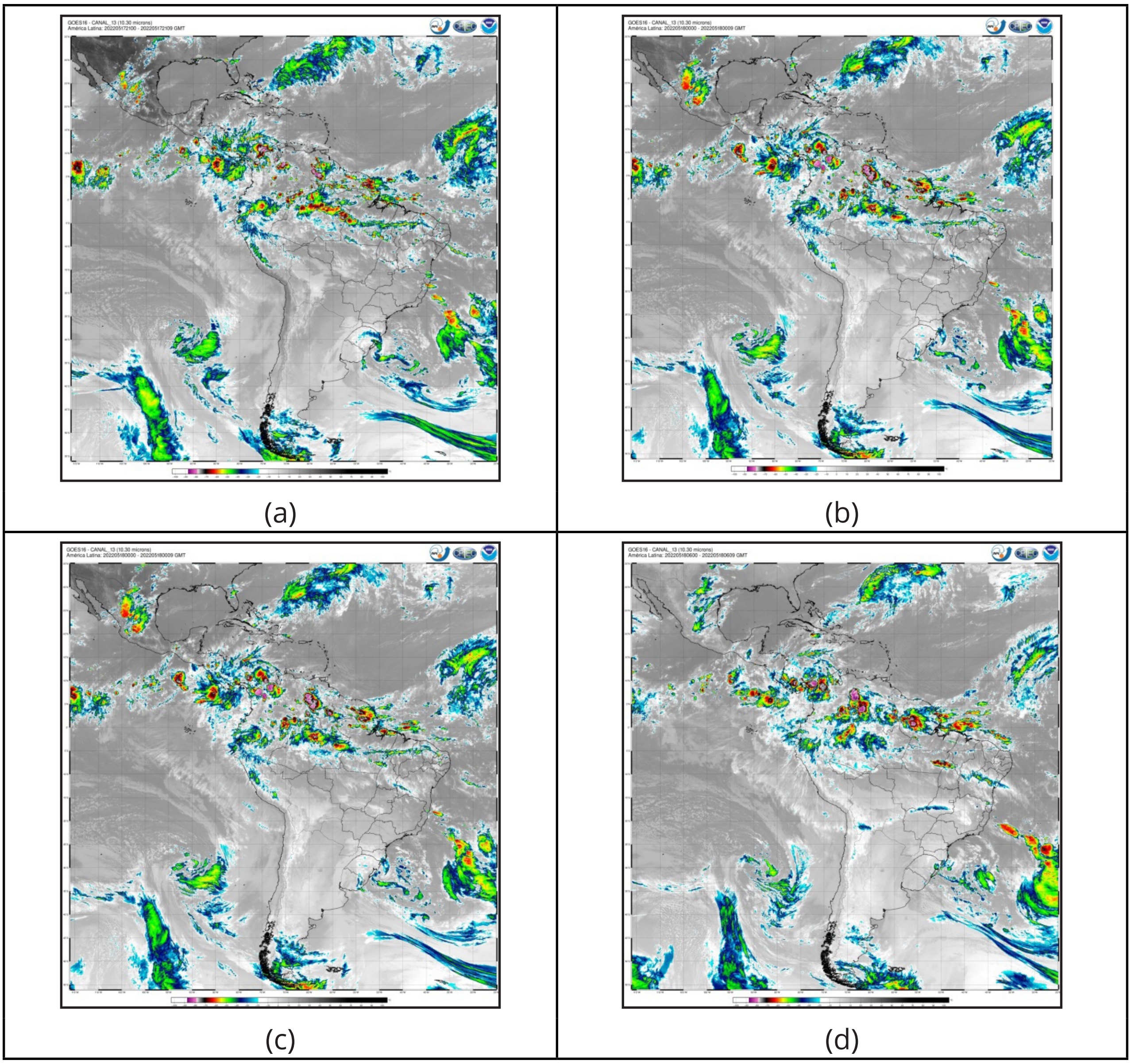
The methodology assumes that the measurements are unbiased, that the variances of the observation errors are known, and that the measurement errors are uncorrelated. More details about the variational assimilation methodology can be obtained in (Barker *et al*., 2004) and (Barker *et al*., 2012).

3 NUMERICAL RESULTS

On May 16th, 2022, the 24 hours leading time weather forecasting, for the west coast of Rio Grande do Sul (RS) and Santa Catarina (SC) provinces, broadcasting by the media, warned about strong winds and the possibility of snow, due to the subtropical storm Yakecan. The National Institute of Meteorology issued a red alert, the most serious of its risk classification system, so that schools and universities in the southern region of RS suspended In-person classes. On the night of the May 16th, strong winds caused the shipwreck of a boat on Guaíba Lake, in Porto Alegre, capital of Rio Grande do Sul, causing the loss of one human life. Yakecan changed from an extratropical to a subtropical cyclone and caused special attention of meteorologists and authorities, as its characteristics, such as a warming core at low levels of the atmosphere and geographical position, were similar to Hurricane Catarina, which hit Santa Catarina in 2004. Catarina is considered the first hurricane registered in Brazil. However, on May 17th, 2022, the phenomenon turned out to be intense as predicted, but with a position further east than the numerical models indicated. Therefore, it caused strong winds in locations closed to west of RS and offshore.

In Figures 1 (a)-(d), is depicted the position and propagation of the cyclone, through the GOES satellite image enhancement, in thermal infrared channel. These images were chosen because at these times the model simulation showed the Cyclone in the continent. It can be seen in the images that at 6 pm on May 17th, 2022, Figure 1(a), that the core of low pressure was over the continent, with winds parallel to the coast, a favorable condition for a storm surge. The image from 21- and 24-hours leading time shows, Figures 1(b) and (c), that the system had already moved towards the ocean and the image on May 28th, 2022, shows the system with core over the South Atlantic.

Figure 1 – GOES satellite image enhancement, in thermal infrared channel



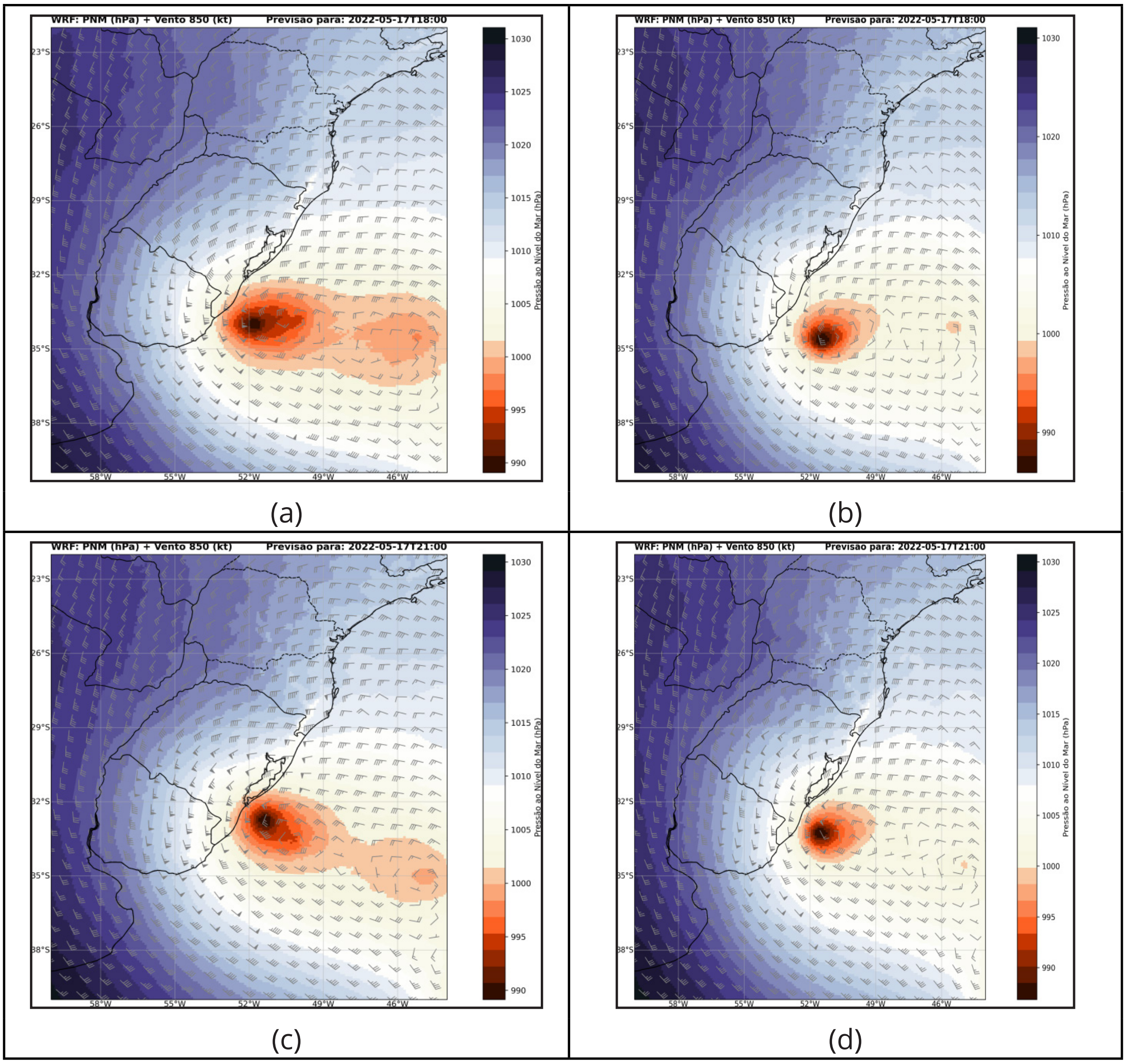
Source: CPTEC/INPE (2022)

Caption: GOES satellite image enhancement, in thermal infrared channel on May 17th, 2022 at (a) 18:00, (b) 21:00, (c) 24:00 and (d) on May 18th, 2022 at 03:00 local time

In Figure 2, is shown the sea level pressure and wind vector fields, resulting from the WRF simulations (model without data assimilation) and WRF3DVAR (model with radiance assimilation) for the same times shown in the GOES images. It is observed that both the WRF (left side, Figures (a), (c), (e) and (g)) and the WRF3DVAR (right side, Figures (b), (d), (f) and (h)) show a delay in the system displacement, which means that the model underestimated the vorticity advection. However, the area of greater amplitude was larger in the WRF fields than in the WRF3DVAR fields, that is, the WRF overestimated the temperature advection. These differences are better perceived in the 6 pm fields as they are less distant in time from the analysis.

Figure 2 – Sea Level Pressure and Wind Vector fields

(Continue)

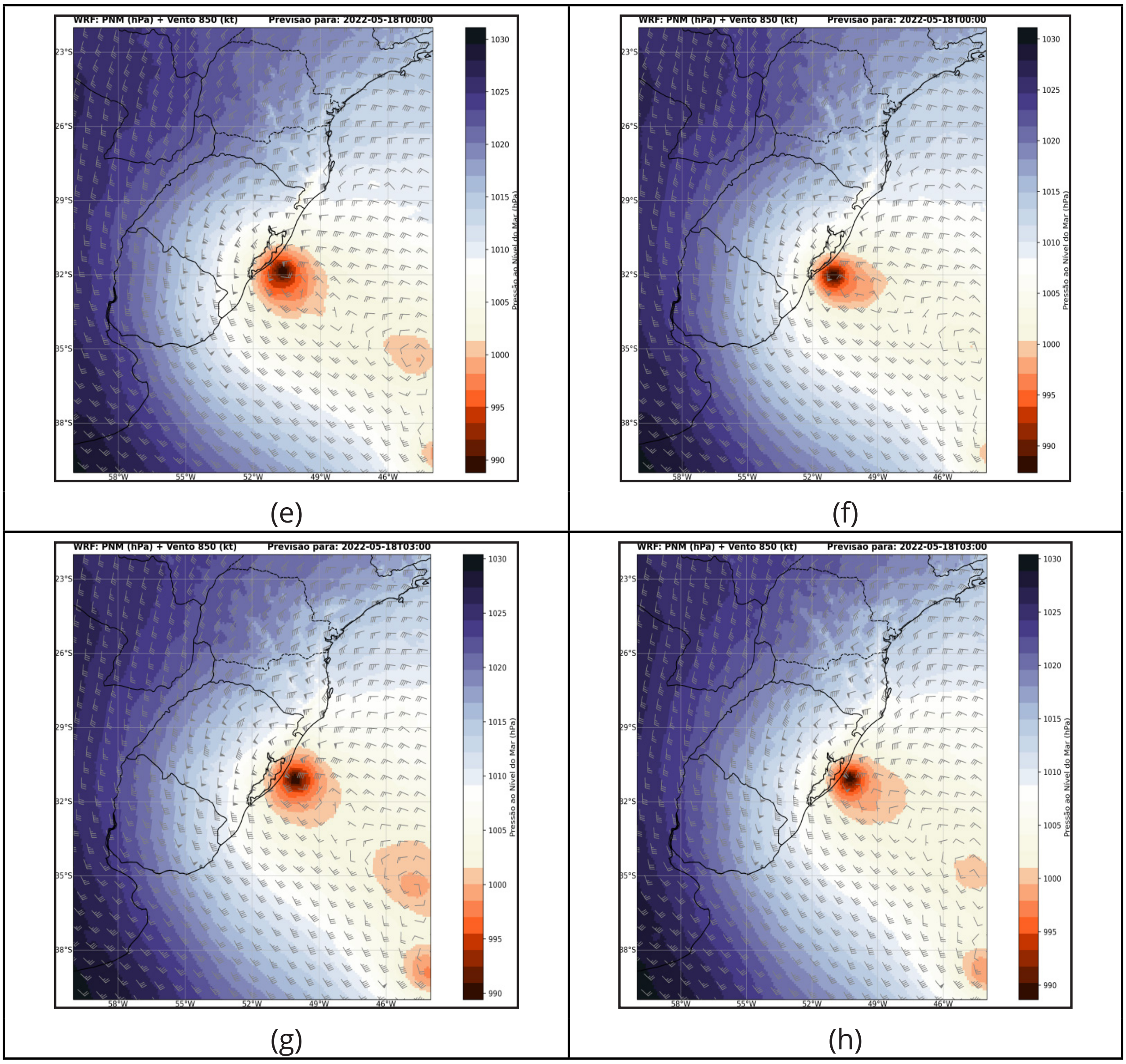


Source: Authors (2022)

Caption: Sea Level Pressure and Wind Vector fields, output from WRF simulations (on the left), Figures (a), (c), (e) and (g) and WRF3DVAR (on the right), Figures (b), (d), (f) and (h)

Figure 2 – Sea Level Pressure and Wind Vector fields

(Conclusion)

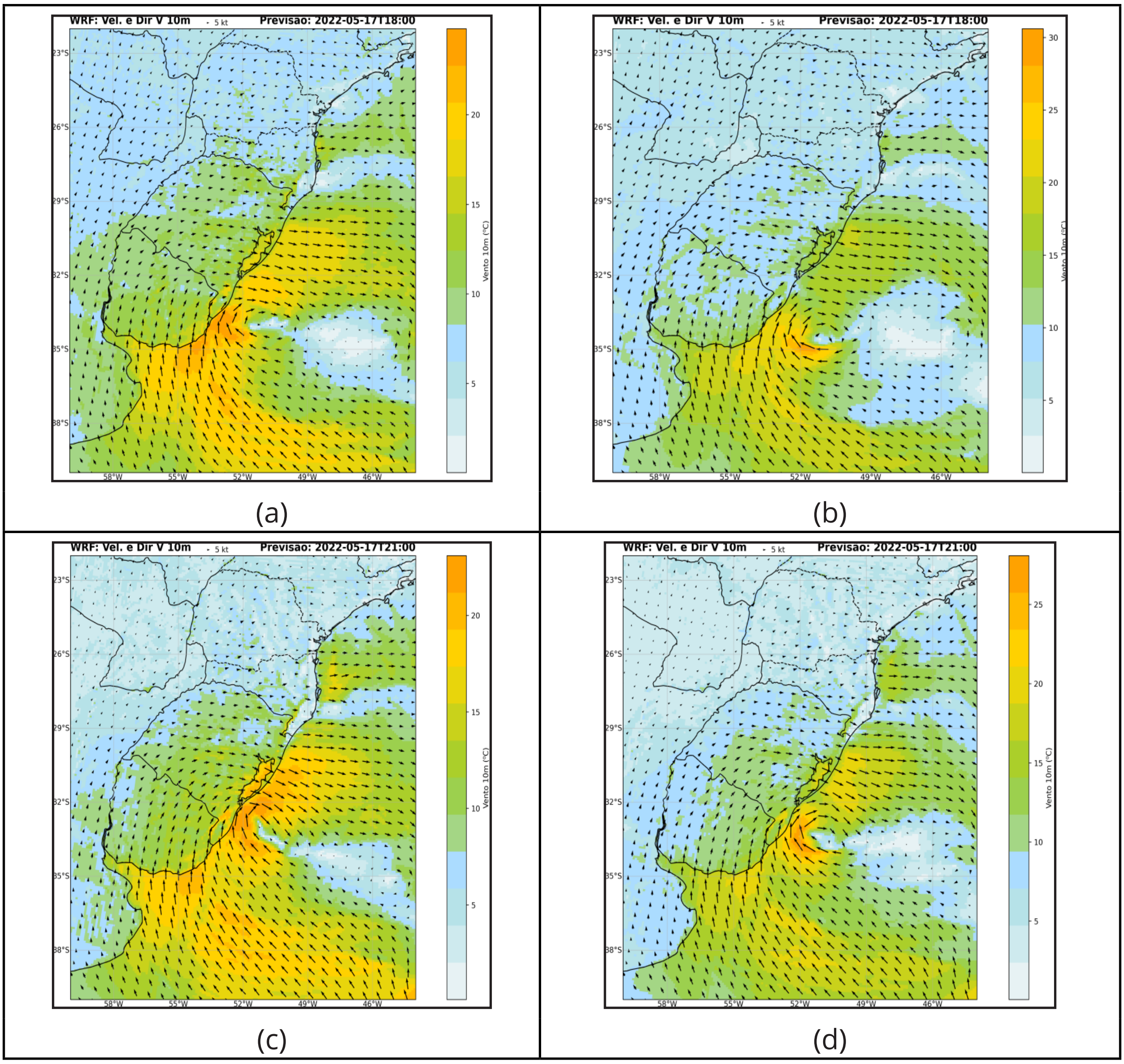


Source: Authors (2022)

Caption: Sea Level Pressure and Wind Vector fields, output from WRF simulations (on the left), Figures (a), (c), (e) and (g) and WRF3DVAR (on the right), Figures (b), (d), (f) and (h)

Figure 3 – Wind Speed and Wind Direction fields

(Continue)

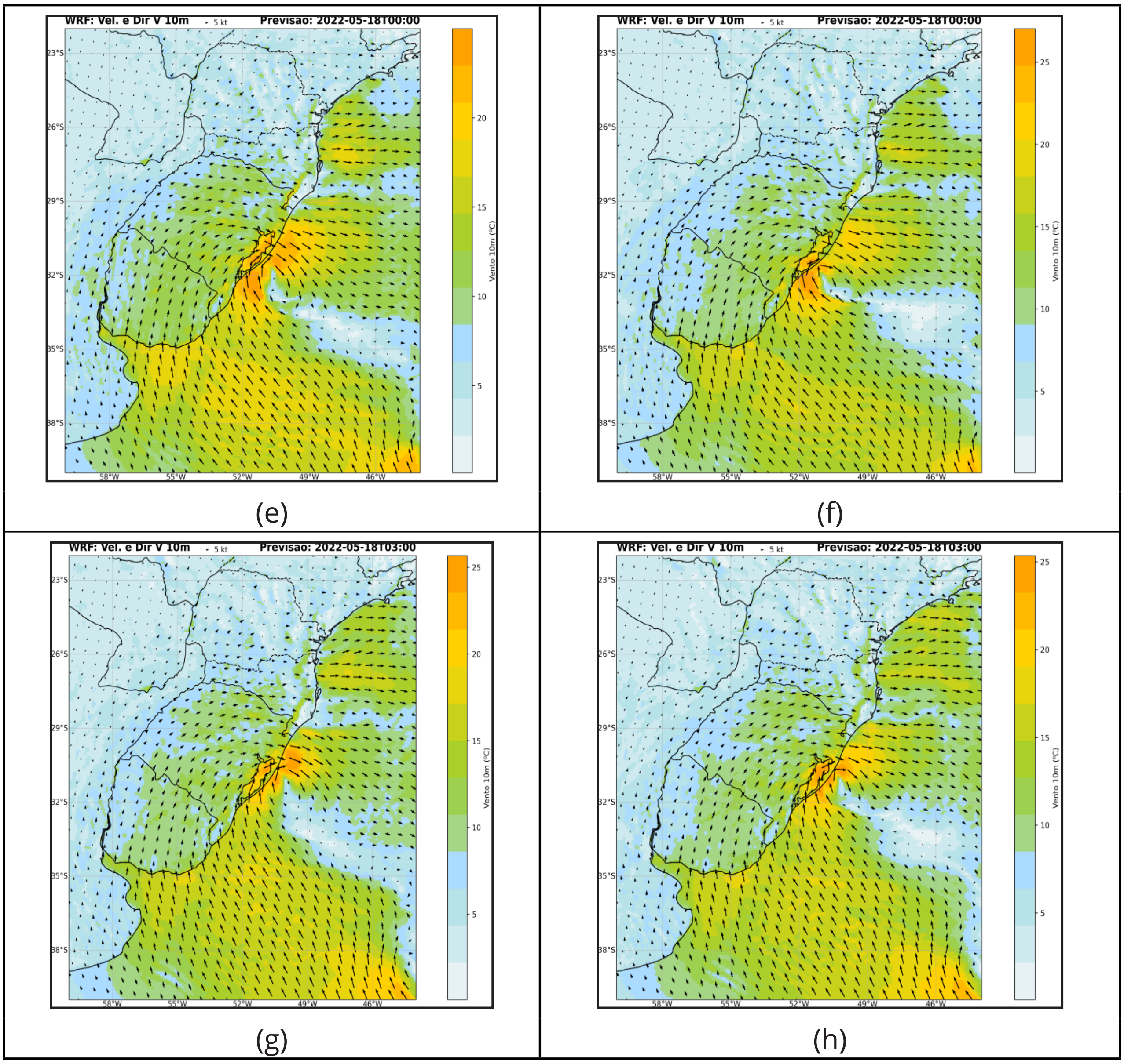


Source: Authors (2022)

Caption: Wind Speed and Wind Direction fields, output from WRF simulations (on the left), Figures (a), (c), (e) e (g) and WRF3DVAR (on the right), Figures (b), (d), (f) and (h)

Figure 3 – Wind Speed and Wind Direction fields

(Conclusion)



Source: Authors (2022)

Caption: Wind Speed and Wind Direction fields, output from WRF simulations (on the left), Figures (a), (c), (e) e (g) and WRF3DVAR (on the right), Figures (b), (d), (f) and (h)

Figure 3, is like Figure 2 for Wind speed and Wind direction fields. WRF3DVAR also in the Wind field, shows a more easterly system compared to WRF. Extratropical cyclones are synoptic-scale systems (thousands of km and days) that propagates as a Rossby wave from West to east. Yakecan, a Subtropical Cyclone, like Catarina, presented an eastward displacement, which, associated with the relatively high temperature in its center, caused special concern to meteorologists. However, the assimilation of radiances generated an Initial Condition (IC), which resulted in a prediction closer to the terrestrial truth, in this case GOES satellite images.

4 CONCLUSIONS

Data assimilation techniques, which consist of combining short forecast numerical models with collected data, are imperative in modern numerical weather forecasting. Three-dimensional variational techniques are particularly important because they require less computational cost than four-dimensional techniques. Therefore, in this work, WRF3DVAR was used to simulate the Subtropical Cyclone Yakecan with the objective of verifying whether the assimilation of AMSU-A radiances is capable of generating an initial condition that reproduces the Yakecan cyclone in a more realistic position than that predicted by the WRF model.

The WRF3DVAR reproduces the position of the system far away from the coast, with a smaller area of stronger winds and consequently closer to ground truth compared to WRF.

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