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Study of the Correlation between WRF Output Variables and Lightning Activity in Southeastern Brazil

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***Abstract*— The Weather Research and Forecasting (WRF) model is suitable to reproduce the thermo-hydrodynamic coupling structure of atmosphere in order to analyze and/or predict the weather conditions. Knowing in advance meteorological scenarios responsible for the occurrence of severe thunderstorms is important since these natural phenomena usually cause huge economic injuries and more than one hundred casualties every year in Brazil. The present work intends to identify common patterns between the meteorological behavior of atmosphere and the occurrence of lightning for convective systems over southeastern Brazil. To accomplish this objective, we will use: (a) total lightning data from BrasilDAT, for constructing lightning activity maps, (b) output variables from high-resolution WRF simulations, for evaluating atmospheric conditions, and (c) correlation methods based on multivariate statistics. The initial study will consist to create, for each WRF grid point, a matrix in which the columns will correspond to the WRF variables to be analyzed, and the rows to the model time step. After the application of the chosen correlation method, the result will again be a matrix, for each WRF grid point, containing the mutual correlation between all variables investigated and lightning activity, allowing to analyze and compare spatially this correlation. Thus, we will intend to better understand the physical process involved in the lightning occurrence, and contribute to the development of indicators that make possible to forecast this kind of phenomenon.**

Keywords* — *WRF, Lightning Activity, BrasilDAT.

I. INTRODUCTION

Despite various experiments simulated in laboratory and a vast amount of data collected over the past decades, our knowledge about the occurrence of lightning remains sparse, especially in the understanding of mechanisms of lightning propagation and clouds electrification at microphysical level [Cooray, 2003; Barthe et al., 2010]. The knowledge of the physical process generating of atmospheric electricity is extremely important to society, since this phenomenon cause every year about one hundred deaths, including a loss of approximately a half billion dollars only in Brazil [Pinto Jr. e Pinto, 2008].

In view of the importance and impact of this phenomenon in the country, recently, studies have begun to be realized using the Weather Research and Forecasting (WRF) mesoescale model with the main objective of evaluating meteorological parameters and their dependence on the formation and occurrence of Cloud-Ground Lightning (CG) in southeastern of Brazil [Zepka, 2011; Zepka et al., 2011]. Other studies have been made for others regions of the world with the same purpose [Deierling and Petersen, 2008; Yair et al., 2008; Lynn and Yair, 2009; Barthe; 2010].

Thus, the study of how certain meteorological variables are related with the lightning occurrence is fundamental to understanding of physical involved. Therewith, this paper aimed to study correlations between some WRF output variables and the lightning activity during actuation of convective cells on the southeastern of Brazil in order to better understand the physical process involved in the lightning occurrence and contribute to the development of indicators that enable the prediction of this kind of phenomenon.

II. DATA AND METHODOLOGY

A. *Observational analyze*

Due to the discrete nature of lightning, it was developed a method to interpolate observational data in order to map lightning activity within the cloud. This method considers that lightning activity decreases exponentially from point where the CG occurred. To adjust the interpolation method it was used satellite enhanced images with 4x4Km resolution (subsatellite point) from the GOES 13 which is located above South America, provided by the Division of Environmental Satellites from the Prediction and Climate Studies Center from the National Institute for Space Research (DSA/CPTEC/INPE). Moreover, these images also were used to identify the behavior of the meteorological system under study. The total lightning data were obtained from the BrasilDAT.

The period analyzed was 2014, December 27 to 30, this period was selected because it was one of the most electrically active period of the summer 2012-2013 in the southeastern Brazil.

B. WRF model and simulation

The WRF model is a primitive equation model and non-hydrostatic which utilizes sigma coordinate in the vertical. The model equations are solved in the C Arakawa grid and provide multiple physics options [Skamarock, 2008].

In the present study, it was realized a simulation with the WRF model using as initial and boundary conditions data provided by Global Forecast System (GFS) model from the National Centers for Environmental Prediction (NCEP) in order to simulate the convective systems that affected southeastern region of Brazil. The model was configured with two nested domains according to Table 1.

Table 1 – Configurations of the domains utilized in the simulation with WRF model.

Domains	1	2
Latitudes	79.06°W – 36.71°W	56.91°W – 42.95°W
Longitudes	47.32°S – 7.19°S	28.77°S – 17.46°S
Horizontal Resolution	0.20°x0.20°	0.07°x0.07°
Vertical Resolution	42 sigma levels	19 pressure levels
Spatial Grid	Nonlinear	Nonlinear

Where 1 is the largest domain which was used in the comparison with the observed synoptic environment and 2 is the lowest domain which was used to simulate the southeastern region of Brazil with a higher spatial resolution (Figure 1). However, the correlation analyses of variables were grounded in the domain located between the longitudes 47.00°W and 44.00°W and latitudes 24.50°S and 22.00°S indicated by a square in the Figure 1b and expanded in the Figure 2. The results of simulations were stored with an interval of 60 minutes for a total integration domain of 73 hours (00:00 UTC 27/12/2012 until 00:00UTC 30/12/2012).

It was used in the simulation the convective parameterization of Grell and Devenyi [2002] and the microphysics parameterization of Thompson [2004] that according with Zepka [2011] presented the best results in the lightning prediction. The others parameterizations were not modified and were used default parameterizations of WRF model version 3.4.1.

To create a correlation between lightning activity and WRF output variables was used the multivariate correlation described in Wilks [2006] where the correlation (R) is defined as:

$$[R] = \frac{1}{n-1}[D]^{-1}[X']^{T}[X'][D]^{-1} \tag{1}$$

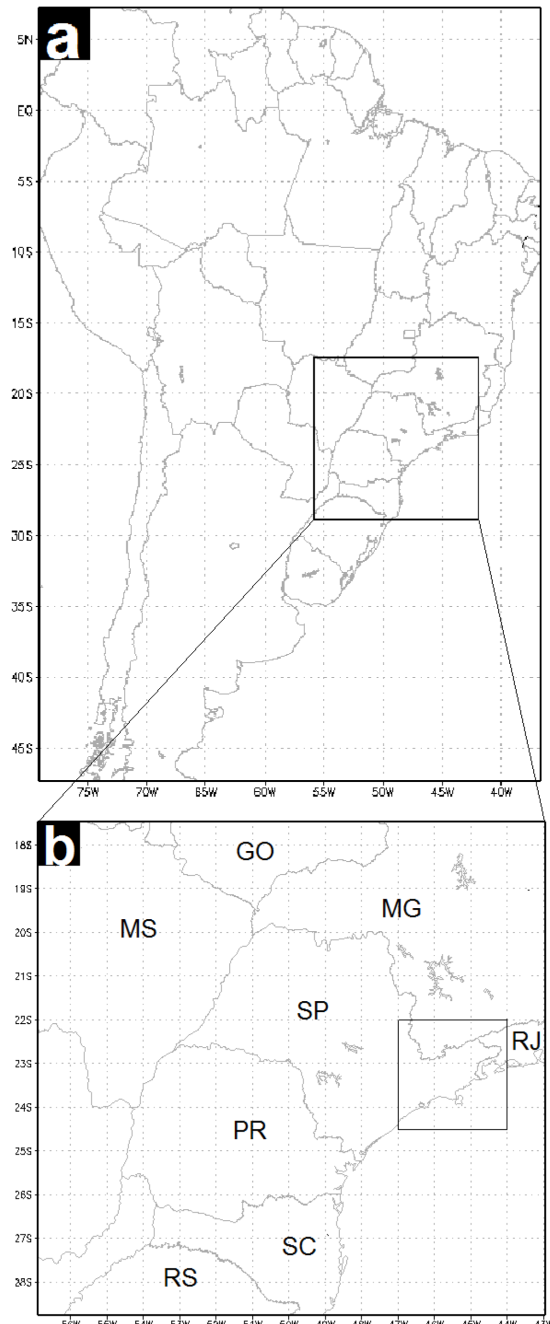

Figure 1 – Nested domains used in the simulation with WRF model. (a) Largest grid centered in South America and (b) lowest grid centered in southeastern Brazil with a square showing study area.

Where n indicates the number of rows of the matrix $[X]$. Knowing that $[X]$ is the matrix containing the variables values under study with each row corresponding an different time step (therefore, n indicates the number of time step) and each column a distinct variable, is defined as anomaly matrix $[X']$ as matrix containing the anomaly of the variables of the matrix $[X]$, where each element is defined as:

$$\boldsymbol{x'_{ij} = x_{ij} - \overline{x_j}} \quad (2)$$

In other words, each value of the matrix $[X']$ ($\boldsymbol{x'_{ij}}$) is calculated by corresponding value in the matriz $[X]$ ($\boldsymbol{x_{ij}}$) minus the variable mean in this column ($\boldsymbol{\overline{x_j}}$).

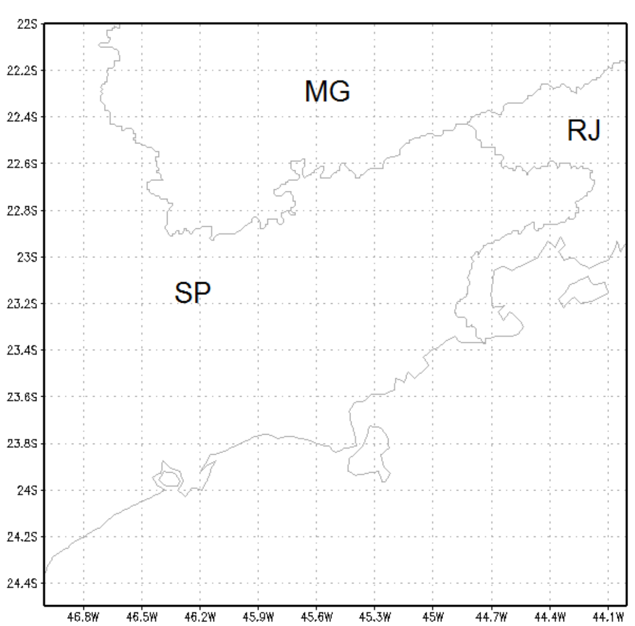

Figure 2 – Study area used in the calculations of correlations.

The matrix $[D]^{-1}$ is the inverse matrix of the standard deviation $[D]$ which is a diagonal matrix given by:

$$d_{kk} = \sqrt{s_{kk}} \quad (3)$$

Each diagonal element of the matrix $[D]$ (d_{kk}) is given by the square root of the element corresponding in the covariance matrix$[S]$, given by:

$$[S] = \frac{1}{n-1}[X']^T[X'] \quad (4)$$

Thus, it was obtained the mutual correlation of all variables. Applying this procedure to all grid points, it was possible create a spatial correlation between WRF output variables and observed lightning activity. It was considered null correlation when the correlation value less than 0.1 and greater than -0.1. The variables studied were: vertical wind velocity at 850, 500 and 250 hPa, Maximum Reflectivity (MRE), Maximum Convective Available Potential Energy (MCAPE) and Maximum Convective Inhibition Energy (MCINE).

III. Results and Discussions

A. *Description of meteorological system*

According to Climanálise [2012] in 2012, December, the El Niño-Oscillation South presented neutral conditions. It was also observed that this month, despite the formation of moisture convergence zones in the central region of Brazil, there was not the configuration of a South Atlantic Convergence Zone (SACZ). However, the convective activity occurred over most of the country, which is compatible with the large lightning activity observed in this month in the Southeast.

Looking at Figure 3 it is noted the presence of a moisture convergence zone throughout the study period, reaching its maximum convective activity in the southeast around 12:00 UTC de 28/12/2012 (Figure 3b). This synoptic situation contributed to the formation of convective cells over southeastern Brazil, which collaborated to the month of December to be the most active month of the summer of 2012-2013, in terms of lightning activity.

Figure 4 shows the fields vorticity and geopotential height at 500 hPa simulated by the WRF model. Comparing satellite images (Figure 3) it can be seen that the model simulated with a good accuracy the observed large-scale environment. Features such as the displacement of a transient cyclone over southern of South America, the region of influence of semi-permanent anticyclone of Atlantic South in the Brazilian coast, a trough of great amplitude and the moisture convergence zone in the central region of the continent were well represented during the simulation model.

With the verification of the simulation quality, it was applied the correlation method for evaluating the best indicators of lightning occurrence as well as the precision that WRF model had to indicate possible scenarios of lightning.

B. *Correlations analysis*

The WRF output variables were compared with the observed lightning activity, which was calculated based on total lightning data obtained from BrasilDAT sensors in the region of Figure 2. This comparison allowed to create spatial correlation between the observed lightning activity and some output variables of the simulation with the WRF model.

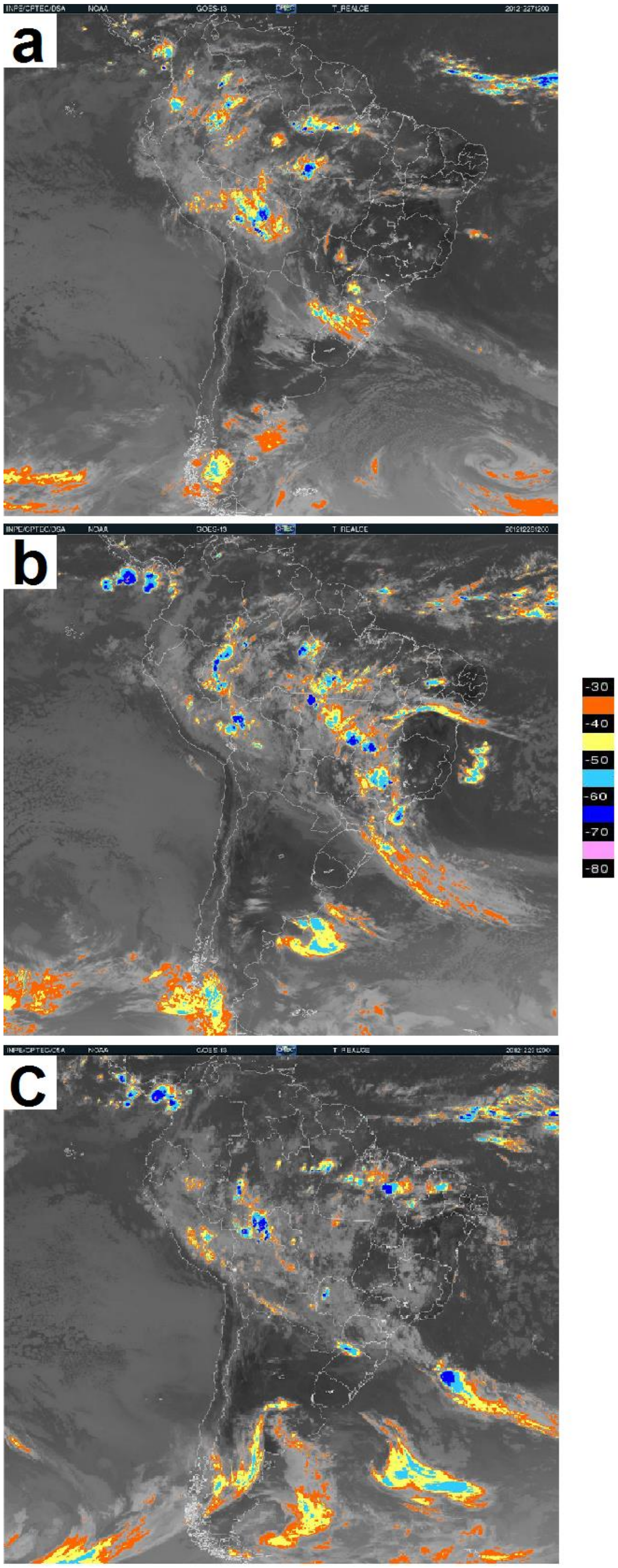

Figure 3 – Satellite images from the GOES 13 showing temperature (°C) of the cloud top at (a) 12:00 UTC 27/12/2012, (b) 12:00 UTC 28/12/2012 and (c) 12:00 UTC 29/12/2012.

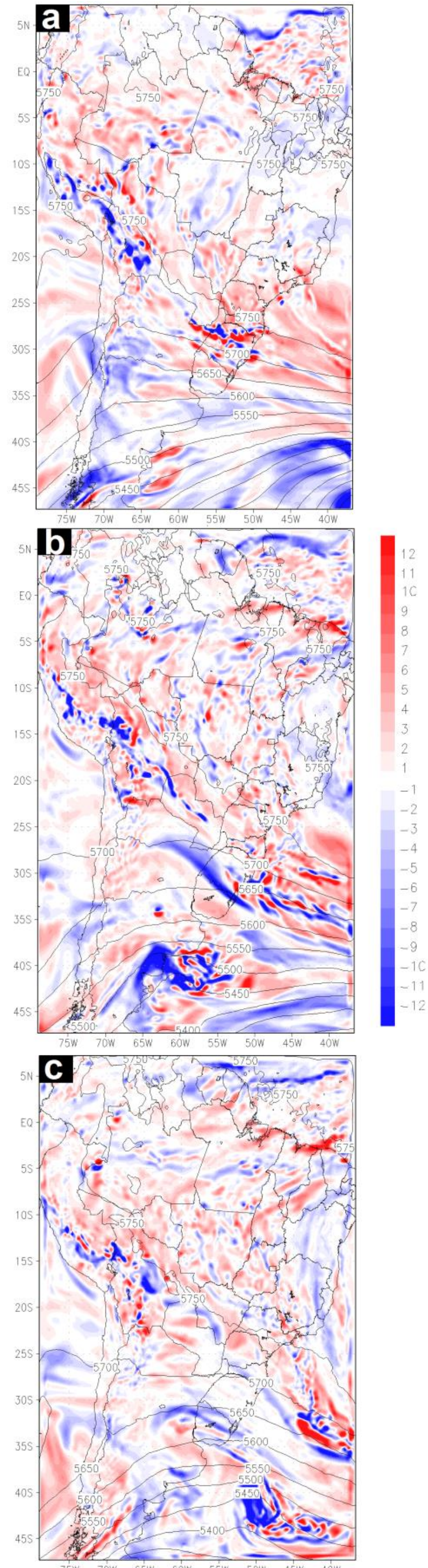

Figure 4 – Vorticity ($10^{-5} \cdot s^{-1}$) and geopotential heights (dam) at 500 hPa simulated by WRF model at (a) 12:00 UTC 27/12/2012, (b) 12:00 UTC 28/12/2012 and (c) 12:00 UTC 29/12/2012.

Figure 5 shows the correlation calculated between the vertical wind velocity at different levels and the lightning activity. It was observed that these variables have significant correlations (positive and negative) with the lightning activity. This correlation is particularity evident at 850 hPa (Figure 5a and 9), where this level showed the lowest area with null correlation among the three levels analyzed. The regions with maximum positive correlations had a value of approximately 0.7 and negatives -0.67. However, the area of positive correlation is significantly larger than area that presents an inverse correlation (Figure 9).

Deierling and Petersen [2008] showed that there is strong correlation between upward flows and total lightning, especially in vertical wind velocities above 5 m/s. Since Williams et al. [2005] found that in the tropical storms the dry bulb temperature and height of the cloud base are important indicators of the lightning activity in the clouds, and the vertical wind velocity was also a good indicator by interference in these variables.

At 500 hPa (Figure 5b) it was observed correlations less than -0.8 and greater than 0.8. However, in this level the areas of correlation are less clearly defined than at 850 hPa.

On the other hand, the 250 hPa level (Figure 5c) showed regions with the highest correlation among the levels analyzed (0.866), however, as 500 hPa level, this level presents areas of sparse correlation which does not are sharply defined making it difficult to identify favorable scenarios of lightning occurrence. The minimum correlation at 250 hPa had a value of -0.682, the lowest negative correlation between three levels.

Another feature to note is the fact of that the area with positive correlation, in general be accompanied by cores negative correlation at all levels, mainly at 850 hPa. There are some explanations for this fact: (1) The lightning activity can be intensified even in regions where the vertical wind velocity is decreasing; (2) The lightning activity can be increased in regions of downdrafts; or (3) The lightning activity can be decreased in regions where the vertical wind velocity increases a lot. However, the exact identification of certain features is not possible since this paper was to analyze a single weather event with lightning occurrence.

CAPE is a thermodynamic index that evaluates the convective available potential energy, i.e. evaluates the level of instability of a particularity air layer. The CAPE can be defined as:

$$CAPE = \int_{Z_o}^{Z} g \frac{T_v - T_{env}}{T_{env}} dz \qquad (5)$$

Where T_v is the virtual temperature of air layer, T_{env} is the environment temperature, g is the gravity acceleration and Z and Z_o are the limits upper and lower of layer, respectively.

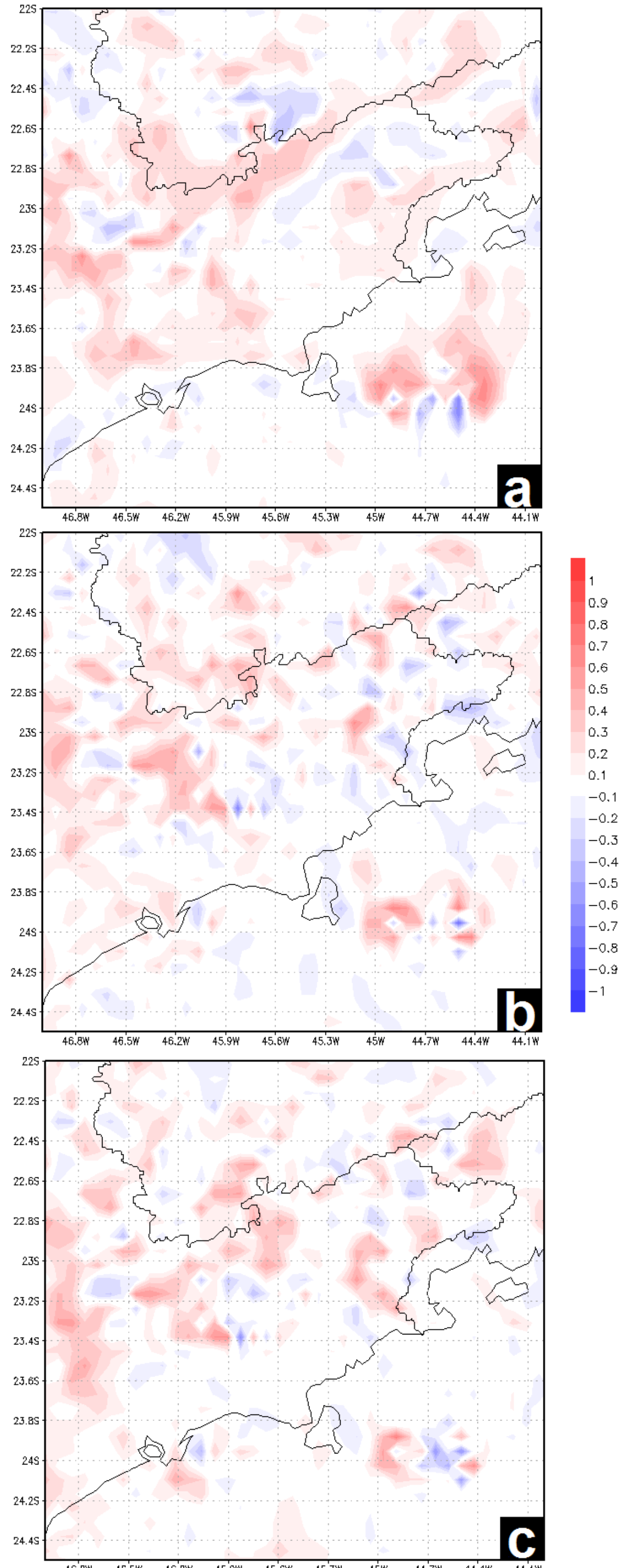

Figure 5 – Spatial correlation between vertical wind velocity and lightning activity at (a) 850 hPa, (b) 500 hPa and (c) 250 hPa.

Due to the WRF simulation has been interpolated to 19 pressure levels, there are 19 values of CAPE. However the work used the MCAPE level (a model output variable). It was noted that the correlation of MCAPE with the lightning activity is predominantly positive (Figure 6 and 9), with some negative values along the coast (Figure 6). Although this variable provide a maximum correlation of 0.562, lower than the other correlations studied, it was showed a lower area of null correlation, feature that makes the MCAPE a good indicator of lightning activity and possibly CG occurrence.

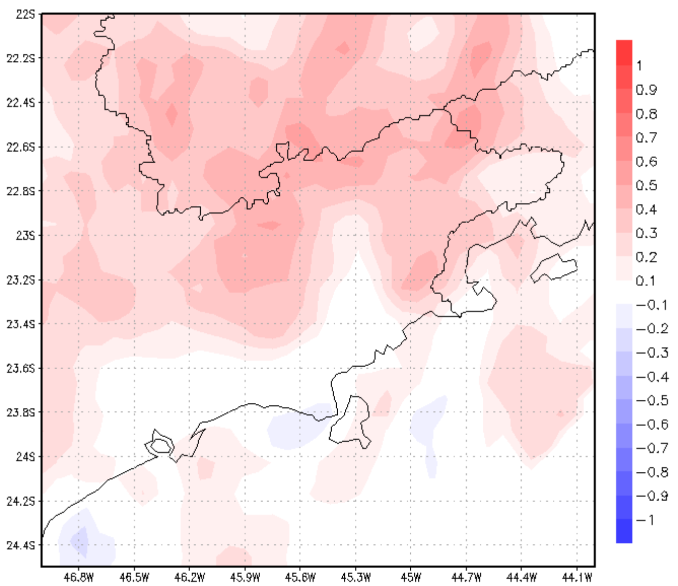

Figure 6 – Spatial correlation between MCAPE and lightning activity.

The positive correlation observed to the MCAPE is intuitive because the greater its value, bigger is the atmospheric instability, which may lead to formation of clouds with large vertical development and subsequently to the formation of thunderstorms. Although some studies shows that dependence of lightning activity with CAPE decreases as the distance from the equator increases, over the years, authors have confirmed that there is indeed a correlation, either greater or lesser proportion, between these variables [Williams et al., 1992; Petersen et al., 1995; Qie et al., 2003; Zepka, 2011; Murugavel et al., 2014].

The reflectivity is a variable that is observed from active sensors that send electromagnetic waves and measure the fraction of this that is reflected (meteorological radars measure reflectivity, for example). Some studies show that reflectivity values greater than 45 dBz at higher altitudes, possibly indicate the presence of hail [Mather et al., 1976; Foote and Knight, 1979; Waldvogel et al., 1979]. This condition is fundamental to charge separation within cloud and consequently in the production of lightning. [Williams et al., 1988].

The MRE variable showed a correlation almost exclusively positive with lightning activity. Moreover, it showed the highest maximum correlation among all variables (0.911). However, this variable also had the largest area with null correlation (Figure 7 and 9). These results suggest there is a threshold of reflectivity at which the clouds begin to electrify, which is in agreement with the expected here. Even in good weather conditions, the air naturally reflects electromagnetic waves and this reflectivity varies with wind conditions, relativity humidity, temperature… Thus, there is a range of reflectivity on which there is not any significant convective activity, causing large areas with null correlation in the map, as it variations in reflectivity within this range do not lead to any significant change in the lightning activity of the region.

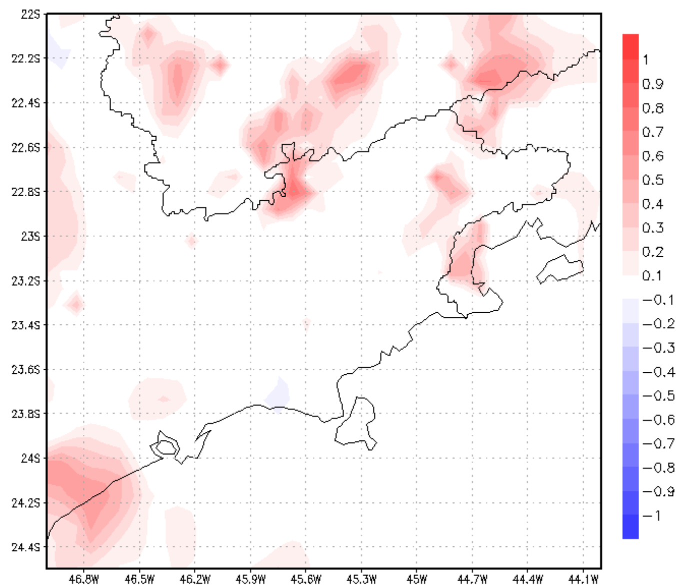

Figure 7 – Spatial correlation between MRE and lightning activity.

The regions that showed positive correlations have possibly presented (over a long time) a reflectivity threshold where larger water droplets and ice crystals begin to be formed, indicating an unstable atmosphere and convective activity. So it was observed in these regions that greater is reflectivity value (above a certain threshold), bigger it will be lightning activity. Others authors also found correlations between lightning activity and the reflectivity measured by meteorological radar [Katsanos et al., 2007; Yeung et al., 2007].

The CINE equation is described in Zheng et al. [2005]. The CINE enables diagnosing the level of stability of a particular layer of the atmosphere, i.e. greater is the value of this variable, bigger it will be the stability of layer. To occur storms, there must be a minimal of CINE for the surplus energy of buoyancy upward is not dissipated early on convection, under these conditions the energy is accumulated in unstable layers favoring deep convection when the energy inhibition convective release. However, it was observed that MCINE has predominantly negative correlation with the lightning activity in the region (Figure 8 and 9), i.e. greater the barrier to convection, lower it will be lightning activity. Zheng et al. [2007] simulating the influence of atmospheric stratification concluded that the combination of CAPE and CINE has a major impact on the dimensions of the vertical velocity and consequently the lightning activity.

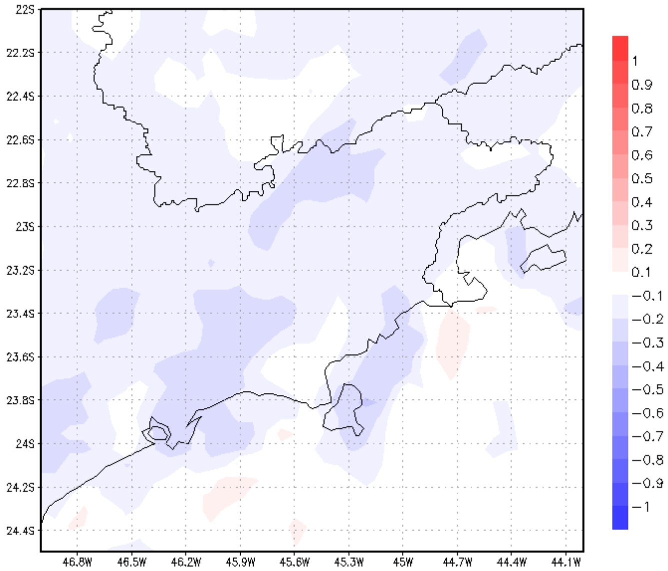

Figure 8 – Spatial correlation between MCINE and lightning activity.

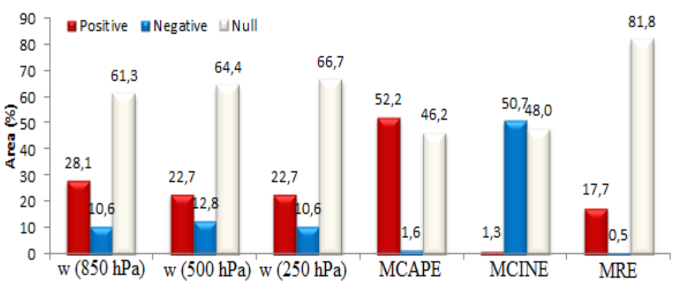

Figure 9 – Fraction of the area with positive, negative and null spatial correlation for each variable. Vertical wind velocity (w).

IV. Conclusions

The study of correlations between WRF output variables and lightning activity in southeastern of Brazil showed that all variables analyzed were correlated.

In the case of vertical wind velocity at 850 hPa presented itself as the best level to identify scenarios favorable to lightning occurrence among the three levels studied. Furthermore, it was observed that areas with positive correlations were accompanied by smaller cores with negative correlations.

For correlation with MCAPE, it was observed that this variable has a predominantly positive correlation with lightning activity, characterizing itself as the most reliable variable to indicate scenarios occurring lightning activity.

The MRE was the variable that had the highest maximum correlation among all the variables analyzed. However, this also showed the largest area of null correlation, indicating possibly the existence of a threshold reflectivity where the storm clouds begin to electrify.

Unlike the other variables, the MCINE was the only variable that showed instead a negative correlation with the lightning. This variable, as well as MCAPE, had an area of negative correlation (in the case of MCAPE, positive) greater than zero correlation area also featuring a good indicator of the lightning activity.

The conclusions obtained in this paper were based on a single weather event, so it was not possible to analyze the dependence of the lightning activity of each specific region with a variable determined.

However, it was possible to characterize the correlations with multivariate statistics, which will help in understanding and modeling and study of the physics involved in lightning.

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