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ASSESSMENT OF LIGHTNING THREADS IN BRAZIL AND THE USE OF LIGHTNING WARNING SYSTEMS FOR HUMAN LIFE PROTECTION

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Abstract - The Atmospheric Electricity Group (ELAT) from CCST / INPE had developed an accurate methodology for cloud-to-ground lightning warning with one hour in advance for regions with less than 100 km^2. Based on real-time total lightning data provided by lightning detection network, electrostatic field-mill measurements, IR satellite images, and weather radar images, cloud-to-ground lightning warnings are issued based on the probability of a thunderstorm to occur in a particular region. This approach is very attractive because for specific regions (like airports, soccer stadiums, oil refineries, mining, parks, etc.), the forecast based only on numerical models or radar images is not suitably accurate in time and/or spatial domains. The main purpose of issuing lightning warnings with some lead time is to protect human life from lightning threads while in outdoor activities. Main results are: less than 20% of false alarms, lead time of about 30 to 40min and warning total duration of about 02 to 03h. The paper also presents a comprehensive risk analysis of lighting threads for outdoor activities showing risk maps for different scenarios as a function of the time of exposure and level of protection. An example, a lightning warning system that combines total lightning data and numerical model simulations is also discussed illustrating how it can predict the occurrence of a severe storm in a particular region with a lead time of 30 min and thus help preventing human casualties.

1 - INTRODUCTION

The Atmospheric Electricity Group (ELAT) from INPE developed, in the last 6 years, a methodology for cloud-to-ground (CG) lightning warning with up to one hour lead time (nowcasting) for regions smaller than 100km^2. This approach is particularly attractive because, presently in Brazil, thunderstorm warning systems are mainly based on numerical models or satellite products, which work better for large areas. For small areas (as city neighborhoods, stadiums, refineries, airports, power plants, construction areas, etc) those lightning warning systems still do not present a satisfactory accuracy in both space and time domains. Nowadays, the more powerful computational resources allow increasing the prediction model time and spatial resolution also adding cloud microphysics calculations in the forecast. However, there is usually a great effort to gather model initialization data at the same spatial and time resolutions. Moreover, local convective storms present highly changeable dynamics and strong dependency on the regional conditions (like the topography, wind circulation, humidity, etc). Therefore, these particular dynamics tend to be neglected by the present meteorological models due to the lake of high-resolution initialization data leading to significant errors in the forecast.

This work intends to show that the present lightning warning methodology can be used as a powerful tool for human life protection since it can be an alternative way to predict lightning occurrence over a particular small area. Moreover, according to the Brazilian Standard (ABNT NBR-5419:2005), the U.S. Standard (NFPA-780:2008) and International Standard (IEC 62305:2.0) there is still no effective protection systems for people working outdoors. Thus it is also presented a simplified risk analysis of lightning threats over Brazil based on CG lightning flash densities computed from LIS historical data with 0.1° resolution.

2 – LIGHTNING THREAT RISKS (R_{dat})

According to the IEC 62305-2 Standard (Ed 2.0), the typical tolerable risk (R_T) for loss of human life or permanent injuries is

$$R_T = 1 \times 10^{-5}\ yr^{-1} \qquad (1)$$

In general, based on a simplified model, the risk of someone working outdoors to be struck by a lightning is

$$R_{dat} = \pi.(d_r)^2.D_f.F_t\ \ yr^{-1} \qquad (2)$$

where D_f is the CG lightning density of the region (given in flashes.km^{-2}.yr^{-2}); d_r is average minimum distance from the lightning strike to cause a fatality (given in km); F_t is time of exposition (an adimensional value that represents a fraction of the year that the person is exposed to lightning threat).

Since the Brazilian average CG lightning flash rate is 6 flashes.km^{-2}.y^{-1} [1], assuming that a lightning strike can cause a fatality up to 20m distance from the person, then the risk of this person working 8h a day, 7 days a week outdoors to be killed by a lightning is

$$R_{dat} = \pi \times (0{,}02)^2 \times 6 \times 0.3333 = 2.5 \times 10^{-3}\ yr^{-1} \qquad (3)$$

It can be stated that a risk of lightning threat (R_{dat}) for someone working outdoors 8h a day, 7 days a week is 250 times higher than the typical tolerable risk (R_T). Therefore, we concluded that, for most of the cases, a CG lightning tracking and warning system is required to protect people working outdoors, since it will tell them when to go indoors safely before the onset of the CG lightning activity.

As an example, Figure 1 shows an estimate of the lightning threat risk (R_{dat}) computed using Equation (2) for the entire country. A high resolution CG lightning flash density map (0.1° x 0.1°) was used [1]. For calculations, it was assumed d_r = 10m and F_t = 1/3, which corresponds to a typical condition for outdoor activities. In general, a lightning strike at 10m distance usually has a high potential to kill at any circumstances. Furthermore, most of the people stays exposed about 1/3 of the year due to outdoors activities.

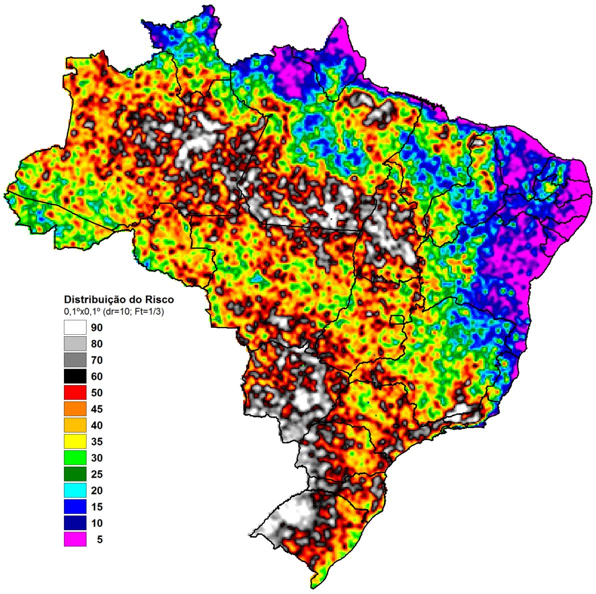

Figure 1 - Lightning threat risk (R_{dat}) computed based on LIS cloud-to-ground flash rates with 0.1° resolution.

Based on this simplified method for R_{dat} calculation, only part of the Northeastern Brazil and a very small part of the Northern region (magenta colors) present a lightning risk threat (R_{dat}) closer or lower than the typical risk (R_T) defined by the IEC 62305-2 Standard.

Still based on Equation 2 and assuming the typical scenario for lightning risk (d_r = 10m and F_t = 1/3), Figure 2 shows the monthly variation of the R_{dat} for the five different regions of Brazil. Clearly the monthly variations of the lightning risk threads changes from one region to another due to different meteorological conditions. Of course that the local conditions of each activity are not taken into account because the values of d_r and F_t are assumed constant. For each type of activity and under what conditions they are executed, the values of d_r and F_t shall change, thus affecting in the final values. A more comprehensive analysis of the outodoor activities is required to improve the R_{dat} estimates.

3 – LIGHTNING WARNING SYSTEMS

3.1 – BRIEF REVIEW

Several works present lightning warning methods based on lightning locations systems (LLS) data [2]. Additionally, other works combine total lightning (TL) data with weather radar information to improve the accuracy of the lightning threat warnings [3]. Finally, some studies present automated lightning warning systems as a combination of LLS data and electric field-mill (EFM) measurements [4][5][6].

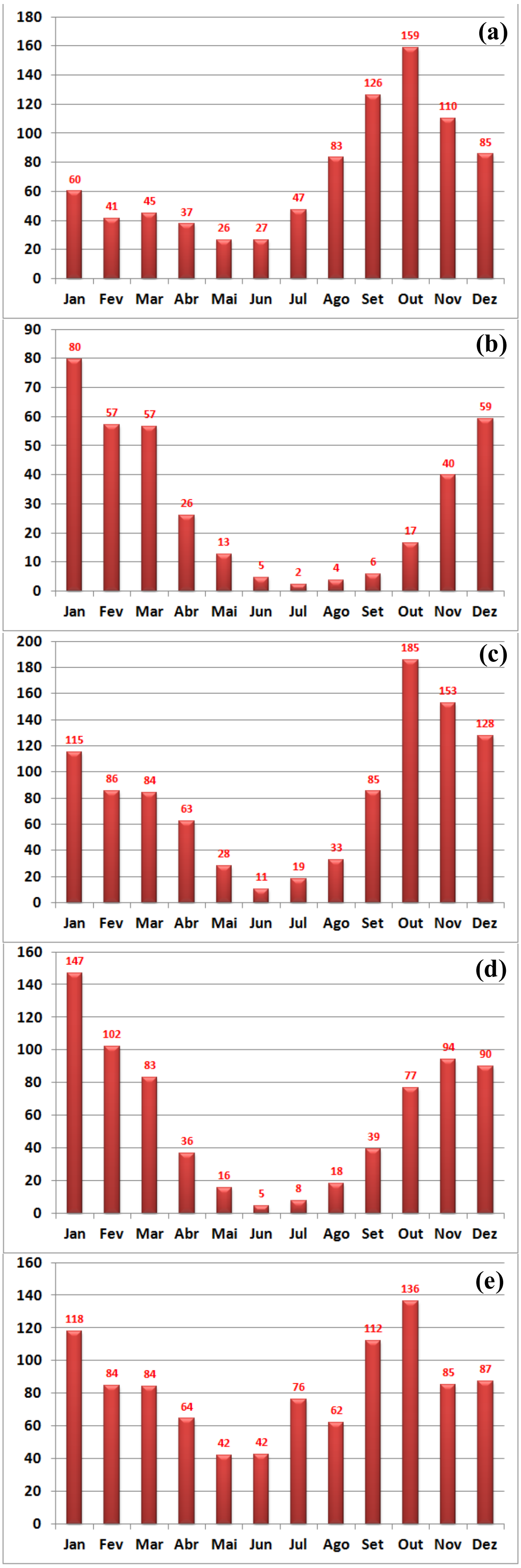

Figure 2 – Monthly variation of the lightning threat risk (R_{dat}) for five different regions of Brazil: (a) Northern; (b) Northeastern; (c) Mid-eastern; (d) Southeastern; (e) Southern. The R_{dat} is computed using Equation (2) for d_r = 10m and F_t = 1/3.

An EFM measures the intensity of the atmospheric electrostatic field (also called slow or quasi-static electric field). Unlike the LLS, which responds to fast transients of the electromagnetic field (caused by the lightning flashes), the EFM detects the quasi-static component of the environment's field (caused by changes in the net charge directly above and in the surroundings of the sensor due to cloud electrification). The effective field measurement range of an EFM varies from a few kilometers up to 20 km [4].

According to Ferro et al. [7], the main reason for using EFM antennas for lightning warning is their ability to detect the development of a thunderstorm in the surroundings or directly over the Area of Concern (AOC). In their study, several AOCs were defined as circular areas of different radius around an EFM installed in São José dos Campos town (23°19'48.20"S; 45°48'31.85"W). In general charge separation inside the cloud causes a reversal of the atmospheric electrostatic field followed by an increase in its magnitude. These two features can be used to trigger a warning, assuming (reasonably) that charge separation precedes lightning producing. However, field reversal may not happen at a particular EFM site and the field magnitude may also vary significantly at that site, both as a function of the distance of the EFM site from cloud charge region [3]. Thus, a warning system based on EFM only can fail to warn in many particular cases.

They also compared CG lightning data detected by a LLS within AOCs of different radius and the lightning warnings provided by the EFM measurements. The nowcast accuracy was evaluated based on two statistical variables: the Probability Of Detection (POD) and the False Alarm Rate (FAR), which are defined as:

- POD = the ratio of the number of successful warnings to the total number of CG lightning strikes within the AOC;
- FAR = the ratio of the number of false warnings to the total number of warnings.

They found that a field threshold of 0.9 kV/m and an AOC of 10km are the most efficient configuration to trigger a lightning threat warning using only one EFM antenna. This particular configuration shows the highest POD (60%) and the lowest FAR (41%). On the other hand, using almost the same methodology, Aranguren et al. [8] achieved POD = 37.5% and FAR = 87.0% in Catalonia (Spain), and Murphy et al. [4] obtained POD = 34.4% and FAR = 74.1% in Florida (USA).

Naccarato et al. [9], using LLS data and measurements from two EFM antennas, show that CG lightning warnings based on EFM data are very sensitive to local conditions (e.g. humidity, wind velocity and direction, soil resistivity, thunderstorm electrical features, etc). These results confirm that EFM data alone are not suitable for an accurate lightning warning system. They conclude that EFM measurements must be combined to further meteorological data (achieved by other techniques) to provide more reliable nowcasts.

3.2 – ELAT LIGHTNING WARNING SYSTEM

The ELAT group from CCST / INPE had developed a methodology for CG lightning warning with up to one hour lead time for regions smaller than 100km^2. The methodology was improved from the previous works by including data from the WRF (Weather Research & Forecast) mesoscale model and the total lightning information as described by Naccarato et al. [10][11]. In this paper, we extend the previous results (which analyzed data from only 6 months) by analyzing 18 months of data as described in Section 4.

As from previous works, the CG lightning warning system was based on four data sources [10][11]:

- The radar reflectivity (MAXCAPPI 400km), which is related to the amount of available precipitation;
- The satellite infrared (IR) images, which are related to the vertical development of the thunderstorms (given by the cloud height top temperature);
- The overall total lightning (TL) activity provided by BrasilDAT, as described by Naccarato et al. [12].
- The local atmospheric instability measured by three different stability indexes provided by the WRF model: the Total-Totals Index (TT), the Showalter Index (SI) and the K Index (KI).

4. RESULTS AND DISCUSSIONS

To extend the evaluation of the ELAT lightning warning system, the same area of Southeastern Brazil was chosen as shown in Figure 3 [10]. This area was called TARGET1.

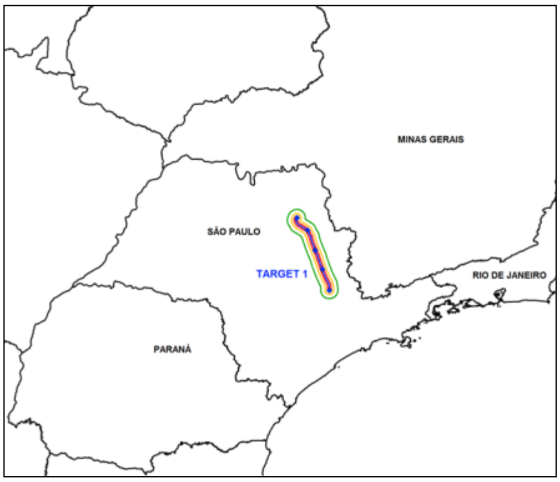

Figure 3 - Location of the chosen area (TARGET1) where the severe thunderstorms were identified and tracked with total lightning data provided by the BrasilDAT network.

Figure 4 magnifies this area and its background shows to the CG lightning flash density provided by LIS sensor with 0.25° resolution and 12 years of data (1998-2009) [1]. This region has a CG flash rate that ranges from 4-10 flashes.km^{-2}.yr^{-1}. The average CG flash rate of Brazil is 5-6 flashes.km^{-2}.yr^{-1}.

Figure 5 shows the monthly distribution of all 1,160 CG lightning warnings that were issued for TARGET1 from Dec/2011 to May/2013 (18 months). Figure 6 shows the Percentage of False Alarm Rate (%FAR) for the CG lightning warnings issued for the same area and period. The %FAR is defined as the ratio of the number of warnings with no CG lightning detected within the 4km buffer and the total number of warnings. Figure 7 shows the average lead time for all the CG lightning warnings.

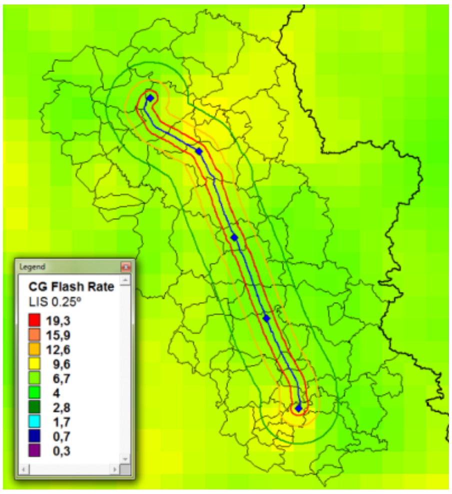

Figure 4 – Zoom of the TARGET 1 area. The background colors correspond to the CG flash rates from LIS. The green line is the 20km buffer which is used to compute the lightning activity.

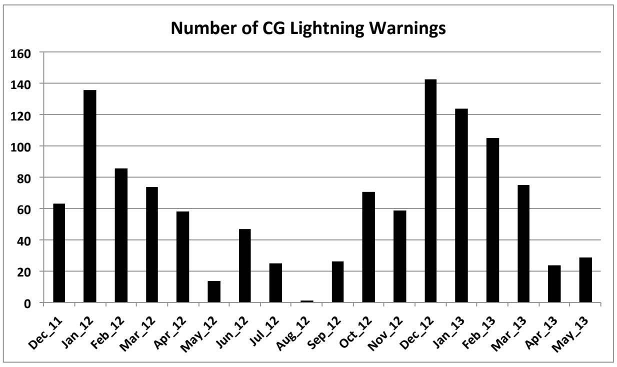

Figure 5 - Number of CG lightning warnings issued monthly for the TARGET1 area from Dec/2011 to May/2013.

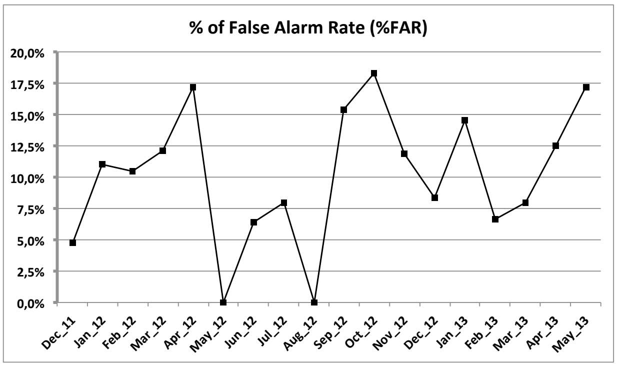

Figure 6 – Percentage of False Alarm Rate (%FAR) for all CG lightning warnings from Dec/2011 to May/2013.

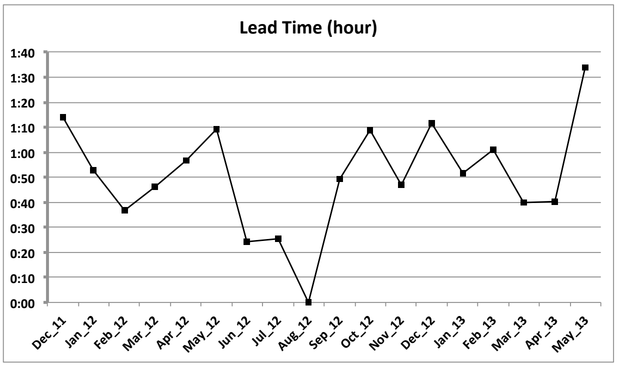

Figure 7 – Average lead time (in hours) for all CG lightning warnings from Dec/2011 to May/2013.

Table 1 summarizes the main results for the ELAT lightning warning system during the 18-month evaluation period (from Dec/2011 to May/2013) when 1,160 CG lightning warnings were issued.

CG Lightning Warning	Avg Values ± StdDev
Warning Durations	02:59h ± 01:50h
Time of the Warnings (LT)	15:02h ± 04:28h
Average Lead Time	01:04h ± 0:29h
% of False Alarm Rate	10% ± 5%

Table 1 – Main results of the ELAT lightning warning system

Figure 8 shows a very important (and strong) correlation between the Average Lead Time (ALT) and the False Alarm Rate (FAR). The ALT is directly correlated to the FAR, which is opposite to the overall warning system accuracy (WSA). Thus, it can be stated that increasing the lead time, will increase the FAR leading to a low WSA. On the other hand, reducing significantly the lead time, will increase the WSA but will also increase the probability that a thunderstorm reaches the monitored area or develops over it without an earlier warning. This can result in human casualties. Thus, to achieve a precise and safe warning system, it must be a commitment between the WSA (or FAR) and the ALT.

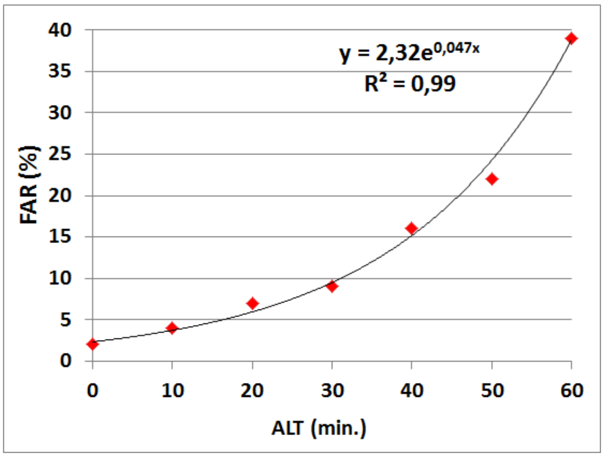

Figure 8 - Correlation between the Percentage of False Alarm Rate (%FAR) and the Average Lead Time (ATL).

This plot was computed based on more than 10,000 CG warnings (from 2010 to 2013) in order to obtain enough statistical significance for each variable. The data was then adjusted by a least-square method for each bin (5 for %FAR and 10min for ATL). After adjustment, both variables are correlated in the plot of Figure 8 and then the exponential trend-line computed.

4 – NEW DATA SOURCE: EFM MEASUREMENTS

In the end of 2013, INPE finished deploying 4 EFM sensors that were integrated into the previous CTA network, which is composed by 7 EFM sensors. Figure 9 shows the final network configuration composed of 11 EFM sensors. The mean baseline is about 20km.

This network became operation in Jan/2014 providing near real-time measurements of the atmospheric electrostatic field (AEF) every 5 minutes. Each sensor samples the AEF every minute when the field is below the critical threshold. Above this threshold, the AEF is sampled every second. The data of each sensor is sent to a central processor that archives the information and interpolates the data. First the central processing synchronizes all received data before starting the interpolation. This avoids any time mismatch in the resulting map. The interpolation is done with all available measurements at that time using the Barnes method [13]. As a result, the system produces a plot (Figure 10) showing the spatial distribution of the AEF based on the available measurements at each site. Over this map, the BrasilDAT lightning solutions for the samen 5-minutes interval (total lightning) is superimposed to provide a visual correlation between the variation of the EFM measurements and the total lightning activity.

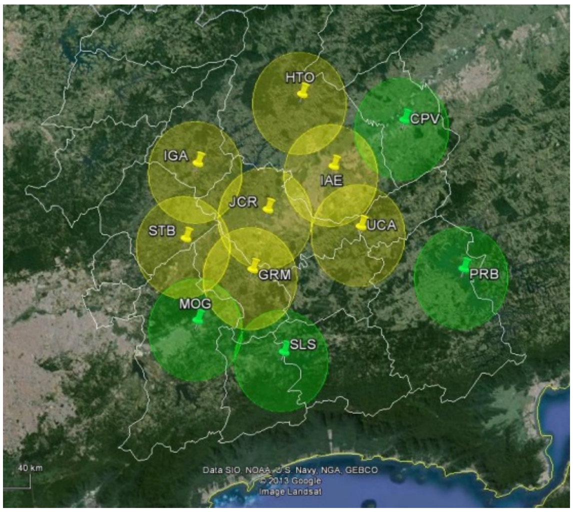

Figure 9 – Location of the 11 EFM sensors of the INPE/CTA network. The mean baseline is ~20km. The circles around each sensor stand for 15km distance. CTA sensors are yellow colored. INPE sensors are shown in green.

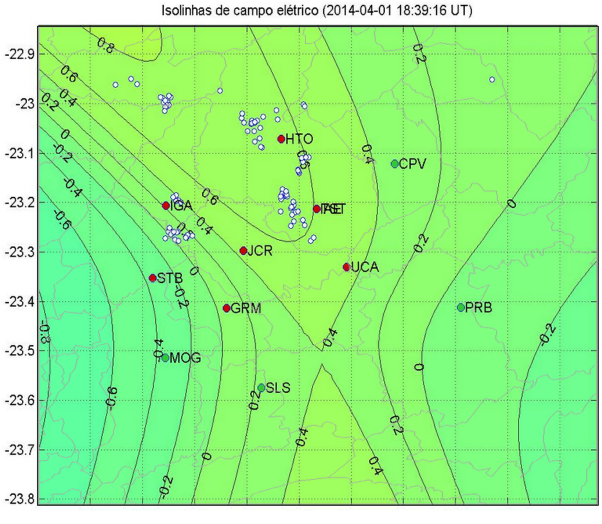

Figure 10 – Spatial distribution of the atmospheric electrostatic field (AEF) computed with the Barnes interpolation method using the available measurements of each site. The white dots are the superimposed BrasilDAT lightning solutions.

In the near future, we plan to introduce the EFM near real-time measurements in the ELAT lightning warning system in an attempt to improve the methodology and reduce the %FAR without a significant decrease in the ATL. Thus, the improved lightning warning system will be based on five data sources:

- The radar reflectivity (MAXCAPPI 400km);
- The satellite infrared (IR) images;
- The overall total lightning (TL) activity
- The Total-Totals Index (TT), the Showalter Index (SI) and the K Index (KI) computed by WRF model;
- The interpolated EFM measurements from a 11-EFM sensor network.

5 - CONCLUSIONS

The ELAT group extended the results of its lightning warning system that was previously presented [10][11]. The results shown that it is possible to accurate warn (False Alarm Rate < 20%) the occurrence of CG lightning over a particular area with an average lead-time of one hour. This methodology uses combined real-time total lighting information from BrasilDAT network, radar and satellite images and stability indices computed hourly by the WRF numerical model. The Average Lead Time (ALT) is conversely related to the False Alarm Rate (FAR). Thus, the more accurate the system is, the smaller the lead time will be. This is an important result that will help find a balance between lead time (which is related to safety) and accuracy (which is related to efficiency).

In the near future, we will introduce the interpolated EFM measurements from a 11-EFM sensor network deployed in Vale do Paraiba Valley, São Paulo. We expected that this new data source would help reducing the Percentage of False Alarm Rate (%FAR) without changing the Average Lead Time (ATL). As we have discussed, reducing the %FAR invariably leads to a reduction in the ATL which is not desirable. Thus, the EFM information might help keep the ATL for a lower %FAR.

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