Relationship between Cloud-Ground Lightning and Penetrative Clouds: A Multi-channel Satellite Application

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ABSTRACT

This work presents a relationship between atmospheric discharges and penetrative convective clouds. It combines Infrared and Water Vapor channels from the GOES-12 geostationary satellite with cloud-ground lightning data from the Brazilian Integrated Lightning Detection Network (RINDAT) during the period from January to February 2005. The difference between water vapor and infrared brightness temperature is a tracer penetrating clouds. Due to the water vapor channel's strong absorption, this difference is positive only during overshooting cases, when convective clouds penetrate the stratosphere. From this difference and the cloud-ground electrical discharge, measured on the ground by RINDAT, it was possible to adjust exponential curves that relate the brightness temperature difference from these two channels to the probability of occurrence of cloud-ground electrical discharges, with a very high coefficient of determination. If WV-IR brightness temperature difference is larger than -15K there is a high potential for cloud-ground lightning activity. As this difference increases the cloud-ground lightning probably increase, for example: if this difference is equal zero, the probability of having at least one cloud-ground electrical discharge is 10.9 %, 7.0% for two, 4.4% for four, 2.7% for eight and 1.5% for sixteen cloud-ground lightning discharges Through this process, was developed a scheme that estimates the probability of occurrence of cloud-ground lightning over all the continental region of South America.

Introduction

Multispectral satellite analysis has demonstrated its ability to depict cloud top features. The combination of water vapor and infrared window channels to describe deep convective clouds has been largely used; for instance, Medaglia et al. (2005) used these channels from geostationary satellites to develop the Global Convective Diagnostic. Schmetz et al. (1997) noted trough simultaneous observation of the METEOSAT infrared window and water vapor channels and a line-by-line radiative transfer model that differences larger than zero degrees between both channels are related to convective clouds with high vertical extension. The simulations show that the larger brightness temperatures in the water vapor channel are due to stratospheric water vapor, which absorbs radiation from overshooting tops and emits radiation at a higher stratospheric temperature. Adler and Mack (1996) studying the cloud top dynamics also found storm tops above the tropopause. Fritz and Laszlo (1993) also noted a brightness temperature from the water vapor channel warmer than from the infrared window channel over a region associated with deep convection. Kurino (1996) showed that the difference between both brightness temperatures can be very useful in defining heavy precipitation related to deep convection. Reudenbach et al. 2001 use this difference to discriminate deep convection from thick Cirrus clouds. Setvak et al. (2007) used the higher spatial resolution images from the MODIS sensor to investigate the correlation between cloud top temperature and the water vapor – infrared window difference. They consider that a positive difference is possible if each storm top generates some amount of moisture in the stratosphere, or by pre-existent stratospheric moisture in a layer above the cloud top. They found some cases that agree with the previous results, where the positive difference is well correlated with the minimal cloud top temperature. However, one case did not agree; the larger difference was not correlated with the minimal temperature. They also suggest that different ice emissivity for each channel can in some cases explain these differences. Further statistical studies should be done to understand cloud top features. Wang (2005), using a three-dimensional non-hydrostatic cloud model studied penetrating convective clouds. He suggests that moisture plumes in the stratosphere above convective clouds are generated by gravity waves and high instability over the cloud top due to convection inside the storm.

The main goal of this study is to test the hypotheses that the difference between the water vapor and infrared channel can be used as a proxy for penetrative clouds, and those clouds are related to cloud-ground lightning.

Section 2 describes the data and the methodology employed in this study. Section 3 presents the results obtained, comparing satellite data and cloud-ground lightning occurrence, and finally section 4 presents the conclusion.

2. Methodology

Schmetz et al. (1997) suggested that positive differences between water vapor and infrared brightness temperature are only possible when deep convective clouds penetrate in the tropopause, moistening the stratosphere. The infrared is located in the window channel; a region of the electromagnetic spectrum where the earth atmosphere's slightly absorbs terrestrial radiation. However, the water vapor channel has strong absorption features and the brightness temperature reported by this channel is nearly always colder than that measured in the infrared channel. Therefore, the difference between the water vapor and infrared window channels is normally negative, except if penetrating clouds go through the tropopause, moistening the stratosphere and then, as the temperature increases in this layer, the difference can be positive. In these cases, these positive differences are related to overshooting, which is normally associated with high deep convective cloud tops with a high amount of ice, chiefly responsible for the development of an electrical field inside the clouds. The atmospheric discharges are the response of the accumulated charges inside the cloud that can breakdown the dielectric air (Pinto Jr et al., 2004). The center of charges (positive and negative) are formed by several cloud microphysical process that transfer positive and negative charges during the formation of cloud droplets, rain drops and ice particles (Mac Gorman and Rust, 1998). Moreover, observational studies revealed that lightning is associated with presence of large ice particles and strong updrafts in the mixing region (0 and -20^{o}C) (Baker et al. 1995; Petersen and Rutledge, 1998). Therefore, these very deep and high extended clouds are responsible for a very high rate of electrical discharges (Abdoulaev et al., 2001). The difference between these two brightness temperatures can be used as a proxy for very deep convection clouds (overshooting cases) associated with a large amount of electrical discharges. Considering these features, we will combine satellite with lightning discharge data to check this hypothesis and quantify this relationship.

2.1 The RINDAT Network

RINDAT is a lightning detection network covering the south and southeast part of Brazil that was established after a consortium of the Brazilian electricity companies and research institutes Pinto (2003). This network uses sensors that measure electric and magnetic field emitted by cloud-ground lightning at the frequency of LF/VLF and are able to detect lightning at distances up to 600 km from each antenna. RINDAT technology is based on LPATS (Lightning Position and Tracking System) and IMPACT (Improved Accuracy Using Combined Technology) sensors that combine Magnetic Direction Finder (MDF) and Time of Arrival (TOA) technique for locating lightning sources at medium and long ranges, through a hyperbolic method. More details about RINDAT can be found in Pinto (2003). During the period of this study, the network was composed of 24 sensors (8 Impact and 16 LPATS sensors), as indicated in Figure 1a. Data from the sensors are sent to a central processor where they are disseminated and stored and later reprocessed to recover data losses from possible delays in communication links. The data employed in this study consist of time and location of the cloud-ground electrical discharges from January to February 2005. RINDAT is able to locate cloud-ground strokes with a precision of 0.5-2 km with a flash detection efficiency of 80-90% (Naccarato et al. 2004, Cummins et al., 1998). Based on detection efficiency studies,, detection efficiency contour lines were drawn over the network (see Figure 1b). This work used only the information for Sao Paulo State that is inside the area covered by lightning detection efficiency greater than 90%.

2.2 GOES 12

The infrared (IR) 10.2–11.2 μm and the water vapor (WV) 6.47–7.02 μm channels from GOES-12 were employed to calculate the penetrating clouds. The data employed in this study were images (Full Disk, Northern Hemisphere Extended and Southern Hemisphere) available every 30 minutes covering the period from January to February 2005. IR and WV channels have the same resolution (4 km at the subsatellite point) and projection, therefore the overlay is straightforward and the difference between the channels is easily performed. We have used full resolution images in the satellite projection to perform the channel differences. The time of each image normally corresponds to the time of the first image scan line. In this work we did not use the image time but the specific time of each scan line to combine precisely with the lightning discharge.

2.3 Probability of Occurrence.

Inside the 90% lightning detection efficiency region we applied the following methodology. The differences between the WV–IR brightness temperatures were calculated during January-February 2005. For each image pixel difference (WV-IR) we searched for the occurrence of cloud-ground lightning reported by RINDAT, 7.5 minutes before or after the time of the scan line, in a region with a 10km radius centered on the pixel position. Figure 1b shows an example of the number of cloud-ground lightning per pixel, integrated during one day and the detection efficiency contour lines.

Statistical analysis was performed for the WV- IR differences in the temperature interval between -15 to + 3 degrees. This interval was chosen considering the significant lightning occurrence observed in the dataset. This information was separated in one-degree bins and the total number of cloud-ground lightning occurrences computed, the amount of time when at least *j* cloud-ground lightning occurred (LD^j_i - occurrence in the WV-IR bin interval *i*) and the amount of time that no electrical discharge was reported (NLD_i – no occurrence in the WV-IR bin interval *i*).

The probability to have at least j cloud-ground lightning occurrence $P_i(\geq j)$ for each temperature bin interval (*i*) was defined as

$$P_i(\geq j) = \frac{LD^j{}_i}{LD^j{}_i + NLD_i} \text{……………………..} \quad (1)$$

Inside the region analyzed we reported 189,577 cloud-ground lightning occurrences, 119,703 in January and 69,874 in February.

3 Results

We have focused the analyses of cloud-ground lightning occurrences over the State of São Paulo, where RINDAT has 90% flash detection efficiency. We also computed the frequency of occurrence of WV-IR differences larger than -3 K. This threshold was used because it corresponds to the WV-IR brightness temperature difference in which 50% of lightning cases occur (see Figure 3). Figure 2a shows the spatial distribution of monthly cloud-ground lightning occurrences during February of 2005 (the grid corresponds to a Cartesian projection spaced by 0.04 degrees). Figure 2b presents the spatial distribution, at the same projection, of the relative frequency (one corresponds to the maximum occurrence) of the WV-IR larger than -3 K. The majority of lightning occurs in the eastern region of the São Paulo State, around large cities, such as São Paulo, and near the orographic region. The interesting result, however, is the similarity of WV-IR spatial distribution and lightning occurrence, showing that this difference is well connected to penetrative clouds and consequently associated with electrical discharge.

Figure 3 shows cloud-ground lightning cumulative frequency of occurrence as a function of the WV-IR brightness temperature difference. It is noted that only 8.4% of cloud-ground lightning occurs for WV-IR smaller than -15K and 99.99% occurs for WV-IR values smaller than 3K. The 8.4% of lightning cases take place over a large interval of WV-IR smaller than -15K. 50% of cloud-ground lightning happens when WV-IR is larger than -3K. This result shows that the combination of these two channels is well associated with storm severity and consequently cloud electrical activity.

The occurrence probabilities for at least one, two, four, eight and sixteen cloud-ground lightning as function of the WV-IR brightness difference was computed using Equation 1. We found an exponential increase in lightning's probability of occurrence as the WV-IR difference increases. Figure 4 shows the relative frequency of occurrence for different numbers of lightning occurrence, as a function of the WV-IR difference. For instance, for the WV-IR difference equal to zero, the probability of cloud-ground electrical discharge is equal to 10.9 %, 7.0%, 4.4%, 2.7% and 1.5% for at least one, two, four, eight and sixteen cloud-ground lightning discharges respectively. The probability of having more than sixteen cloud-ground lightning discharges in 15 minutes only occurs for a WV-IR difference larger than -4K. Due to a strong decrease in the number of cases of

WV-IR differences larger than 3K we have computed the differences up to this value. For 3K differences, the probability of having cloud-ground lightning is 18.6%, 13.2%, 8.6%, 3.7% and 1.2% for at least one, two, four, eight and sixteen cloud-ground lightning discharges respectively. We can note that eight and sixteen lightning occurrences inside the 15-minute interval for WV-IR equal to 3K are slightly smaller than for 2K, it is probably due to small amount of cases reporting for 3K.

It was possible to adjust an exponential curve that relates WV-IR difference to probability of occurrence of a given number of electrical discharges, with a high coefficient of determination around 0.9, as shown by Equation 2. Figure 5 shows the adjusted exponential curves for each case of cloud-ground lightning occurrence.

$$
\begin{aligned}
P_i(\geq 1) &= 9.3 * \exp(0.19 * i) \\
P_i(\geq 2) &= 6.2 * \exp(0.21 * i) \\
P_i(\geq 4) &= 3.9 * \exp(0.21 * i) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)} \\
P_i(\geq 8) &= 2.2 * \exp(0.21 * i) \\
P_i(\geq 16) &= 1.0 * \exp(0.21 * i)
\end{aligned}
$$

Where, (*i*) corresponds to the WV-IR brightness temperature difference in Kelvin.

Based in this result and considering that the statistical results obtained in this study can be extrapolated to a larger region, we extrapolate this estimation of probability of occurrence of cloud-ground lightning for all continental South America. The validation of these assertions can only be evaluated when the RINDAT network has been improved with more sensors covering the other regions. Figure 6 shows an example of the operational product, using GOES 12 images and the number of cloud-ground electrical discharges per pixel in 15-minute intervals reported by the RINDAT network for the same time. We can note the similarity of the results even outside the region of high detection efficiency.

4 Conclusions

This study combines water vapor and infrared window channels to detect cloud-ground lightning discharges. The WV-IR brightness temperature difference can be used as a proxy for deep convection. We have found that values larger than -15K are associated with deep convective clouds with potential for cloud-ground lightning activity. As the brightness temperature difference increases, the probability of lightning increases. These differences are also associated with the number of lightning discharges. For instance, if this difference is equal zero, the probability of having at least one cloud-ground electrical discharge is 10.9 %, 7.0% for two, 4.4% for four, 2.7% for eight and 1.5% for sixteen cloud-ground lightning discharges. The probability of cloud-ground lightning discharge can be expressed as an exponential function of the WV-IR brightness temperature difference.

The physical processes behind these results is that WV-IR values larger than -15K are associated with deep convective clouds close to the tropopause or penetrating storm tops in the stratosphere (overshooting clouds). Thus these clouds are very deep and highly extended, having a large amount of ice and strong updrafts, therefore having a considerable potential for strong lightning activity.

Based in these results it is possible to estimate the probability of cloud-ground lightning using GOES images over South America over the region not covered by the RINDAT network. This result should be tested over other continental regions to analyze if the statistical results obtained over this region can be extrapolated to all other continental regions and seasons.

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6 References

Abdoulaev, S., Marques, V. S., Pinheiro, F. M. A., Martinez, E. F. A., Lenskaia, O., 2001. Analysis of mesoscale system using cloud-to-ground flash data. *Brazilian Journal of Geophysics,* 19, (1), 75-95.

Adler, R. F. and R. A. Mack, 1986: Thunderstorm cloud top dynamics as inferred from satellite observations and a cloud top parcel model. *J. Atmos. Sci*., 43(18), 1945-1960.

Baker, M.B., H.J. Christian, J. Latham, 1995: A computational study of the relationships linking lightning frequency and other thundercloud parameters, *Q. J. R. Meteorol. Soc*., 121, pp. 1525-1548.

Cummins, K.L; Murphy, M.J., Bardo, E.A., Hiscox, W.K., Pyle, R.B., Pifer, A.E., 1998. A Combined TOA/MDF Technology upgrade of the U.S. National Lightning Detection Network. *Journal of Geophysical Research*. 103 (D8), 9035-9044.

Fritz, Sigmund and Laszlo, Istvan, 1993. Detection of water vapor in the stratosphere over very high clouds in the tropics. *Journal of Geophysical Research*, 98(D12), 22959-22967.

Kurino, T., 1997: A satellite infrared Technique for estimating “Deep/Shallow” precipitation. *Adv. Space Res*., 19 (3), 511-514.

MacGorman, D.R. and Rust, W.D., 1998: The Electrical Nature of Storms, New York,Oxford University Press.

Medaglia, C. M., C. Adamo, M. Formenton, and F. Piccolo, 2005: Nowcasting of convective cells over Italian Peninsula. *Advances in Geosciences*, 2, 173–176.

NACCARATO, K.P., PINTO JR., O., PINTO, I. R. C. A,2004: Application of a detection efficiency model to correct cloud-to-ground flash density maps in Southeastern Brazil, ILDC 2004, Helsinki.

Petersen, W.A. and S.A. Rutledge, 1998: On the relationships between cloud-to-ground lightning and convective rainfall, *J. Geophys. Res. Atmos*., 103 (D12), 14025-14040.

Pinto Jr., O., 2003: The Brazilian lightning detection network: a historical background and future perspectives, Proceedings of VII International Symposium on Lightning Protection (SIPDA), Curitiba, Brazil.

Pinto Jr., O., Saba, M.M.F., Pinto, I.R.C.A., Tavares, F.S.S., Solorzano, N.N., Naccarato, K.P., Taylor, M., P.D. Pautet, Holzworth, R.H., 2004: "Thunderstorm and lightning characteristics associated with sprites in Brazil", *Geophys. Res. Lett*., 31(13): 13103-13106.

Reudenbach, C., G. Heinemann, E. Heuel, J. Bendix and M. Winiger, 2001: Investigation of summertime convective rainfall in Western Europe based on a synergy of remote sensing data and numerical models. *Meteor. Atmosph. Phys*. 76; 23-41.

Schmetz, J., Tjemkes, S. A., Gube, M., and Van de Berg, L., 1997: Monitoring deep convection and convective overshooting. *Adv. Space Res*., 19 (3), 433-441.

Stevak, M., R.M. Rabin and P. K. Wang, 2007: Contribution of the MODIS instrument to observations of deep convective storms and stratospheric moisture detection in GOES and MSG imagery. *Atmos. Res*. 83, 505-518.

Wang P.K, 2007: The thermodynamic structure atop a penetrating convective thunderstorm. *Atmos. Res*., 83, 254-262.

FIGURE CAPTIONS

Figure 1 – a) Location of RINDAT sensors and the Institution responsible for each sensor. b) Number of cloud-ground electrical discharges per day on November 1st 2007, and lightning efficiency detection for 20, 60 and 90%

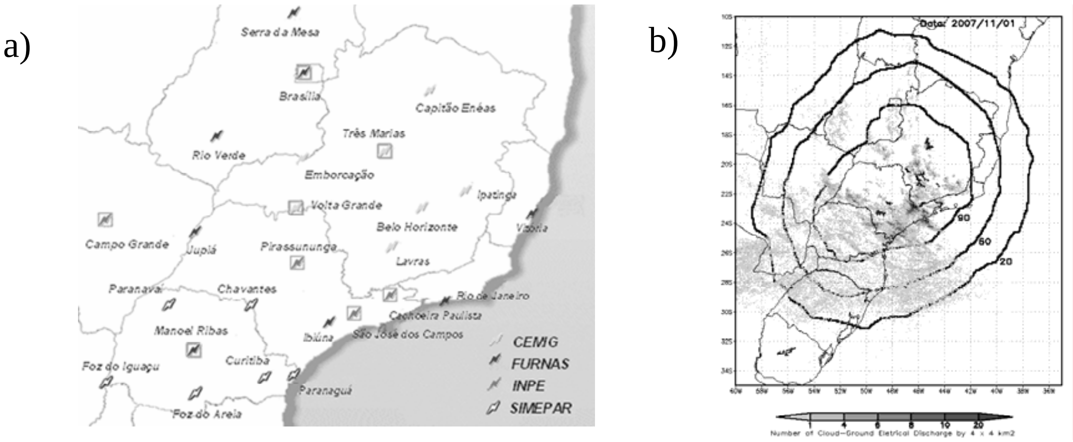
Figure 2 – a) Spatial distribution of the cloud-ground electrical discharges occurring February 2005 in Sao Paulo State. b) Spatial distribution of the relative frequency of WV-IR brightness temperature differences larger than -3K, in February 2005 in Sao Paulo State. One corresponds to the region of maximum occurrence.

Figure 3 – Cumulated frequency (%) of cloud-ground electrical discharge occurrence as function of the WV-IR brightness Temperature (K).

Figure 4 – Frequency of occurrence of cloud-ground electrical discharge as a function of the WV-IR brightness temperature difference for the probability of having at least one, two, four, eight and sixteen lightning discharges in 15-minute intervals.

Figure 5 – Adjusted exponential curves for the probability of cloud-ground electrical discharge as a function of the WV-IR brightness temperature difference for the probability of having at least one, two, four, eight and sixteen lightning discharges in 15-minute intervals.

Figure 6 – a) Probability of lightning occurrence for November 6th 2006 at 03:30 GMT. b) Number of cloud-ground electrical discharges per pixel 7.5 minutes before and after 03:30 GMT on the same day.



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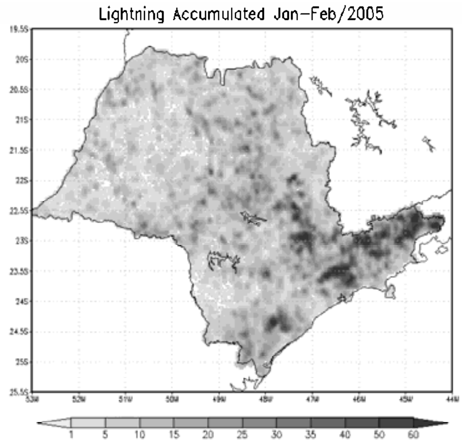

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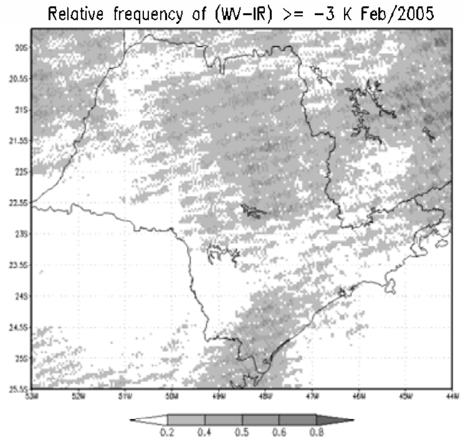

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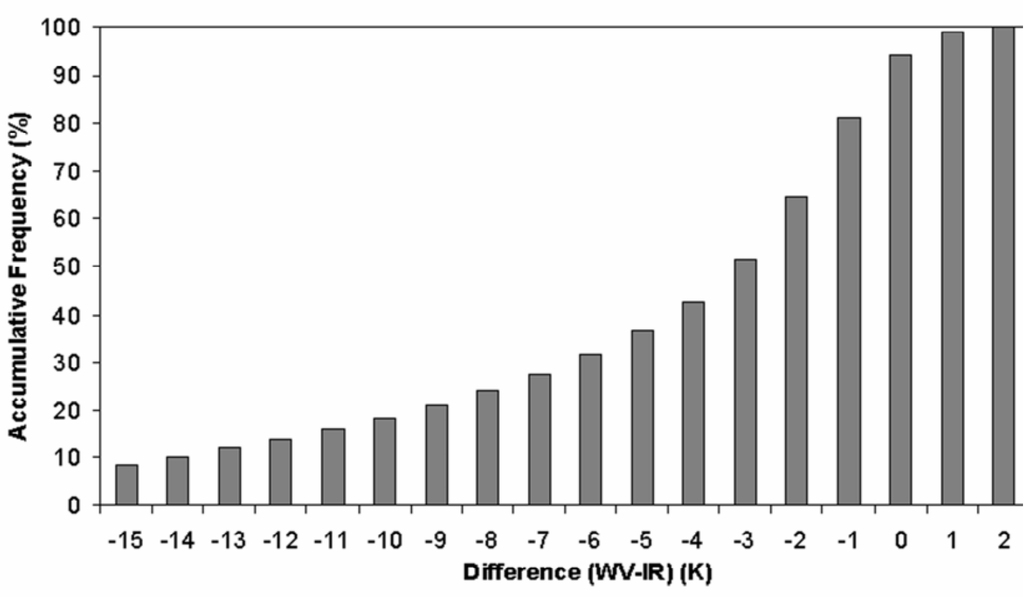

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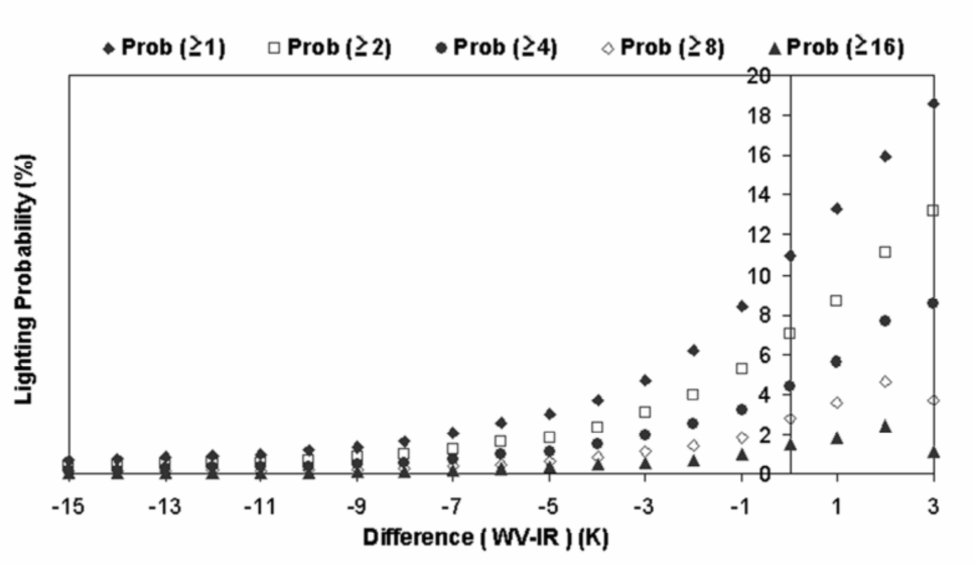


Figure 4 – Frequency of occurrence of cloud-ground electrical discharge as a function of the WV-IR brightness temperature difference for the probability of having at least one, two, four, eight and sixteen lightning discharges in 15-minute intervals.

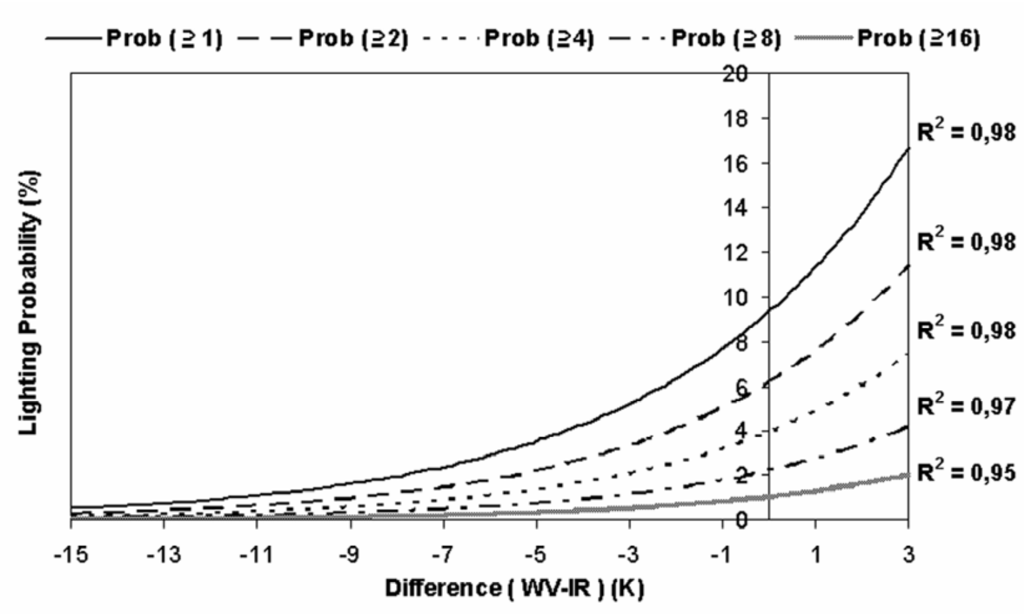
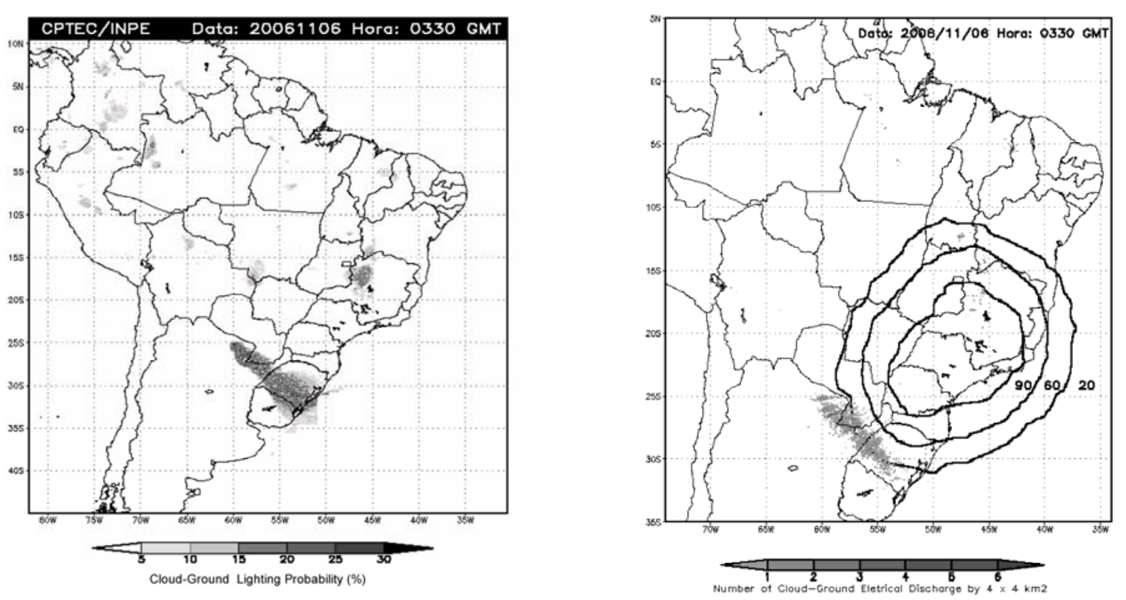


Figure 5 – Adjusted exponential curves for the probability of cloud-ground electrical discharge as a function of the WV-IR brightness temperature difference for the probability of having at least one, two, four, eight and sixteen lightning discharges in 15-minute intervals.



(a) (b)

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