Lightning Urban Effect over Major Large Cities in Brazil

Kleber P. Naccarato[1,*], Diovane R. Campos[1], Victor H. P. Meireles[2]

1. ELAT / CCST / INPE, São José dos Campos, SP, Brazil
2. FUNCATE, São José dos Campos, SP, Brazil

ABSTRACT: The urban effect on the lightning activity remains a controversial topic, beginning with works in 90's and then followed by several studies in US, Europe and Brazil. Most of them speculated on two factors to explain their findings: the increase of cloud condensation nuclei (CCN) due to anthropogenic emission of particulate matter (PM_{10}) and SO_2, and the enhancement of the convergence due to the urban heat island (UHI) effect. First works in Brazil have shown that the urban effect on lightning activity can be a combination of a thermodynamic effect (caused by the enhancement of the sensible heat flux due to the UHI) and a microphysical effect (caused by a high concentration of anthropogenic aerosol in the atmosphere). In this paper, we have selected all major large cities of Brazil (with more than 400,000 habitants) and looked for positive and/or negative cloud-to-ground (and intra-cloud) lightning anomalies based on data from two different detection systems: a lightning location network that operate in VLF range and an optical sensor on board of satellite. The analysis showed up very interesting results where some large cities do not present any type of lightning anomaly while other large cities revealed pronounced positive CG lightning anomalies.

INTRODUCTION

The lightning urban effect is known as an enhancement of the number of cloud-to-ground (CG) lightning flashes over a particular urban area compared to its surroundings, which is called positive CG lightning anomaly. This effect remains a controversial topic, beginning with the first publication of Westcott (1995), followed by many others publications in Europe, Asia, USA and Brazil (e.g. Orville et al. 2001; Steiger et al. 2002; Soriano and Pablo 2002; Naccarato et al. 2003; Pinto et al. 2004; Kar et al. 2007; Farias et al. 2009, 2012). Most of them speculated on a combination of two factors to explain their findings: the increase of cloud condensation nuclei (CCN) due to anthropogenic emission of 10μm particulate matter (PM_{10}) and sulfur dioxide (SO_2), and the enhancement of the convergence due to the heat island effect. In general, all studies discuss a particular topic related to CCN interactions with cloud microphysics and/or the increase of temperature in urban areas, what is called the Urban Heat Island (UHI). The UHI is related to many physical differences between urban and rural areas, among them absorption of sunlight, increased heat storage of artificial surfaces, obstruction of re-radiation by buildings, absence of plant transpiration, and differences in air circulation (Oke 1982; Steward 2011). The UHI magnitude, defined as the difference between urban and rural temperatures, is influenced by the Bowen

∗ Kleber P. Naccarato, ELAT / CCST / INPE, P.O. Box 515, 12227-010, S. J. Campos, SP, Brazil (kleber.naccarato@inpe.br)

ratio of contrasting surfaces, synoptic weather conditions, urban morphology, timing of temperature observations and, categorization of "rural" areas adjacent to the city (Steward and Oke, 2012). By the other hand, the influence of aerosols on the cloud microphysics, rainfall and cloud electrification has been comprehensively studied and the effect of aerosol concentration on cloud electrification has been discussed by a number of authors (e.g. Rosenfeld 2000; Graf 2004; Rosenfeld et al. 2008; Kar et al. 2009; Yuan et al. 2011; Mansell and Ziegler 2013).

According to first work in Brazil (Naccarato et al. 2003), the urban effect on lightning activity can be a combination of a thermodynamic effect (the enhancement of the sensible heat flux due to the UHI) and a microphysical effect (due to a high concentration of anthropogenic aerosol in the atmosphere). Pinto et al. (2004) and Farias et al. (2009, 2012) supported the strong positive CG lightning anomaly over large urban areas in Brazil. Later, Naccarato et al. (2010) showed a light negative intra-cloud (IC) anomaly over large urban areas in Southeastern Brazil. Pinto et al. (2004) confirmed the previous results showing a decrease in the percentage of positive CG lightning over Belo Horizonte urban area. Naccarato et al. (2003) proposed that the anthropogenic aerosols could appreciably affect the charge separation in the urban thundercloud by increasing the negative CG lightning activity. Thus, lightning incidence can be enhanced by changes in aerosol loading, causing changes in either amount or polarity of CG lightning as the aerosol concentration changes (Farias et al. 2009).

Another impact of the urban area over the lightning activity is the weekly cycle (or weekend effect). The probability to detect a weekly cycle in a climatic data is very low. However, such cycles exist within urban centers and surrounding areas and their causes are attributed to anthropogenic actions (Gordon 1994). In Brazil, it was found a strong evidence of the weekly cycle of the lightning activity, SO_2 and PM_{10} over São Paulo city (Farias et al. 2012). Other evidences of the weekly cycle of lightning activity were also found by Mullayarov et al. (2005), Bell et al. (2009) and, Stallins et al (2013).

In this paper we have selected all major large cities of Brazil (with more than 400,000 habitants) and looked for positive and/or negative CG lightning anomalies based on data from two different detection systems: the WWLLN global range lightning detection system and the LIS optical sensor on board of TRMM satellite. The analysis show up very interesting results where some large cities do not present any type of lightning anomaly while other large cities revealed pronounced positive CG lightning anomalies.

DATA DESCRIPTION

Lightning data were obtained from the World-Wide Lightning Location Network (WWLLN) and the Lightning Imaging Sensor (LIS) as described below.

The WWLLN system

The WWLLN is a ground-based network consisting of 62 sensors installed across the world, which monitors very low frequency (VLF) radio waves from lightning (called sferics). The network uses a time of group arrival (TOGA) technique on the detected sferic waveforms to locate lightning to within ~5 km location accuracy and <10μs timing resolution (Dowden et al. 2002). High peak current strokes are preferably detected (Lay et al. 2004). The global detection efficiency of WWLLN is estimated to be ~10% (Abarca et al. 2010; Hutchins et al. 2012), which allows it to detect almost all lightning-producing storms. More information about the WWLLN network can be found at http://wwlln.net.

The LIS optical sensor

LIS is an optical sensor on board the Tropical Rainfall Measuring Mission (TRMM) satellite that was launched in 1997 into a 35^{o} inclination orbit (Christian et al. 1999; Christian 1999). Since the sensor's detection efficiency presents a diurnal variation and the sampling time near the tropics is significantly higher than over the equator (due to satellite inclination), data have to be corrected before the analysis as comprehensively described by Naccarato et al. (2008). Additional information about the sensor and the TRMM satellite can be found at http://lightning.nsstc.nasa.gov/lis/

RESULTS AND DISCUSSIONS

Figure 1 shows a high-resolution map (1x1km) of the cloud-to-ground (CG) lightning activity over Brazil provided by WWLLN from 2005 to 2013 (9-year dataset). This map presents the number of VLF lightning events and not the CG lightning flash rate. The CG lightning activity is color-coded as low, average, high and very high because the relative differences are actually important for the urban effect characterization and not the absolute values.

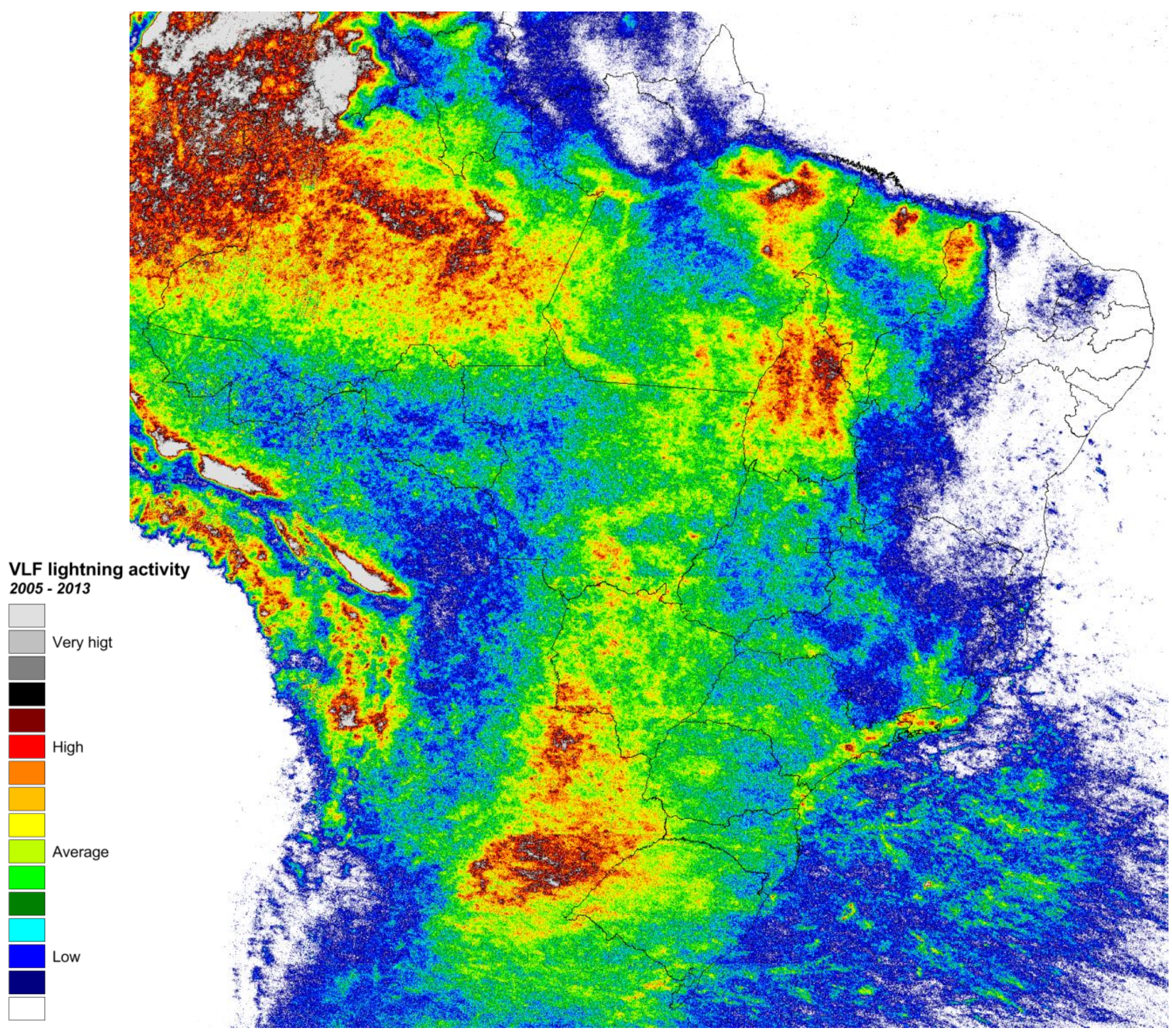

Figure 1 – Hi-res. (1x1km) cloud-to-ground lightning activity over Brazil provided by WWLLN (2005-2013)

As described by Naccarato et al. (2008), the WWLLN presents a latitude-dependent variation of its detection efficiency (DE) over South America. Thus, the network DE over the Northern Brazil is higher than over the Southern area. In order to roughly correct this effect, the LIS data over Brazil is used as a reference. The LIS also has a latitude-dependent variation of its viewtime due to the polar orbit of the satellite (±35º). This low orbit causes the sensor to image longer over the Tropics than over the Equator. This effect was correct as described by Naccarato et al. (2008). Using the corrected CG flash rate map from LIS (presented by Naccarato et al. 2011), the WWLLN CG lightning activity map was divided in 9 latitude ranges (from 8ºN to 37ºS in 5º bins). The average lightning value of every range is then compared from both maps and a correction factor was applied to the WWLLN map in order to better represent the actual latitude variation.

Table 1 summarizes the results from each large urban area in Brazil. Mainly the major metropolitan areas of the country are the principal cities of each Brazilian State. There are two exceptions: the Paraiba Valley Metropolitan Area (PVMA) and Campinas Metropolitan Area (CMA). The PVMA has about 2.5 million habitants living in 39 cities. It is located between the two largest metropolitan areas of Brazil: the São Paulo Metropolitan Area (SPMA), that has about 20 million habitants (composed of 39 cities), and Rio de Janeiro Metropolitan Area (RJMA), that has about 12 million habitants (composed of 21 cities). The CMA has about 3 million people living in 20 cities. It is located about 100km northwest of SPMA.

Table 1 – Major urban areas in Brazil, except to the Northeastern Region

Urban Area / State	**Lightning Anomaly**	**Figure #**
Belém/PA	Well defined and very pronounced, with a long displacement to southwest	2
Macapá/AP	No effect	2
Belo Horizonte/MG	Well defined, but not pronounced	3
Boa Vista/RR	Some evidence of urban effect, with a slight displacement to southeast	4
Campo Grande/MS	Not a clear effect, maybe due to the high CG lightning activity around	5
Cuiabá/MT	Some evidence of urban effect, with a slight displacement to south	6
Curitiba/PR	No effect	7
Goiânia/GO	No effect	8
Brasília/DF	No effect	8
Manaus/MA	Well defined and very pronounced, with a long displacement to northwest	9
Porto Alegre/RS	Some evidence of urban effect, with a slight displacement to northeast	10
Porto Velho/RO	Some evidence of urban effect, with a slight displacement to southeast	11
Rio Branco/AC	Not a clear effect, may be due to the low CG lightning activity around	12
São Luís/MA	Well defined and very pronounced, with a long displacement to southwest	13
São Paulo/SP	Well defined and very pronounced over the area	14
Campinas/SP	Well defined over the area, but not pronounced	14
Rio de Janeiro/RJ	Well defined and very pronounced, with a displacement to northeast	14
Volta Redonda / RJ	Well defined and pronounced, with a displacement to the surroundings	14
S. José dos Campos/SP	Well defined and pronounced, with a displacement to southeast	14
Vitória/ES	No effect	15

Those four largest metropolitan areas (PVMA, CMA, SPMA, and RJMA) are shown in Figure XX. For each metropolitan area, the CG lightning activity distribution is shown in separate high-resolution (1x1km) maps (according to Table 1). The urban areas are shown in magenta and the topography is given by the white isolines. The major metropolitan areas of the Northeastern Region of Brazil are excluded from the analysis because the CG lightning activity over that region is extremely low (Figure 1). Thus, no lightning anomaly due to urban effect can be analyzed.

Some large metropolitan areas have been studied, e.g., São Paulo Metropolitan Area (Naccarato et. al. 2003a; Morales et al. 2010; Farias et al. 2008, 2012), Belo Horizonte Metropolitan Area (Pinto et al. 2004), Manaus Metropolitan Area (Pinto Jr. et al. 2013), Campinas and São José dos Campos Metropolitan Areas (Naccarato et al. 2003b). Those areas present very pronounced lightning anomalies (indicating a strong urban effect) that has been already detected by the regional lightning detection networks. Naccarato et al. (2003a) and Farias et al. (2008, 2012) discussed in details the possible explanation for their findings over the SPMA. They concluded that the urban effect can be a combination of a thermodynamic effect (caused by the enhancement of the sensible heat flux due to the UHI) and a microphysical effect (caused by a high concentration of anthropogenic aerosol in the atmosphere) is plausible. On the other hand, Morales et al. 2010 presented some evidences that the thermodynamic effect is prevailing over the aerosol, which effect is negligible for the SPMA.

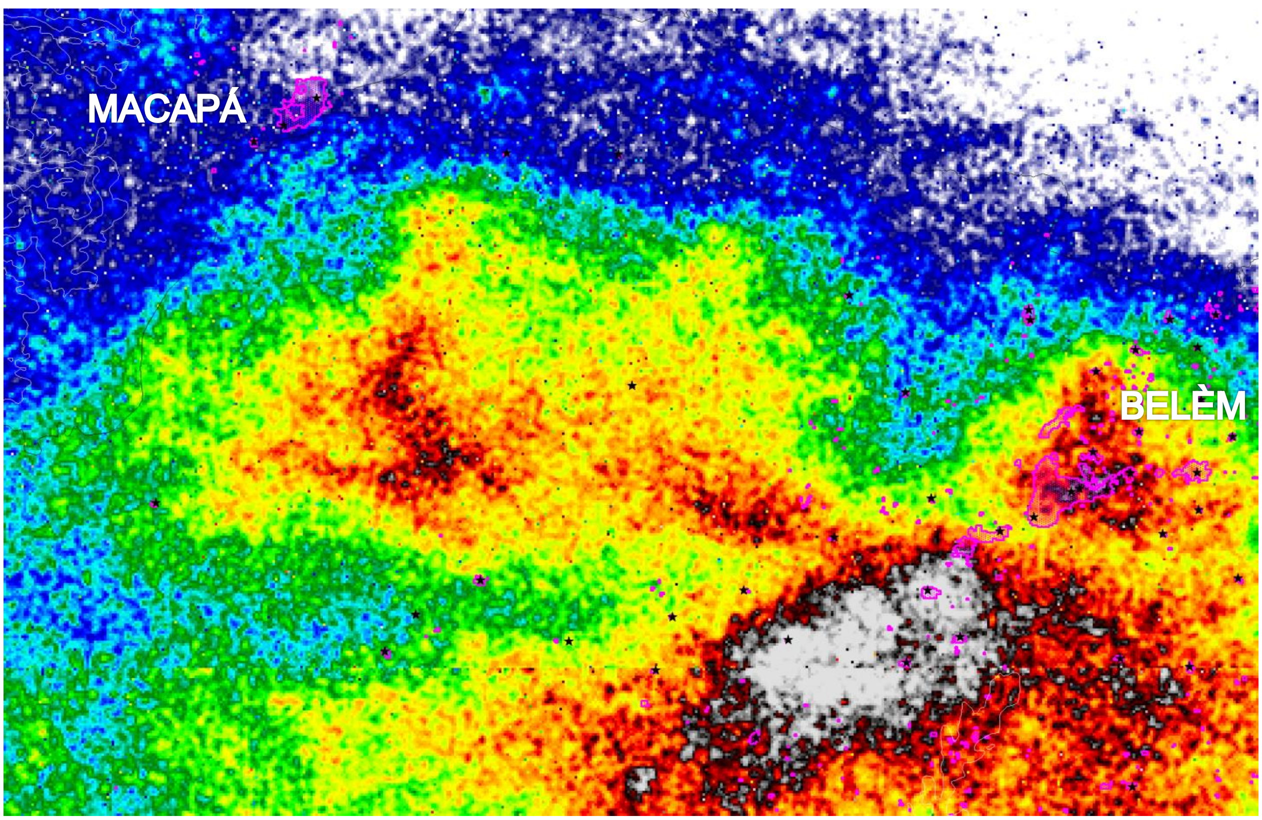

Figure 2 – WWLLN cloud-to-ground lightning activity over Macapá/AP (northwest) and Belém/PA (east).

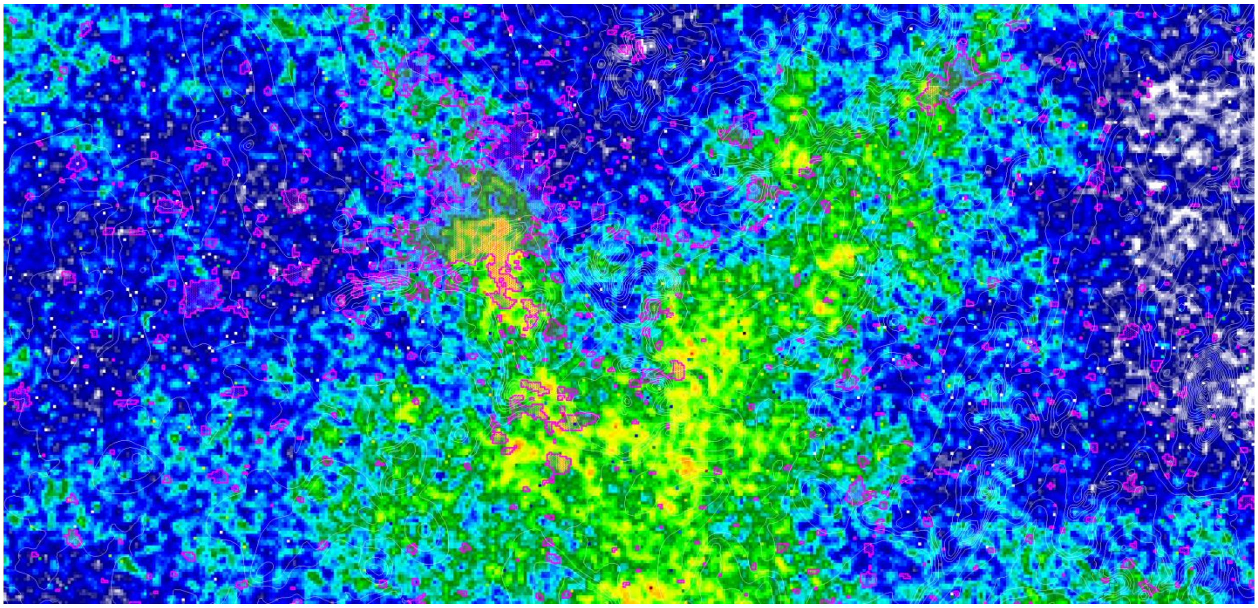

Figure 3 – WWLLN cloud-to-ground lightning activity over Belo Horizonte/MG.

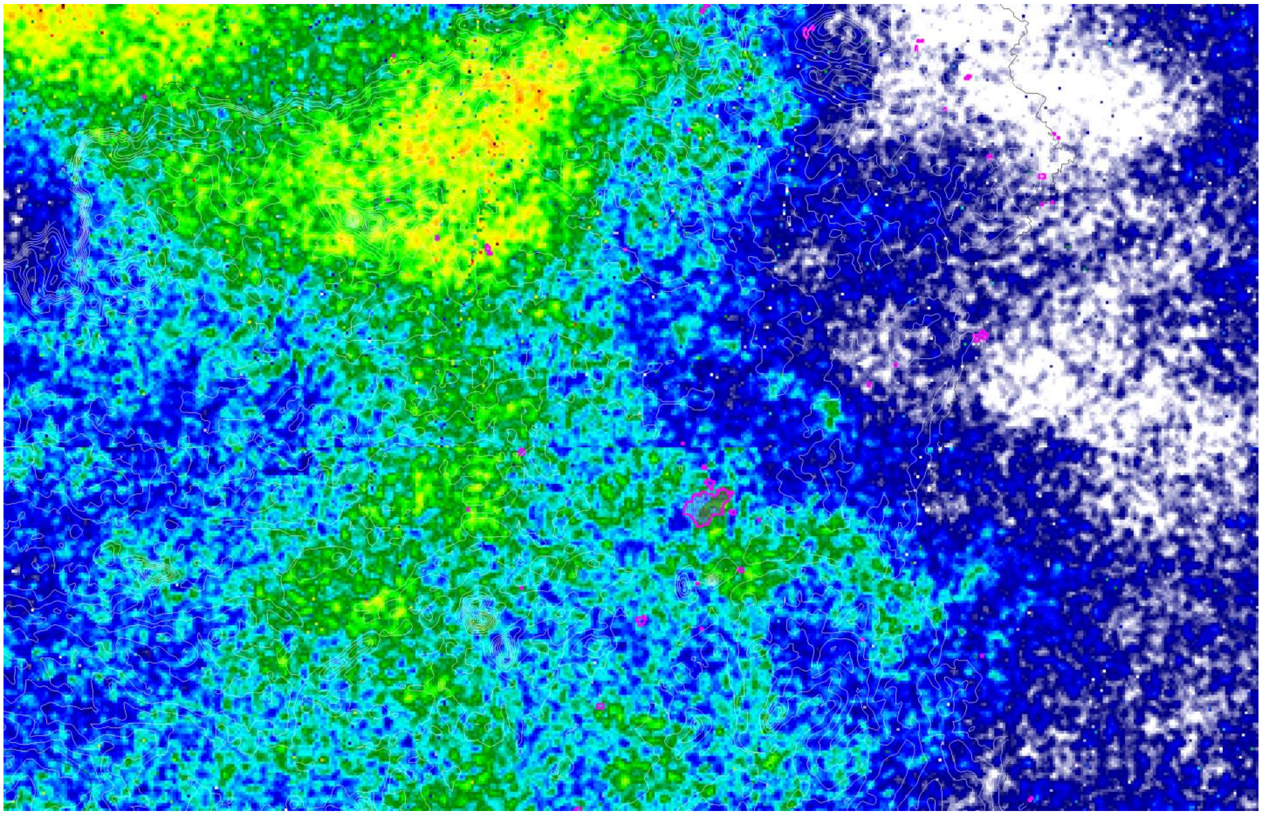

Figure 4 – WWLLN cloud-to-ground lightning activity over Boa Vista/RR.

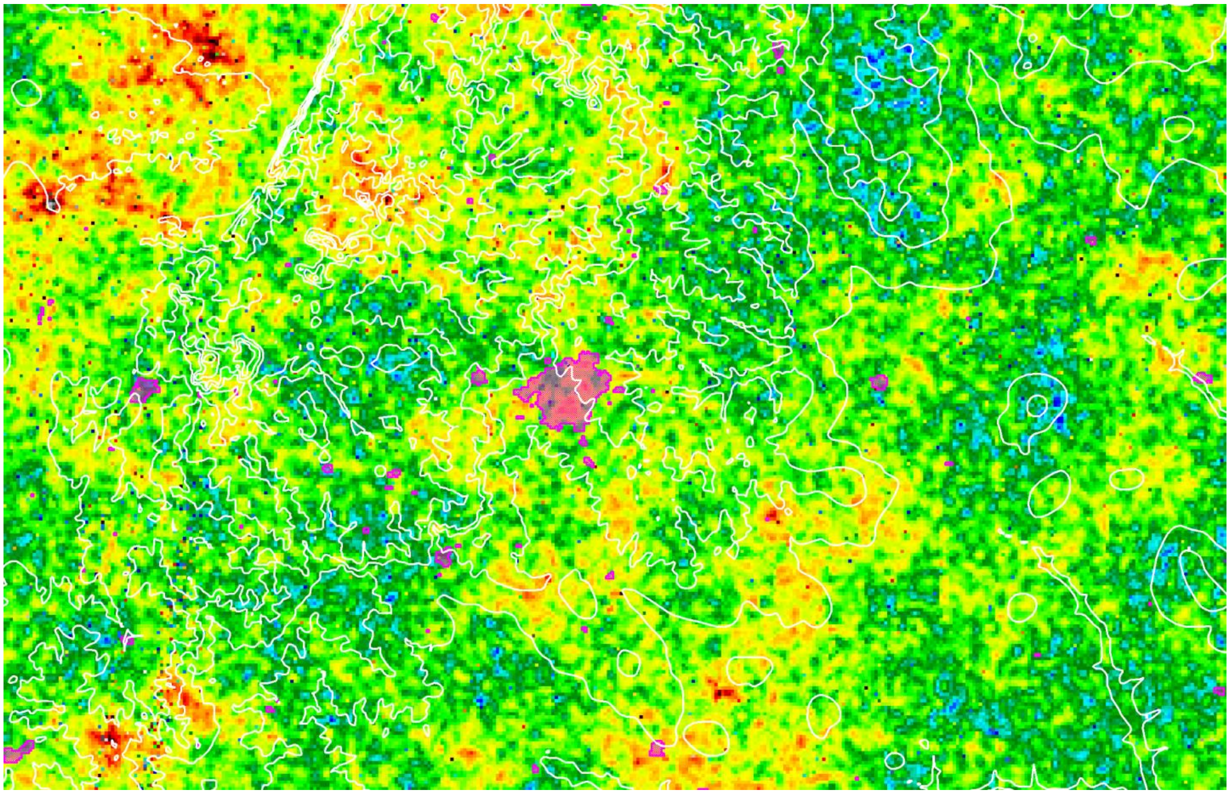

Figure 5 – WWLLN cloud-to-ground lightning activity over Campo Grande/MS.

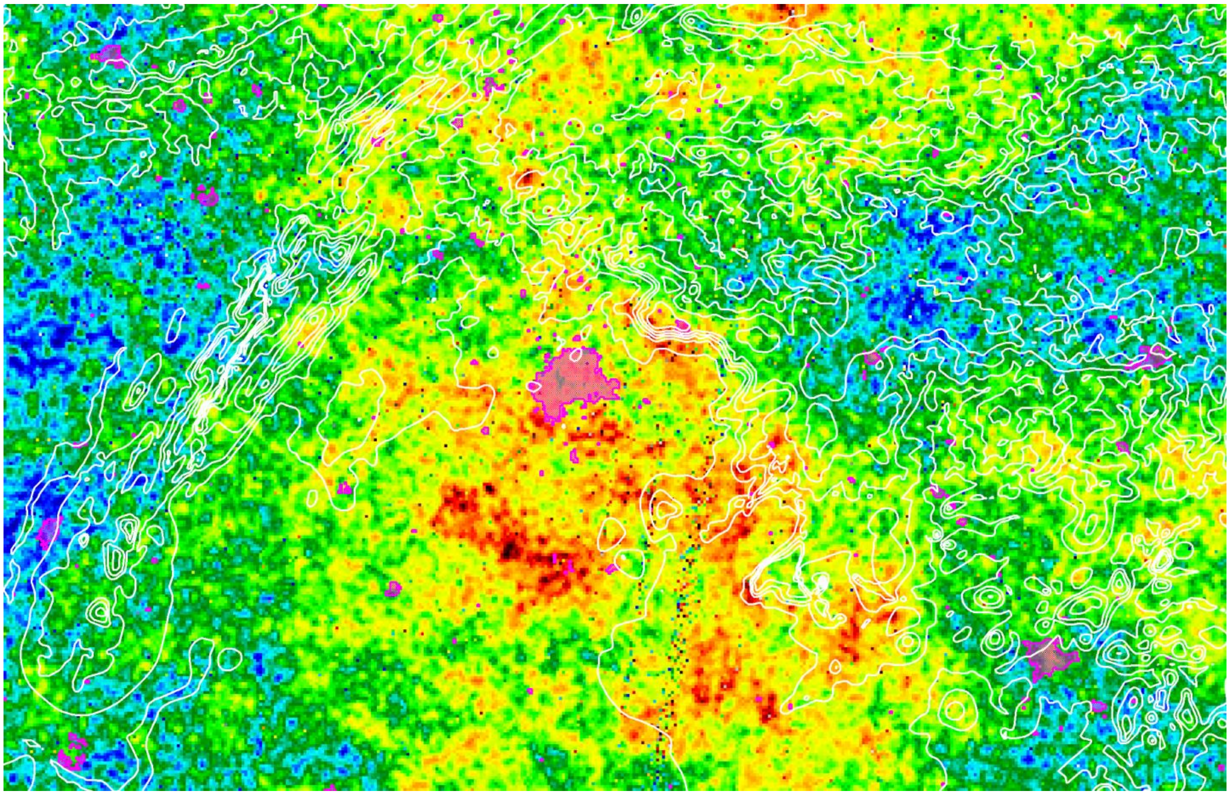

Figure 6 – WWLLN cloud-to-ground lightning activity over Cuiabá/MT.

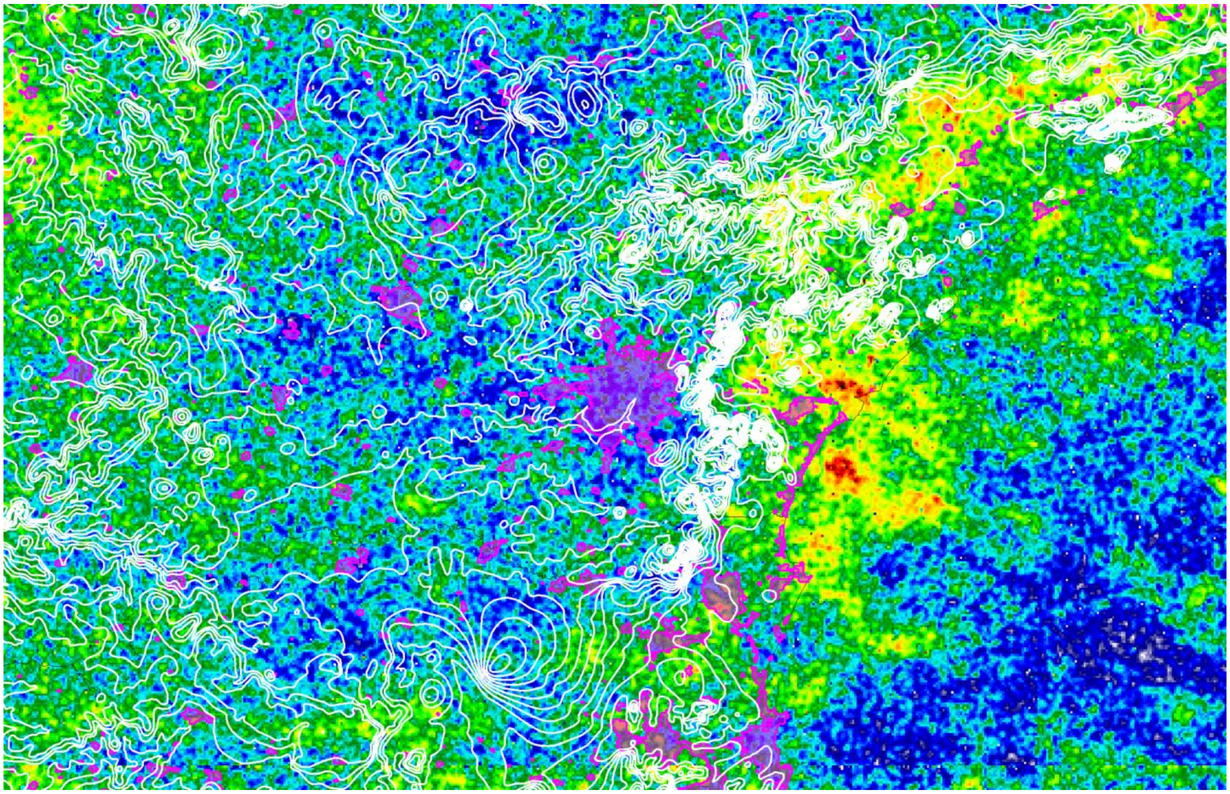

Figure 7 – WWLLN cloud-to-ground lightning activity over Curitiba/PR.

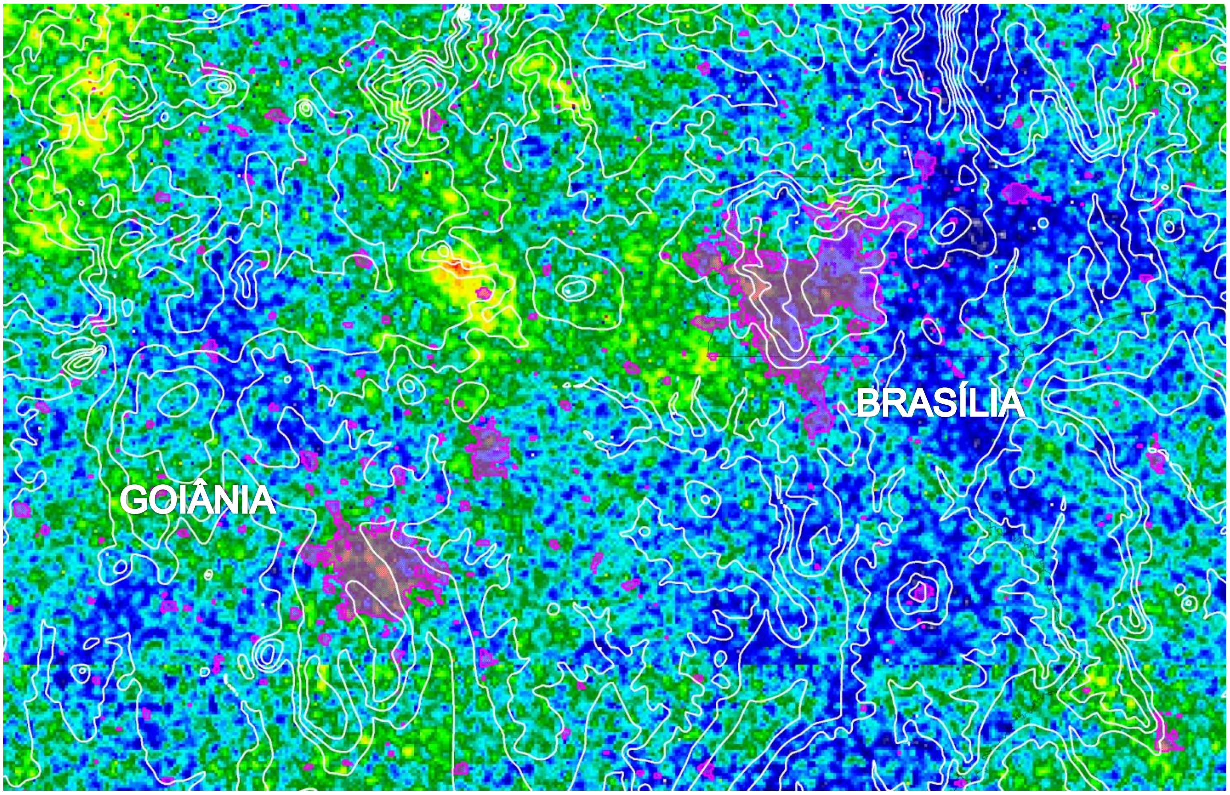

Figure 8 – WWLLN cloud-to-ground lightning activity over Goiânia/GO (southwest) and Brasília/DF (northeast).

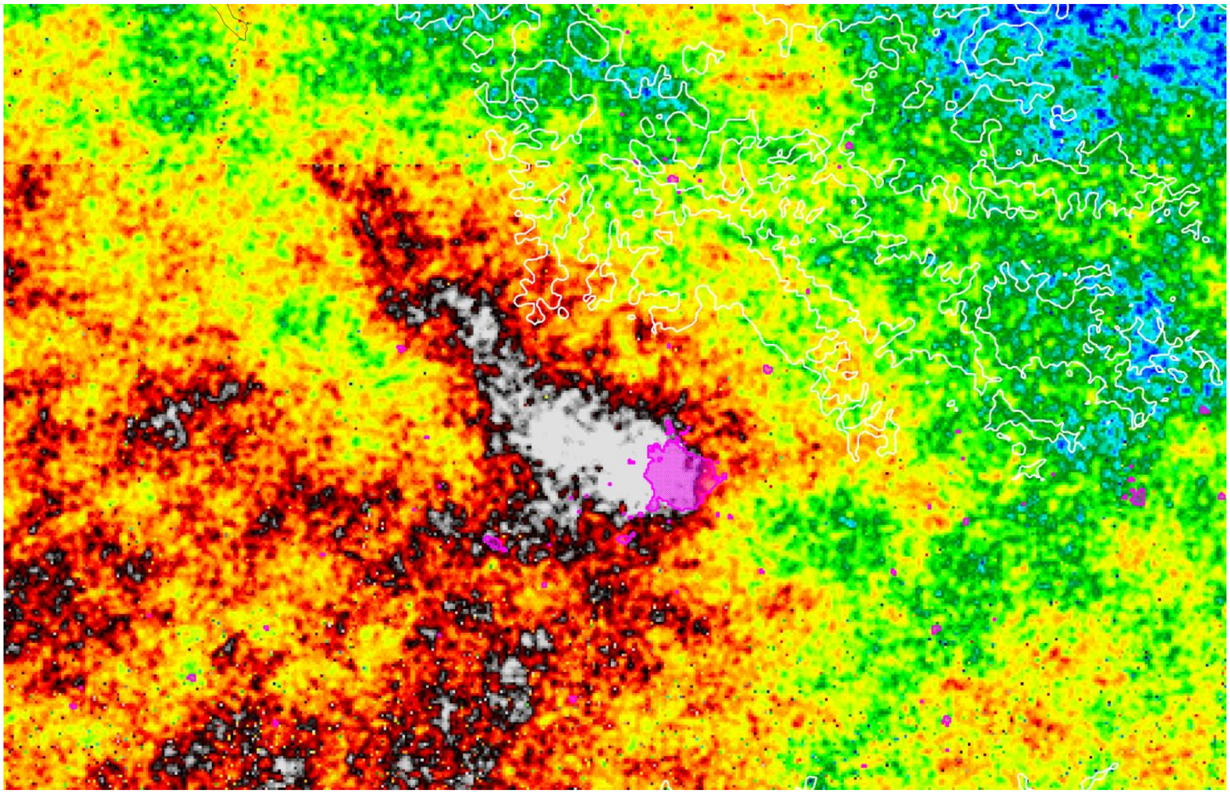

Figure 9 – WWLLN cloud-to-ground lightning activity over Manaus/AM.

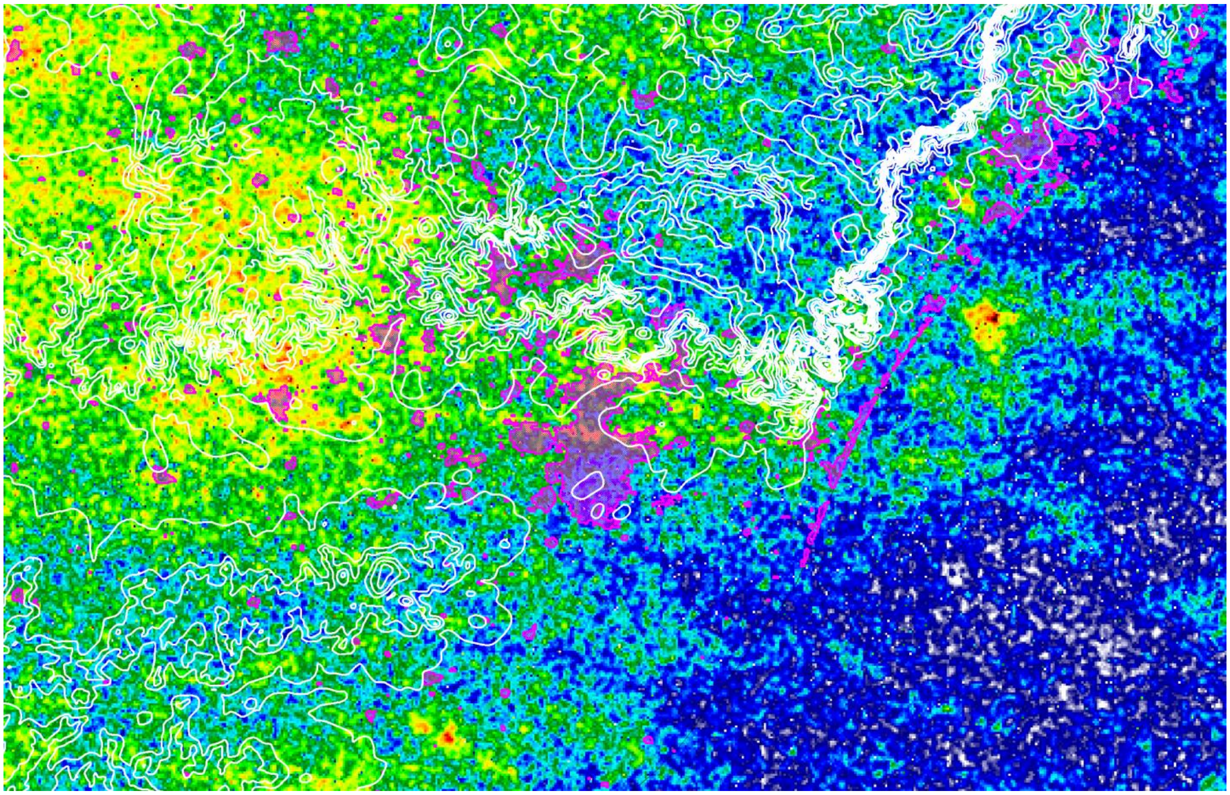

Figure 10 – WWLLN cloud-to-ground lightning activity over Porto Alegre/RS.

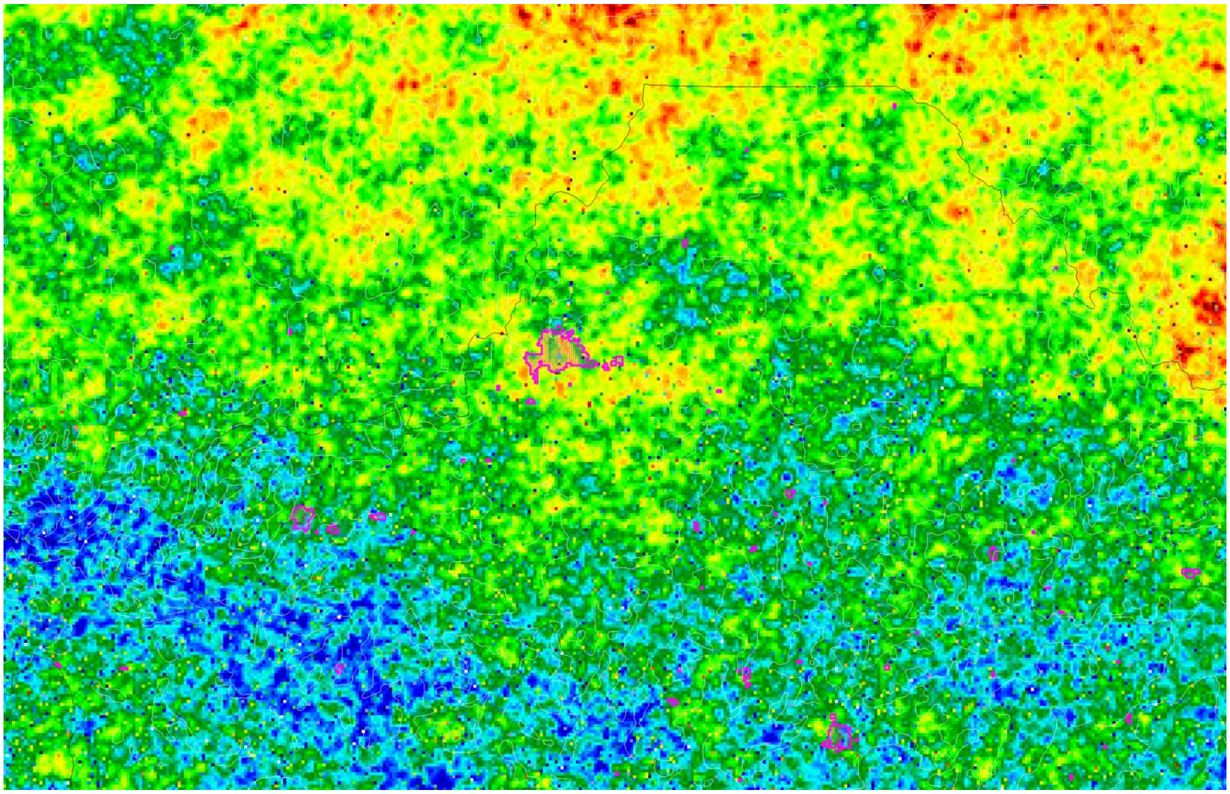

Figure 11 – WWLLN cloud-to-ground lightning activity over Porto Velho/RO.

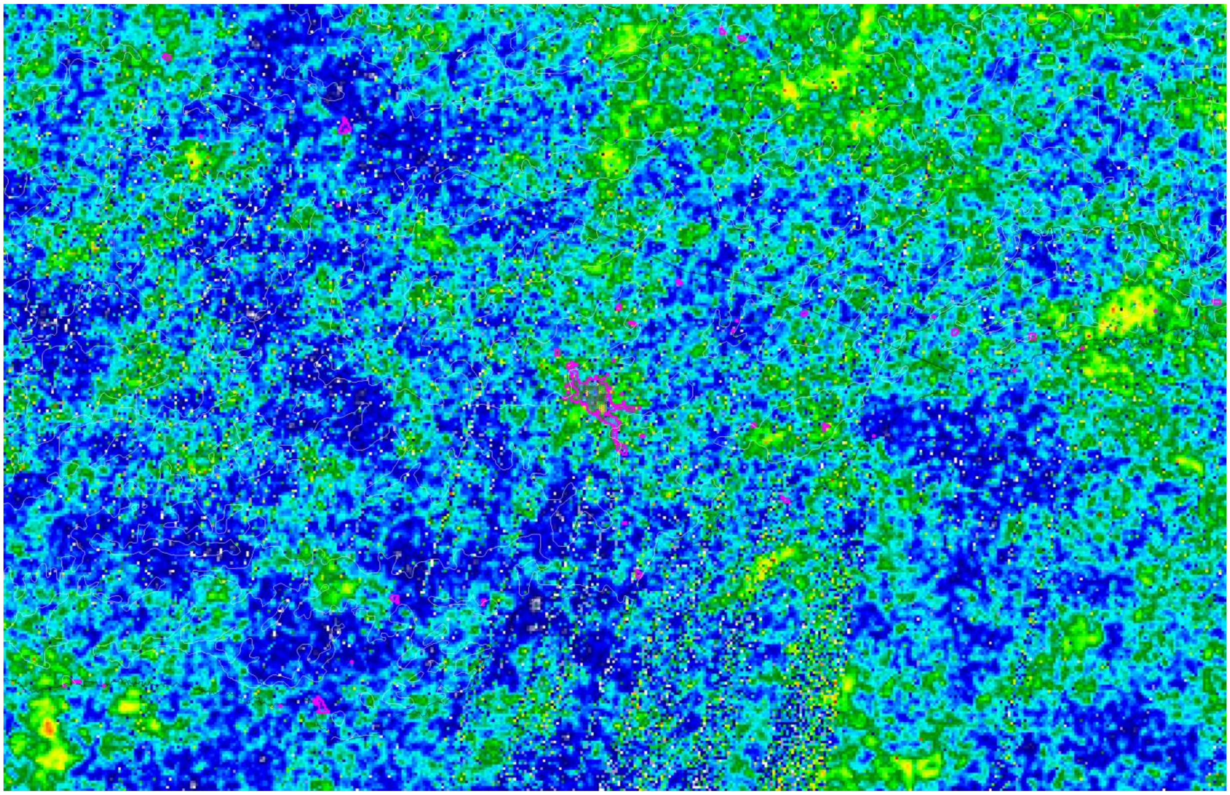

Figure 12 – WWLLN cloud-to-ground lightning activity over Rio Branco/AC.

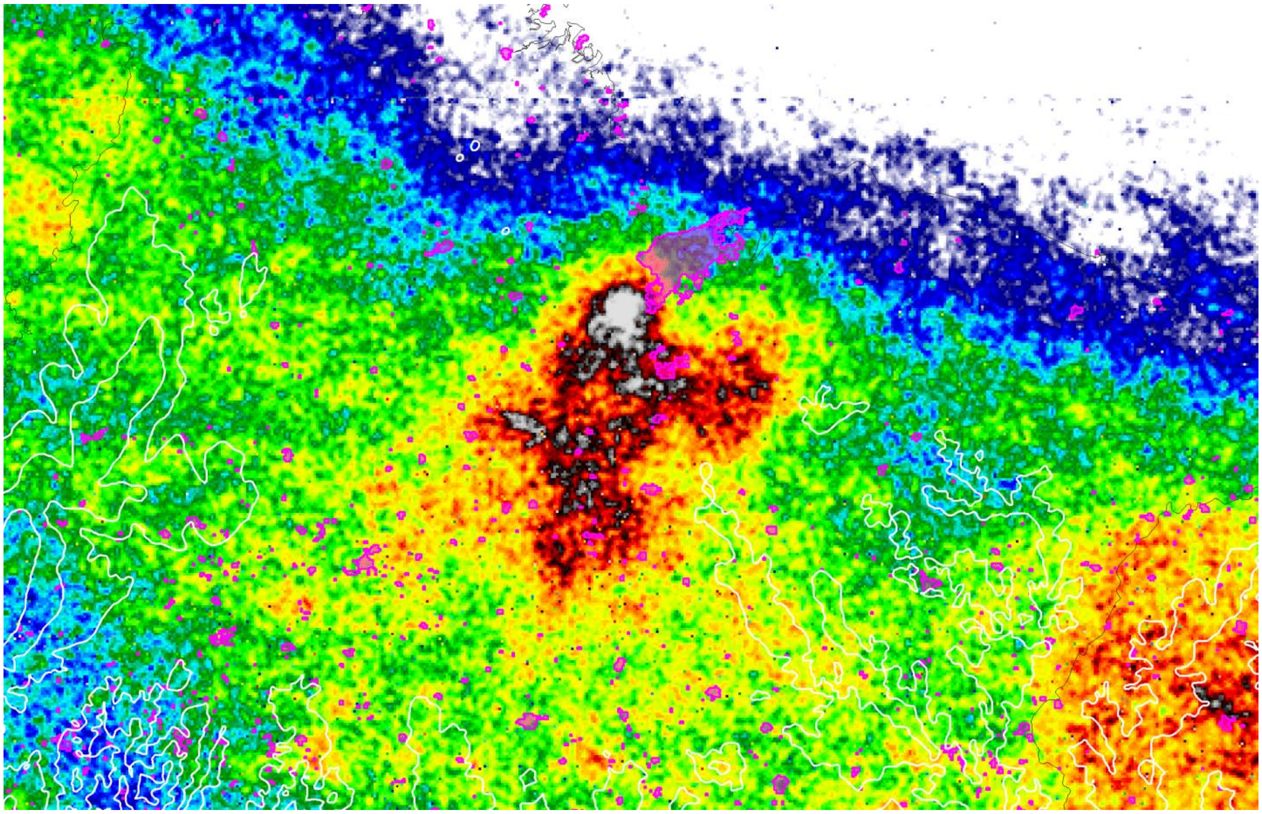

Figure 13 – WWLLN cloud-to-ground lightning activity over São Luis/MA.

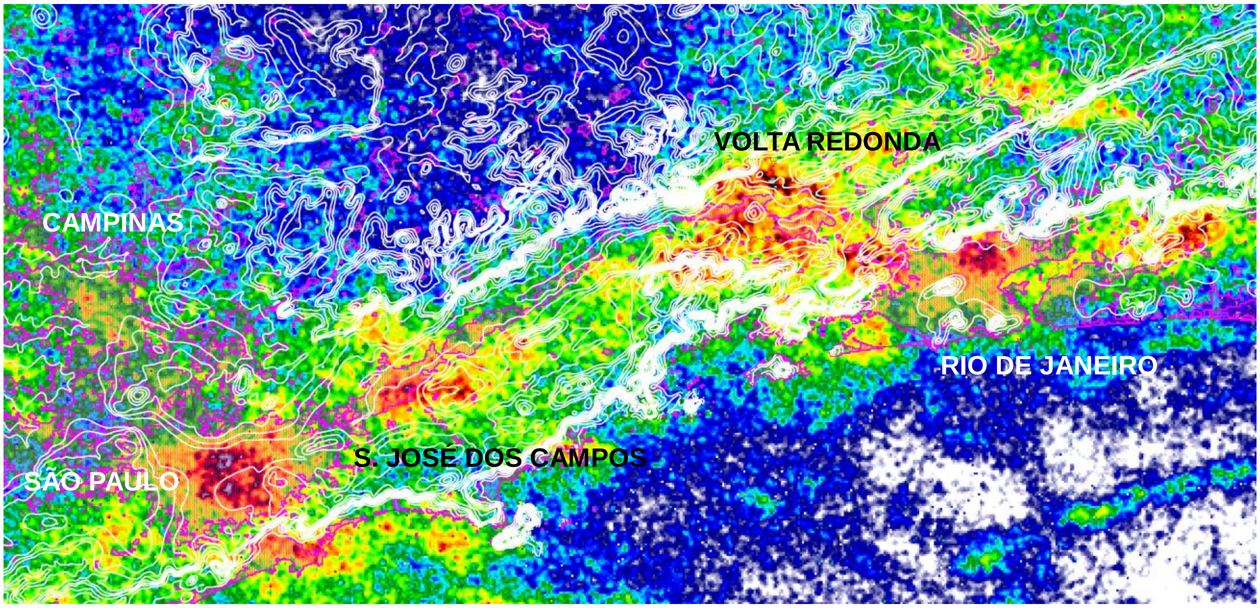

Figure 14 – WWLLN cloud-to-ground lightning activity over CMA, SPMA, PVMA and RJMA.

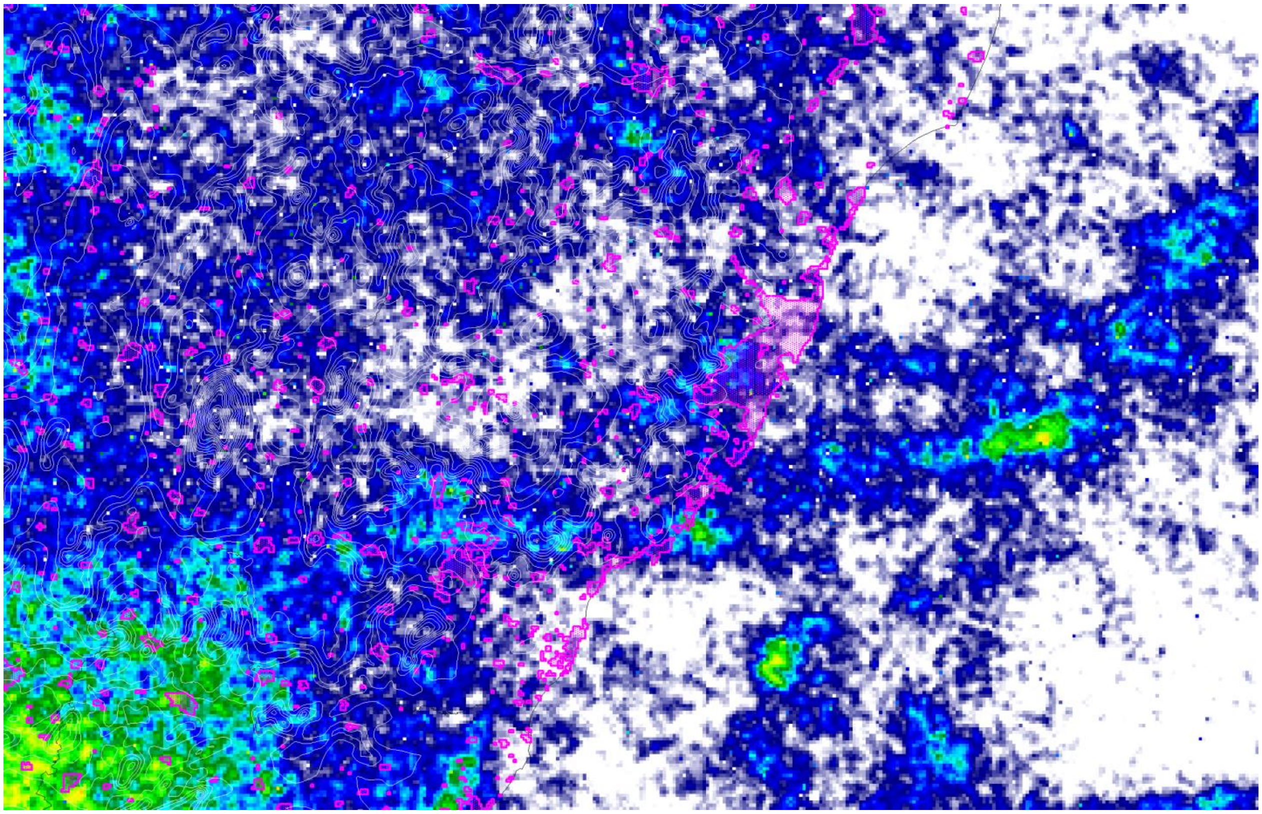

Figure 15 – WWLLN cloud-to-ground lightning activity over Vitória/ES

CONCLUSIONS

This work used CG lightning data provided by WWLLN (Worldwide Lightning Location Network) from 2005 to 2013 to generate a very high-resolution (1x1km) map of the CG lightning activity over Brazil. The latitude-dependent variation of the WWLLN detection efficiency was roughly corrected using the Brazilian CG flash rate map based on LIS dataset (1998-2011). The hi-res WWLLN map was then used to identify lightning anomalies over the major metropolitan areas of Brazil (the so-called urban effect). The urban effect on the lightning activity is still a controversial topic with several studies in US, Europe and Brazil. Basically there are two factors that can potential explain the recent findings: the increase of cloud condensation nuclei (CCN) due to anthropogenic emission of particulate matter and SO_2, and the enhancement of the convergence due to the urban heat island (UHI) effect.

In this study, seven major metropolitan areas presented a pronounced urban effect on the CG lightning activity: São Luis/MA, Belém/PA, Manaus/AM, Rio de Janeiro/RJ, São Paulo/SP, Volta Redonda/RJ, and São José dos Campos/SP. Two metropolitan areas (Campinas/SP and Belo Horizonte/MG) showed a light urban effect and other five urban areas (Boa Vista/RR and Cuiabá/MT, Porto Alegre/RS, Campo Grande/MS, and Porto Velho/RO) presented some evidence, which requires a more detailed study. Finally, five metropolitan areas do not present any urban effect: Macapá/AP, Curitiba/PR, Goiânia/GO, Brasília/DF, and Vitória/ES. The major metropolitan areas of the Northeastern Region of Brazil are excluded because no lightning anomaly can be identified due to the very low CG lightning activity.

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