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# Improvements in the detection efficiency model for the Brazilian lightning detection network (BrasilDAT)

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ABSTRACT

The detection efficiency (DE) is the most important performance gauge of a lightning detection network (LDN). Moreover, the main motivation for evaluating the DE of a LDN is to separate the geographical variations of the CG lightning parameters from the variations regarding the network performance. A review of previous relative DE techniques and simple methods to correct the cloud-to-ground (CG) lightning flash density maps is presented. In addition, recent improvements in the flash DE model for the Brazilian lightning detection network (BrasilDAT) are discussed. The DE estimated values are based on the sensor individual DE probability functions, which are derived from a large amount of CG stroke data provided by the network considering different distances from the sensor and specific peak current ranges. The new approach provides better results when compared with the previous developments, since the calculation of the sensor DE probability functions neglects the lightning data provided by the minimum number of reporting sensors. Hence it is possible to minimize the unrealistic enhancement of the DE closer to the network boundaries ("border effect") without affecting significantly the performance inside the network. The main result is a more realistic correction of the CG flash density maps, particularly at the outermost network areas, leading to an improvement in the model sensitivity.



## 1. Introduction

Like any other detection system, a lightning detection network (LDN) has its own limitations. Perhaps the most significant one is its detection efficiency (DE), which is the ratio of the number of detected events divided by the real number of events. Due to the high variability of the CG lightning physical features, a LDN will never be able to detect all events, thus its DE will never reach 100%. Such errors can be more or less significant depending on the frequency of sensor faults, communication problems or the sensor network geometry, which may be unfavorable (Schulz, 1997; Cummins et al., 1998; Naccarato, 2006a,b) leading to distortions in the data. Furthermore, the type of the sensors plays a very important role. It is well established that the two existing technologies *Time of Arrival* (TOA) and *Magnetic Direction Finding* (MDF) have their advantages and limitations (Naccarato, 2006a,b). Basically, the LPATS sensors work only with the TOA technology, while the IMPACT sensors combine the TOA and MDF technologies to improve their performance (Cummins et al., 1995, 1998). A high performance network will be obtained only when the distribution of the sensors is relatively homogeneous over all coverage area. Unbalanced networks (with more LPATS than IMPACT sensors and/or specific areas covered by a fewer number of sensors) clearly tend to present lower performance in terms of DE (Naccarato et al., 2004a).

The main purpose for evaluating the DE of a LDN is to separate the geographical variations of the CG lightning parameters from the variations due to the LDN performance (Cummins and Bardo, 2004). In Brazil, this is particularly important because the configuration of the sensor network has been changed throughout the last years (mainly after 2005). Fig. 1 shows the present configuration of the Brazilian Lightning Detection Network (BrasilDAT), which is composed of 47 sensors as a result of the integration of three other regional networks: SIDDEM, SIPAM and RINDAT. The RINDAT network is the oldest one, and started to operate in the end of 1998 with 7

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**Fig. 1.** The Brazilian lightning detection network (BrasilDAT) which is composed of 47 sensors (both LPATS and IMPACT) as a result of the integration of three regional networks: SIDDEM, SIPAM and RINDAT.

IMPACT and 17 LPATS sensors. RINDAT covered the entire southeastern Brazil (states of São Paulo, Rio de Janeiro, Paraná, Espírito Santo, Minas Gerais e Goiás), and remained almost unchanged until 2004. The SIPAM network started to operate at the end of 2003 with 12 LPATS sensors covering the states of Tocantins, Maranhão and the northern half of Pará. Finally, the SIDDEM network was installed at the beginning of 2005 covering the states of Rio Grande do Sul, Santa Catarina and Mato Grosso do Sul (in the mid-southern Brazil) with 11 IMPACT sensors. As can be seen, the BrasilDAT network is composed of both LPATS and IMPACT sensors (a hybrid network) and further details can be found in Pinto et al. (2007).

This paper briefly reviews the present knowledge about relative detection efficiency models (RDEM) and presents a new approach for a relative flash detection efficiency model (RFDEM) for the BrasilDAT network. The new model is an improvement on previous works (Naccarato et al., 2004b, 2006a), which were based on the development of Murphy et al. (2002) — a relative stroke detection efficiency (RSDE) technique for the National Lightning Detection Network (NLDN), Rompala et al. (2003) — a RSDE method for a small LDN installed by NASA in the north of Brazil (Rondônia), and Schulz (1997) — a first-stroke detection efficiency model for the Austrian lightning detection network (ALDIS). In addition to the previous improvements (e.g. changing the sensor network geometry, considering different type of sensors, etc.), the new RFDEM introduces a new approach that takes into account the "border effect" caused by the fewer number of CG strokes detected closer to the network boundaries. At the border areas, since almost all local sensors are required to get a solution, an

artificial increase of the DE occurs, which prevents the model from recovering the actual CG flash density values. In order to compare the results of this new RFDEM with the previous model, only data from the RINDAT regional network (Fig. 2) will be considered, since it provides the largest CG lightning dataset.

## 2. Review of the previous models and/or methodologies

Several approaches for developing a RDEM were already proposed in the literature: Schulz (1997), Murphy et al. (2002), Rompala et al. (2003), and Naccarato et al. (2004b). All of them use a set of CG lightning data reported by the network to compute its relative detection efficiency (RDE). Since the CG lightning dataset used as reference is usually collected over areas with higher values of DE (known from other independent observations), the resulting RDE can be roughly approximated to the absolute detection efficiency (ADE).

Cummins et al. (1992, 1993) and Schulz (1997) were the first to publish a comprehensive description and a clear methodology for an absolute detection efficiency model (ADEM) based on data from NLDN and ALDIS, respectively.

Schulz (1997) presents a model to estimate the network first-stroke detection efficiency, allowing the correction of the peak current distributions based on the data provided by the same network. The stroke DE was defined in the same way regarding the individual strokes. The relation between stroke and fla0073h DE strongly depends on the distribution of the number of strokes per flash, and the flash DE is always higher than the stroke DE (Rubinstein, 1995). According to Schulz, to estimate the FSDE of a given LDN for a specified peak current range it is required to assume a sensor DE function. Then, using these individual sensor DE functions, the entire network DE is computed based on the combined probability of each sensor to detect a first-stroke, considering its peak current intensity and the distance from the sensor. Of course, the propagation effects are intrinsically taken into account, since the particular DE of each sensor is computed based on first-stroke data detected by the network for different distances. The author presented two different approaches for

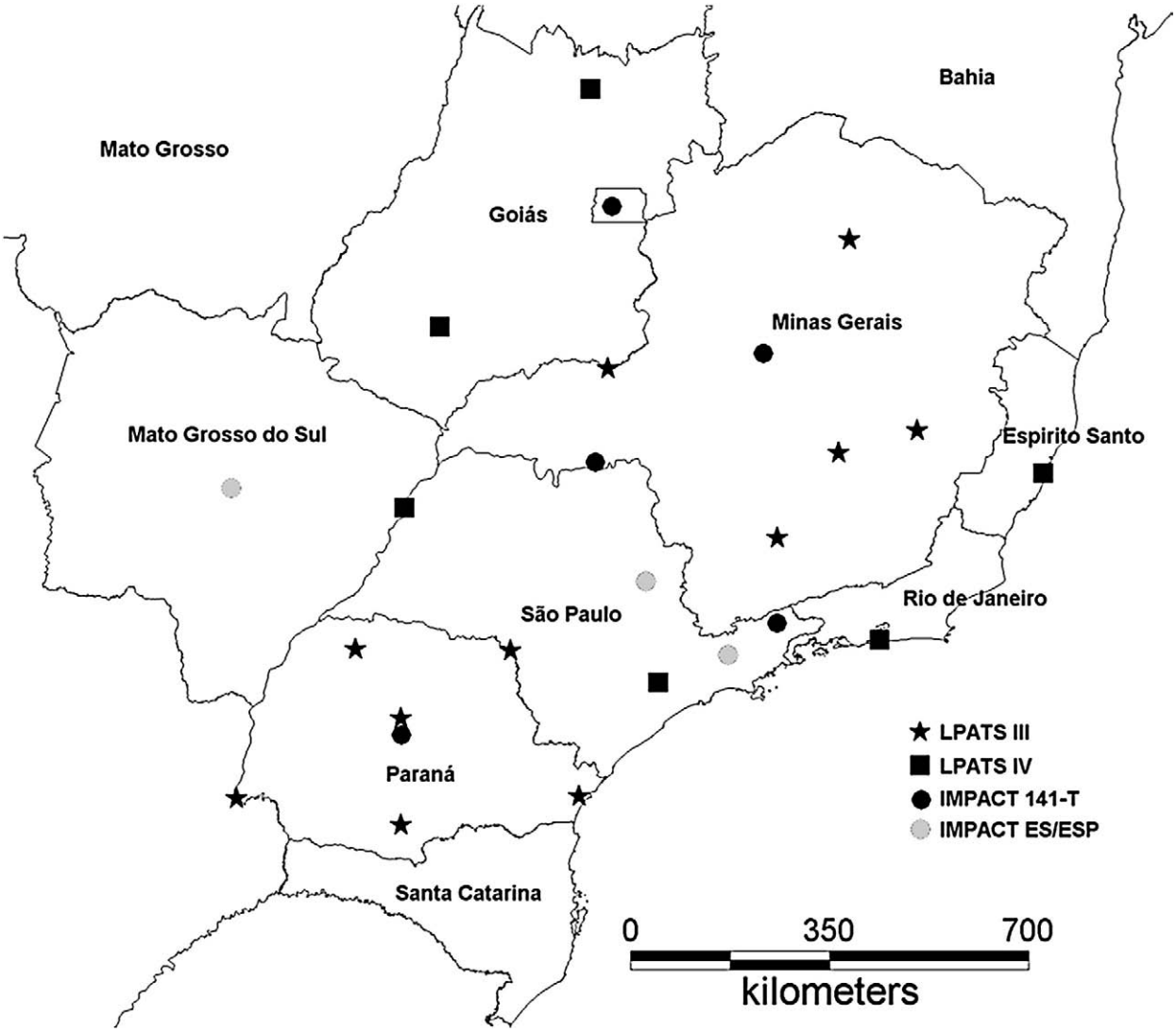


**Fig. 2.** The RINDAT hybrid network composed of 25 sensors: 8 IMPACT and 17 LPATS. The three sensors in gray were installed during the years of 2001 and 2002.

computing the total network first-stroke DE for a particular area: (1) Calculation of the detected peak current distribution from an assumed theoretical distribution (e.g. Berger distribution) representing 100% of CG flashes. The ratio of the two distributions is the estimated total network DE in this area; (2) Correction of the detected peak current distribution to a "natural" lightning current distribution. The frequency of each peak current amplitude bin is corrected by the corresponding peak current network DE. The total network DE regarding the total distribution of peak currents is given by the ratio of the sum of detected frequencies divided by the sum of corrected frequencies. It is important to note that this second approach does not require the assumption of a particular natural peak current distribution as did the former method.

The first results regarding an absolute flash detection efficiency model (AFDEM) for the NLDN were published by Cummins et al. (1992, 1993, 1995). The model computed the network FDE on a 50×50 km grid over the coverage area. At each grid point, the model generated specific values of peak current and computed the signal strength that should arrive at each sensor in the network using a signal propagation model. The model then used a look-up table to relate the computed signal strength at each sensor to that sensor FDE, thus providing the probability that the flash will be detected by the sensor. The look-up table contained the response of each type of lightning sensor as a function of the incident signal amplitude, and the values ranged from zero probability at threshold to a maximum probability (less than one) at 2–3 times threshold. Then the final network FDE was computed for all combinations of sensors that reported a discharge, assuming that the sensor probabilities are all independent. Thus, the network FDE was simply the product of the probabilities of detection (and non-detection) for each sensor. This process was repeated over the entire range of peak currents at each grid point, and an overall estimate of the network FDE was produced. Fig. 3 shows the FDE for the RINDAT regional network computed by the GAI/Vaisala ADEM.

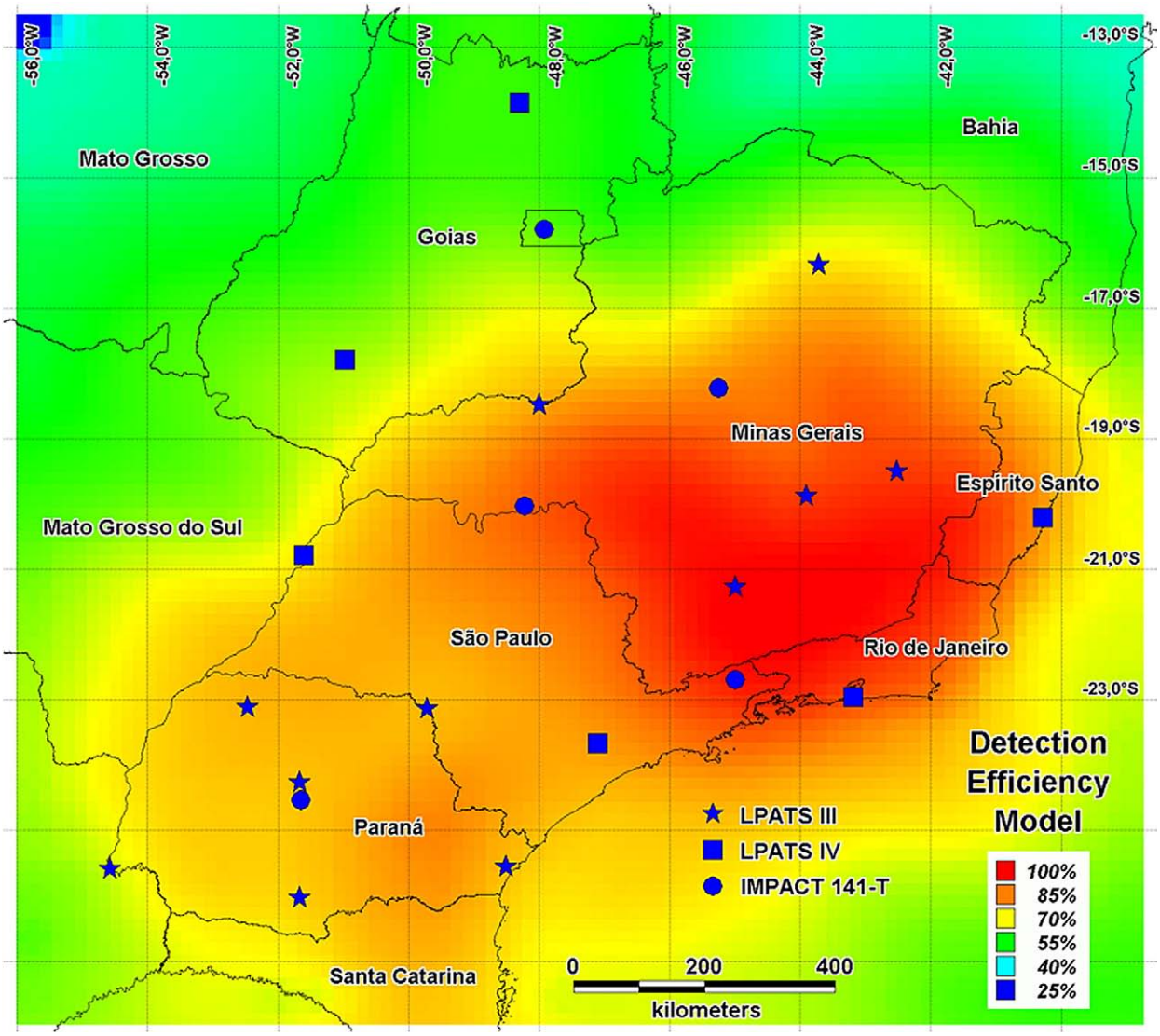


**Fig. 3.** The FDE contour plot for the RINDAT regional network derived from the first NLDN absolute flash detection efficiency model (AFDEM).

Several years later, Murphy et al. (2002) used a very simple methodology to estimate the improvement in the NLDN stroke detection efficiency (SDE) due to the 2002 upgrade. Two sets of CG stroke data were analyzed: one before and another after the upgrade for the same area and time period. The cumulative peak current distribution (PCD) was then computed for the two datasets and the early PCD (before the upgrade) was then fitted to the new PCD (after the upgrade), which was considered the reference (100% SDE). The ratio between the reference PCD and the fitted PCD represented the RSDE improvement of the network.

Rompala et al. (2003) developed a method to estimate the SDE contours for the Rondonian lightning detection network in Brazil. They first selected an area in the middle of the network (composed of only 4 IMPACT sensors), which was assumed to have the best performance. This region was called central quad (QUAD). The PCD for the CG stroke data in the QUAD was computed and adjusted to a theoretical probability distribution function (PDF), which was considered to be representative of the stroke distribution at any location over the region. After that, the network coverage area was divided into blocks (cells) of a specific size and the PCD was computed for all strokes detected in each cell. The reference PCD was then applied to each cell to assess what proportion of the lightning set would be detected. Finally, the cell SDE was taken as the ratio of the computed values divided by the total number of events.

Combining the Murphy and Rompala methodologies described previously, Naccarato et al. (2004b) developed a quite simple technique to assess the relative flash detection efficiency (RFDE) of a LDN showing a relatively good agreement with the expected network behavior. Of course, like any other method that requires CG lightning datasets, this approach was highly dependent on the number of detected events to provide good results. Thus, the higher the number of events, the longer is the calculation time. In that work, the authors used CG flash data from a hybrid LDN composed of 17 LPATS and 5 IMPACT (the so-called old RINDAT network). Almost 13 millions CG lightning flashes were detected by the 22-sensor LDN within the 5-year dataset (from Oct/1998 to Oct/2003). A 450×450 km region was chosen as the QUAD area (Rompala et al., 2003), which was used to assess the reference cumulative PCD. This distribution was then normalized to the total number of detected CG flashes and represents the proportion of events above a specified peak current value. The coverage area of the LDN was defined as a rectangular area of 1800×1700 km (over 10 million CG flashes were detected in this region), divided in blocks of 50×50 km and the number of CG lightning flashes was computed for each block (or cell). In order to ensure good statistics, the number of flashes for each cell was calculated as the sum of the events of the 8 surrounding cells and the cell itself. Finally, the PCD for each cell was computed individually and adjusted to the reference PCD (Murphy et al., 2002). The ratio between the adjusted and the reference PCD at the 0 kA axis corresponded to the RFDE of the network in that cell. Fig. 4 presents the resulting RFDE map for the methodology described above (the red color represents 100% DE due to the relative calculation approach). It can be seen that this methodology is able to identify the areas of maximum DE and also to describe the continuous decrease of the DE far away from the sensors. For

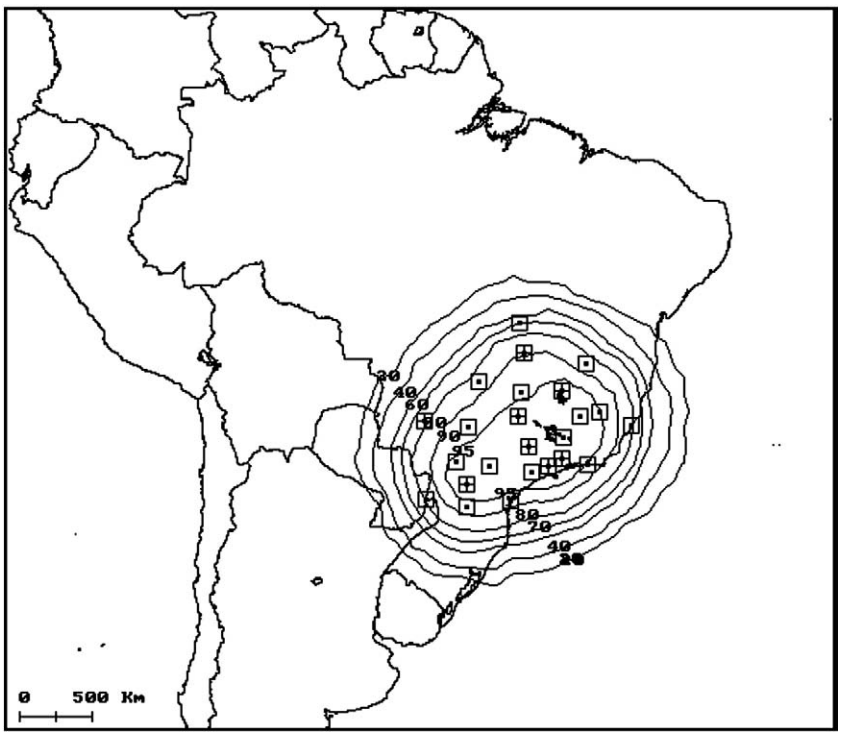


**Fig. 4.** RINDAT RSDE computed by the combined Murphy and Rompala technique for a 22-sensor hybrid network. The grid resolution is 50×50 km.

example, regions outside the network presented DE values lower than 55%. Due to variations in the sensor geometry, it is possible to see its effect on the network performance, particular over states of Paraná and Goiás.

## 3. The RINDAT Network RFDEM

### 3.1. Overall description

As already discussed, the work of Naccarato et al. (2004b) combined the Murphy and Rompala methods to produce a quite simple technique to assess the RFDE of a LDN without the use of an explicit physical model. Furthermore, that methodology requires calculating the PCD for each grid cell based on thousands of CG flashes detected within it, thus leading to very long processing times. These two limitations motivated the development of a RFDEM for the RINDAT regional network in 2004, which provided the largest CG lightning dataset at that time, since the SIDDEM network only started its operation in 2005 and the SIPAM network had been operating for less than one year.

The RINDAT network RFDEM (Naccarato et al., 2006a) also requires the lightning data detected by the network (the CG stroke data), but now they are used only to compute the RSDE distribution function for each sensor (e.g., Fig. 5), which depends on the peak current and the distance from the stroke due to the propagation effects. Thereby, using these individual sensor RSDE curves, the network RSDE is computed based on the combined probability of each sensor to detect (or not) the stroke. This new approach employs a physical model (Schulz, 1997) and reduces significantly the calculations (leading to very short computation times), therefore allowing an easy evaluation of the network DE due to changes in its sensor geometry (by enabling or disabling specific sensors or including new virtual sensors). Moreover, this new approach considers that a valid CG stroke solution can be achieved by both the minimum required number of angles (IMPACT sensors) and/or times (IMPACT and/or LPATS sensors) or by only two IMPACT reports (i.e., two bearing and two timing information). This technique (described in detail in the following lines) offers a more precise method for DE calculation that leads to a more realistic result, particularly at regions closer to the network boundaries where few strokes are usually detected.

The first step to assess the network SDE is to compute the RSDE distribution function for each sensor, which depends on the peak current and the distance to that sensor. Additionally, the individual sensor status was evaluated from Jan/1999 to Dec/2004, identifying their uptime periods. This information defines the network geometry for each month throughout the entire 6-year period (Naccarato, 2006a,b). After that, the CG strokes detected by each sensor (during the same 6-year period) are separated and the RSDE curves are computed based on the peak current value and the distance. The sensor RSDE curve corresponds to the ratio of the number of CG strokes reported by the sensor divided by the total number of CG strokes detected by the network for each peak current range ($I_p$=5 to 40 kA, bins of 5 kA), and for each distance interval ($d$=0 to 1500 km, bins of 10 km):

$$\mathrm{RSDE}(k,d,I_p) = \frac{\mathrm{NS}(k,d,I_p)}{\mathrm{NN}(d,I_p)} \tag{1}$$

where RSDE($k$,$d$,$I_p$)=stroke DE of the $k$th sensor at distance $d$ for peak current $I_p$; NS($k$,$d$,$I_p$)=number of CG strokes detected by $k$th sensor at distance $d$ for peak current $I_p$; NN($d$,$I_p$)=number of CG strokes detected by the network at distance $d$ for peak current $I_p$. Figs. 5 and 6 show an example of a RSDE distribution function considering different peak current ranges for an IMPACT and a LPATS sensor, respectively. The sensor RSDE curve integrated for all peak current distribution is also presented. The figures illustrate the differences between IMPACT and LPATS regarding the sensor nominal range, dependence on peak current intensity and gain variation. All sensors are set to the default values for signal threshold and peak-to-zero IC discrimination criteria. This approach is particularly useful since it directly incorporates

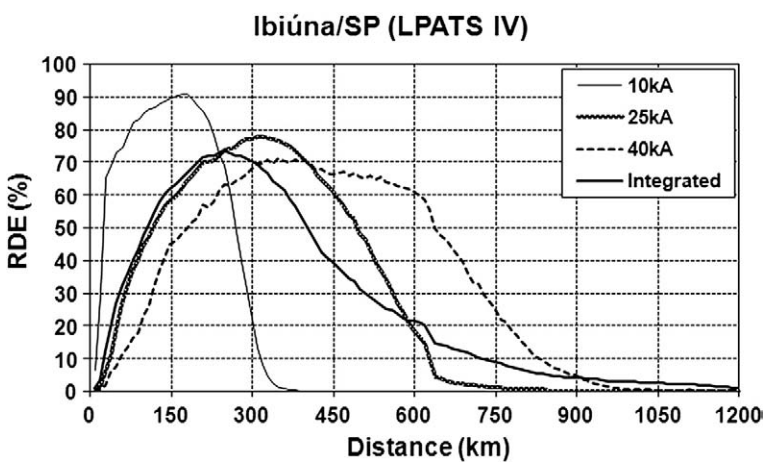


**Fig. 5.** Example of a RSDE distribution function for an IMPACT sensor employed by the RINDAT network RFDEM showing its dependence on different peak current values and the curve integrated for all peak current distribution.

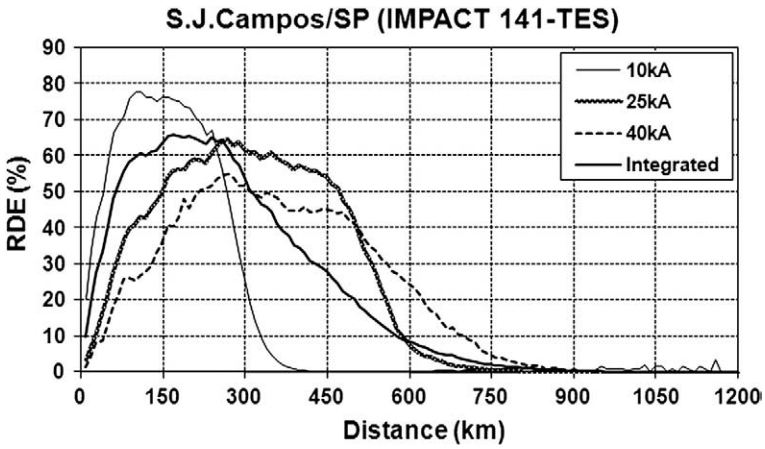


**Fig. 6.** Same as Fig. 4, but for LPATS sensor.

the distinct IMPACT / LPATS sensor dynamics, the propagation effects and the overall noise in the sensor RSDE curves, which avoids the need of modeling each feature separately. However, the model will be always dealing with relative SDE values, hence other independent measurement techniques (like satellites, high-speed cameras, etc.) are required to estimate the network absolute stroke detection efficiency (ASDE).

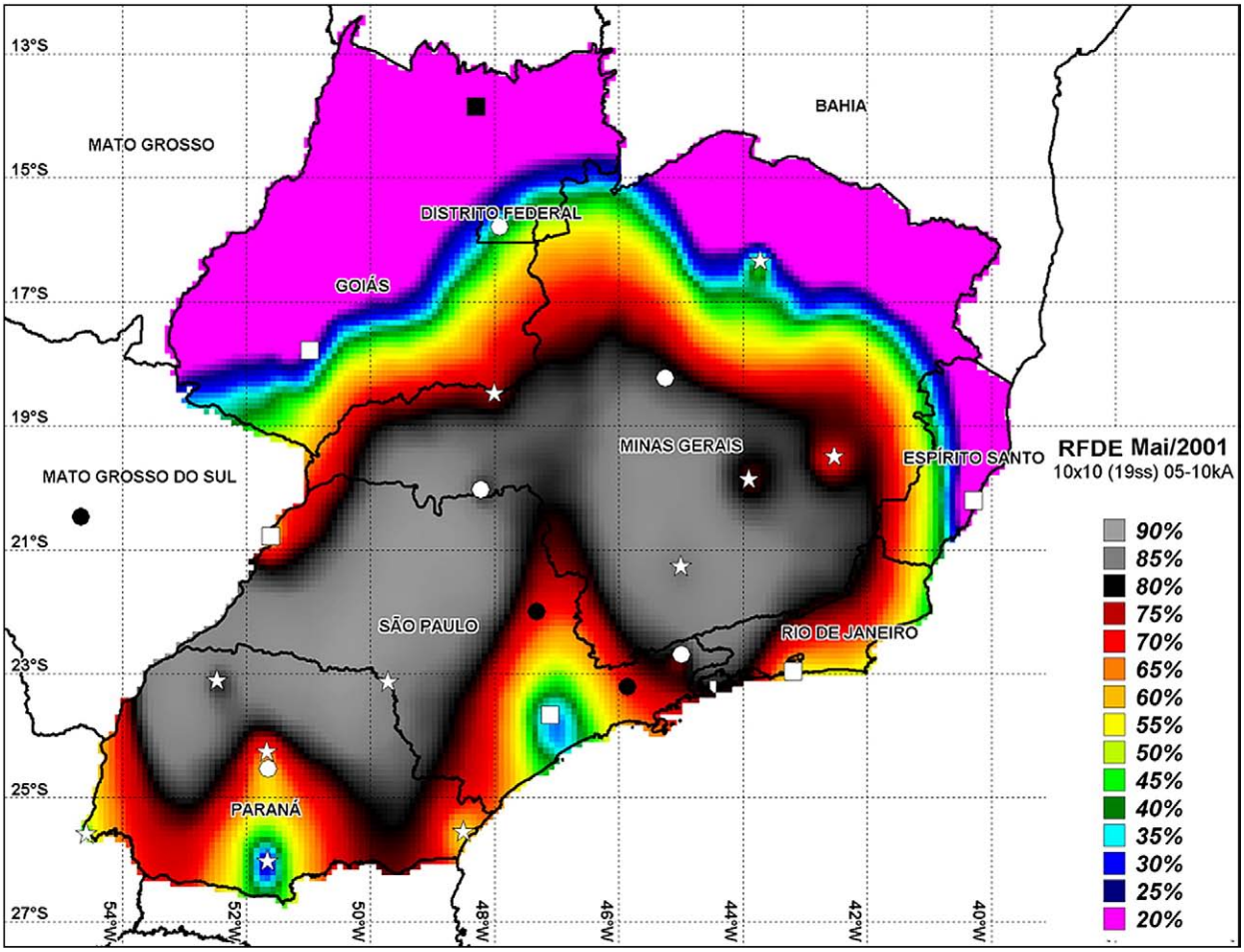


**Fig. 7.** RINDAT network RFDE computed for 5–10 kA peak current range in May 2001, when only 19 sensors were operating (in white). The grid resolution is 10 × 10 km.

Based on the sensor RSDE distribution functions and the monthly sensor status, a specific computational algorithm splits the network coverage in cells (which defines the spatial resolution) and calculates the probability of the network to detect one particular CG stroke at each cell within each peak current range. For an IMPACT network (which provides both bearing and timing information), only two sensors reporting a stroke are required to get a valid solution and therefore the smallest possible network size is a two IMPACT sensor network. On the other hand, for a LPATS network (which provides only timing information), four sensor reports are required to obtain a valid solution and thus the smallest possible network size is a four LPATS sensor network. For a hybrid network (like RINDAT), different cases must be considered: a two IMPACT solution, a four LPATS solution and anything in between (e. g. one IMPACT and two LPATS reports).

The recursive algorithm used to compute the network DE in each grid cell was adapted from Schulz and Cummins (2008), mainly to optimize the processing speed and also to allow considering the solutions given by a hybrid network like RINDAT. Thus, the present algorithm now assumes an existing network of known DE, where a single sensor is added, and the DE for the new network is then calculated. This process continues recursively until the total number of sensors is reached. For example, the overall DE of an $n$-sensor generic network is calculated in the following way:

(1) The DE for a 2-sensor network to detect a CG lightning event with peak current $I_p$ is:

$$F(2,2,I_p) = p_1(I_p) \cdot p_2(I_p) \tag{2}$$

where $p_1(I_p)$ and $p_2(I_p)$ are the probabilities of sensor 1 and sensor 2 respectively to detect the event (dependent on the distance to the sensor) with a certain peak current $I_p$;

(2) One more sensor is added to the network and the DE for the total system (the additional sensor and the previous 2-sensor network) is calculated still for a specific peak current $I_p$. The result is the DE for a

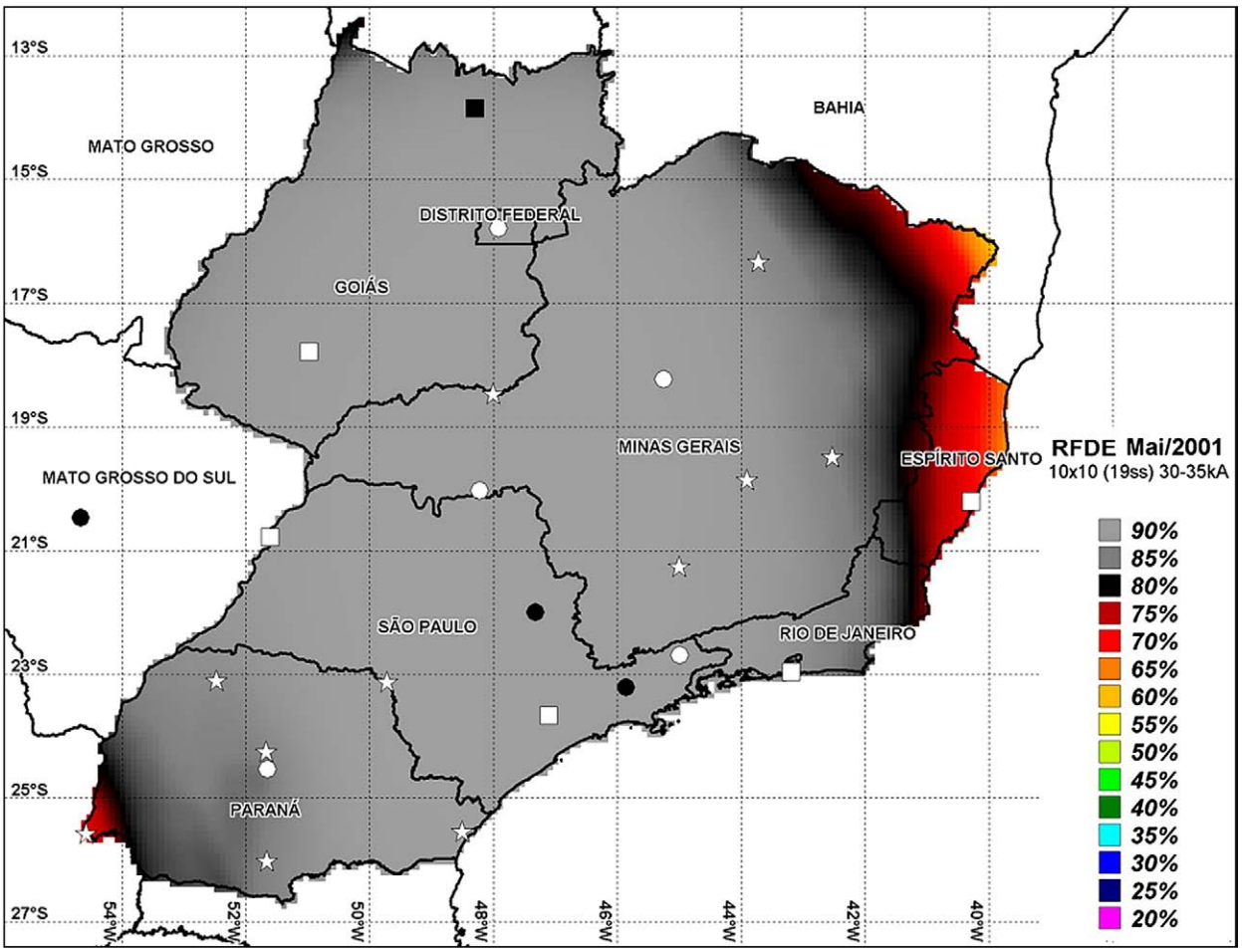


**Fig. 8.** Same as Fig. 7, but for 30–35 kA peak current range.

3-sensor network, considering solutions given by 2 reporting sensors:

$$F(3,2,I_p) = p_1(I_p)\cdot p_2(I_p)\cdot p_3(I_p) + p_1(I_p)\cdot p_2(I_p)\cdot q_3(I_p) + p_1(I_p)\cdot q_2(I_p)\cdot p_3(I_p) + q_1(I_p)\cdot p_2(I_p)\cdot p_3(I_p) \quad (3)$$

where $p_i(I_p)$ is the probability of a stroke with peak current $I_p$ to be detected by the $i$th sensor and $q_i(I_p)$ is the probability of the $i$th sensor to miss the event ($p_i = 1 - q_i$).

(3) Based on Schulz and Cummins (2008), this algorithm can be generalized into a recursive formula (Eq. (4)). Thus, considering a $n$-sensor network where solutions are given by $m$ reporting sensors, the addition of a sensor ($n$+1) results in the following network DE:

$$F(n+1,m,I_p) = q(n+1,I_p)\cdot F(n,m,I_p) + p(n+1,I_p)\cdot F(n,m-1,I_p) \quad (4)$$

where the first product accounts for the probability of a stroke of specific peak current $I_p$ to be missed by sensor ($n$+1) but to be detected by the $n$-sensor network considering $m$ reporting sensors; the second term represents the probability of a stroke (peak current $I_p$) to be detected by sensor ($n$+1) but to be missed by the $n$-sensor network, considering ($m$−1) reporting sensors; it is important to assume that $n \geq m$ and $m \geq 2$. The two extreme terms of the recursive function $F(n, 0, I_p)$ and $F(m, m, I_p)$ are defined in Eqs. (5) and (6).

$$F(n,0,I_p) = \prod_{i=1}^{n} q(i,I_p) \quad (5)$$

$$F(m,m,I_p) = \prod_{i=1}^{m} p(i,I_p) \quad (6)$$

In summary, the described algorithm uses the sensors RSDE curves to assess the probability of a stroke of a particular peak current $I_p$ to be detected by each sensor within each grid cell, and then recursively computes the probability of the

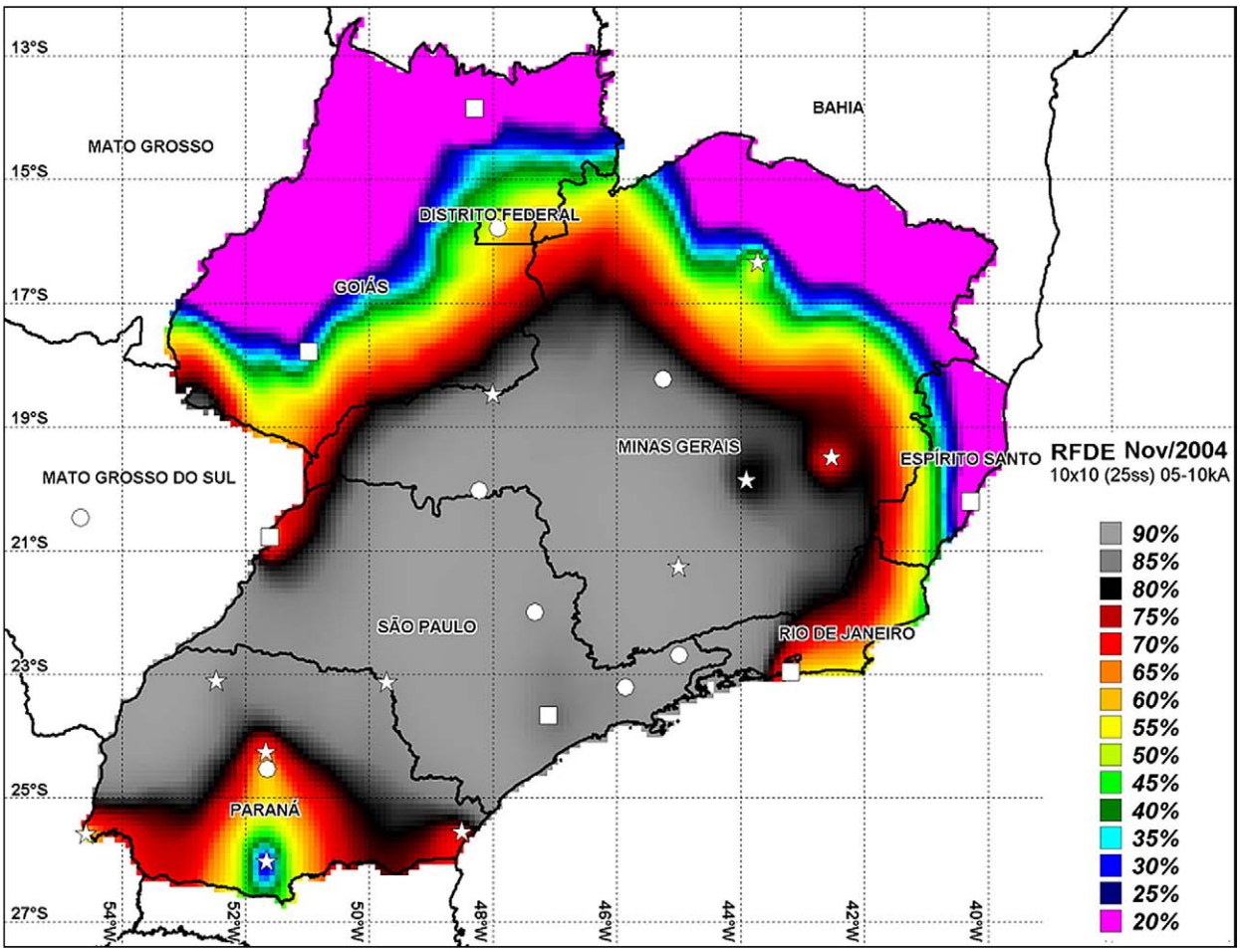


**Fig. 9.** RINDAT network RFDE computed for 5–10 kA peak current range in Nov. 2004, when all 25 sensors were operating. The grid resolution is 10×10 km.

stroke to be registered (or not) by the network within that cell taking into account the minimum required number of sensor reports. For the RINDAT regional network, the RSDE within each cell is a combination of bearing and timing information, as stated in Eq. (7):

$$\mathrm{RDE}_S(I_p) = F(j, 2, I_p) + F(k, 4, I_p) \tag{7}$$

where $\mathrm{RDE}_S(I_p)$ = network RSDE for a specific peak current $I_p$ within a grid cell; $j$ = number of IMPACT sensors (bearing information) and $k$ = number of IMPACT + LPATS sensors (timing information).

According to Schulz and Cummins (2008), the network stroke DE ($\mathrm{DE}_S$) and the flash DE ($\mathrm{DE}_f$) are directly related by the following equation:

$$\frac{\mathrm{DE}_S}{\mathrm{DE}_f} = \frac{m}{M} \tag{8}$$

where $m$ = measured average flash multiplicity; $M$ = true average flash multiplicity. Due to the intrinsic LDN limitations, $M > m$ and thus $\mathrm{DE}_f > \mathrm{DE}_S$. Ballarotti et al. (2006) show that the RINDAT regional network presented a $\mathrm{DE}_f = 88\%$ and $\mathrm{DE}_S = 55\%$ in the Paraiba Valley region, in agreement with the results presented by Biagi et al. (2007). Since this model uses a RDE approach, it may obtain network SDE values of 100%. Thus, in order to correct the CG flash density maps, the RSDE is normalized to 55% and then the network RFDE is computed based on Eq. (9):

$$\frac{\mathrm{DE}_S}{\mathrm{DE}_f} = \frac{0.55}{0.88} \Rightarrow \mathrm{DE}_f = 1.6 \cdot \mathrm{DE}_S \tag{9}$$

It is important to note that the $\mathrm{DE}_f/\mathrm{DE}_S$ ratio of 1.6 was estimated for the Paraíba Valley only. However, due to the absence of high-speed camera measurements for other regions of Brazil, this value is assumed to be approximately valid for all the network coverage area.

### 3.2. Results and discussion

Fig. 7 shows the RINDAT network RFDE after Eq. (9) conversion with 10×10 km spatial resolution computed

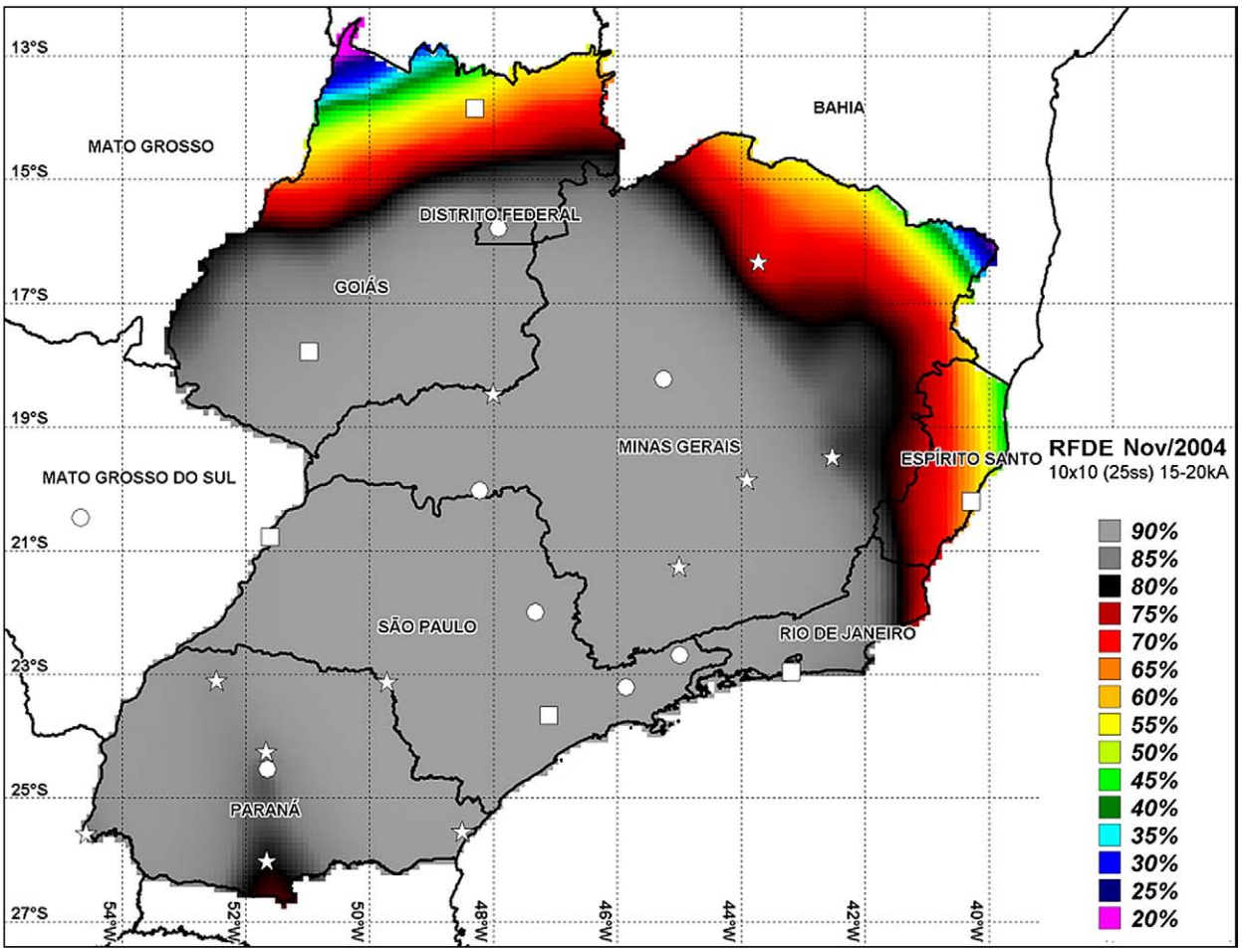


**Fig. 10.** Same as Fig. 9, but for 15–20 kA peak current range.

for 5–10 kA peak current range in May 2001, when only 19 sensors were operating (in white). The São José dos Campos, Pirassununga and Campo Grande sensors (the red circles) were still not installed at that time, and the Serra da Mesa sensor (located at the north of Goiás) was down. A network RFDE anomaly closer to outermost sensors can be clearly observed, particularly in the south of São Paulo and Paraná. Since the weak CG strokes that occur closer to these sensors tend to be missed (due to saturation), and at the same time the low peak current strokes are not able to trigger the adjacent (and more distant) sensors, the minimum information required to produce a solution is not reached. Thus, the network RFDE in these areas decreases significantly for this peak current range (5–10 kA), showing that the model can reproduce this effect.

Fig. 8 shows an opposite scenario. Due to the higher peak current values (30–35 kA range), the CG lightning strokes are strong enough to trigger a sufficient number of sensors, minimizing the network RFDE anomalies mentioned previously. It is also evident that the network RFDE is approximately uniform in almost the whole area of coverage, except for the state of Espírito Santo, due to the lack of sensors in northeastern Minas Gerais.

Fig. 9 shows the RINDAT network RFDE (10 × 10 km spatial resolution) computed for the 5–10 kA peak current range in February 2004, when all the 25 sensors were operating (in white). It shows an interesting result that confirms the proper behavior of the model. Comparing with Fig. 7, it can be observed that the RFDE anomaly around the Ibiúna sensor (south of São Paulo) disappeared due to the presence of São José dos Campos and Pirassununga sensors. However, the RFDE anomaly in the south of Paraná remained unchanged, as the network geometry in that region had not been modified.

Fig. 10 shows the RINDAT RFDE for the 15–20 kA peak current range also in February 2004. It can be noted that the network presented a fairly good performance even for a lower peak current range, covering almost the whole state of Paraná and the southeastern region of Brazil with 88% RFDE

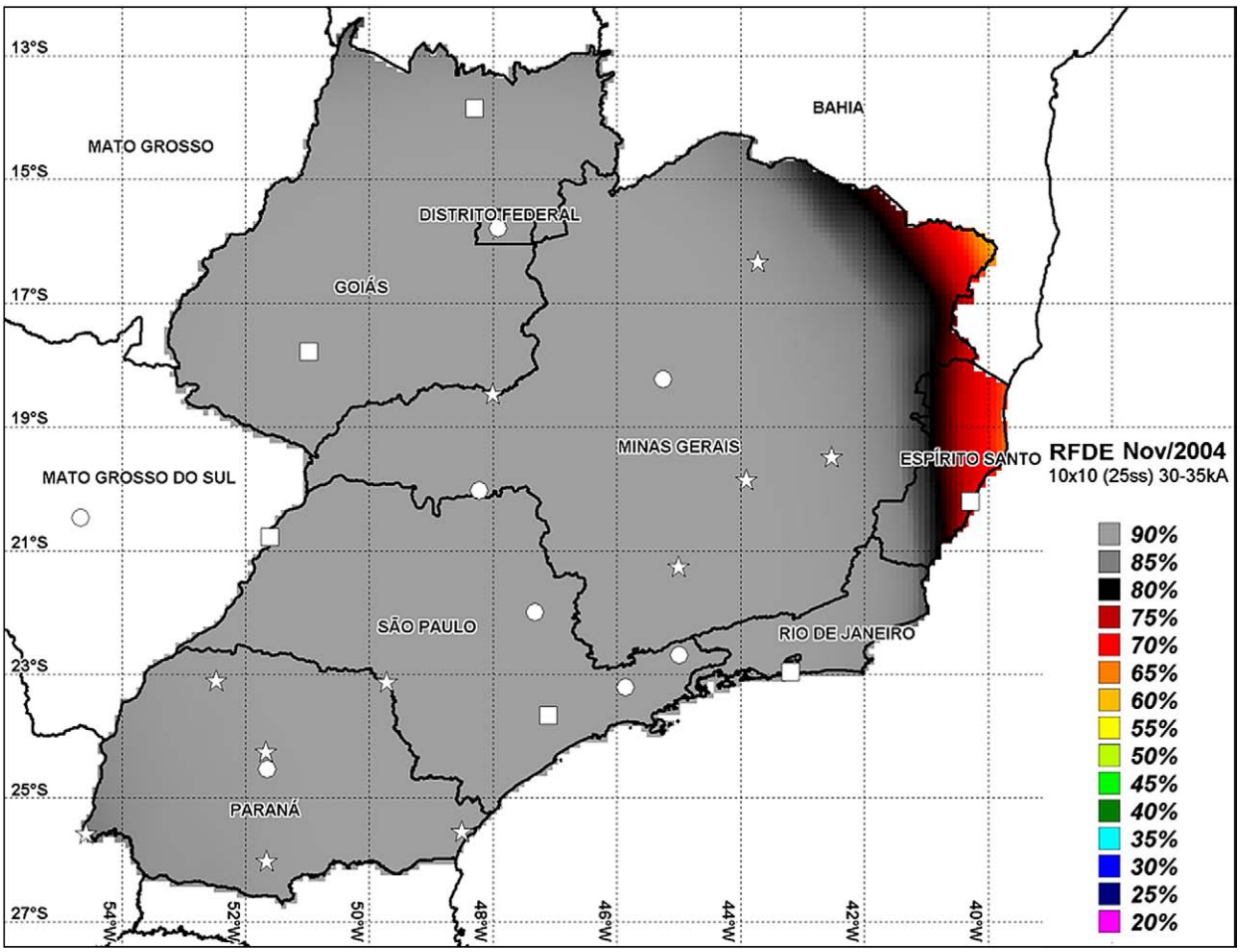


**Fig. 11.** Same as Fig. 9, but for 30–35 kA peak current range.

(maximum estimated value). Once again, the lack of sensors in northeastern Minas Gerais affected the performance of the network in state of Espírito Santo.

Fig. 11 presents the RINDAT RFDE for the 30–35 kA peak current range, showing that the network has a very good performance (88% RFDE) over almost all southeastern Brazil, including the states of Goiás and Paraná, except for state of Espírito Santo.

Comparing Figs. 3, 9–11 it is possible to observe that the RINDAT RFDEM reproduces several features of the network performance that the previous methodology (Naccarato et al., 2004b) is not able to do. The results show that changes in the network geometry (which can be due to different factors as already discussed) produce distinct effects in its performance. It was shown that the RINDAT RFDEM had enough sensitivity to reproduce these important aspects of the LDN behavior: (1) variations in the network RSDE as a function of the peak current distribution; (2) the occurrence of RSDE anomalies closer to the outermost network sensors for lower peak current ranges; (3) the distinct effect of LPATS and IMPACT sensors in the overall network RSDE (presented by Eq. (7)).

### 3.3. Correction of the CG flash density values

As discussed previously, the main goal of correcting the CG flash density maps is to minimize the relative geographical variation in the CG lightning data associated with variations in the network DE. Thus, after correction, the relative differences in the CG flash density values are expected to be due more to physical factors than the LDN performance. Fig. 12 shows the original CG flash density map (without correction) for southeastern Brazil considering a 6-year CG lightning flash dataset (1999–2004). Fig. 13 shows the corrected CG flash density values regarding the RINDAT network RFDE.

Comparing Figs. 12 and 13, it can be observed that the correction of the CG flash density values works effectively only for regions with network RFDE values between 60%

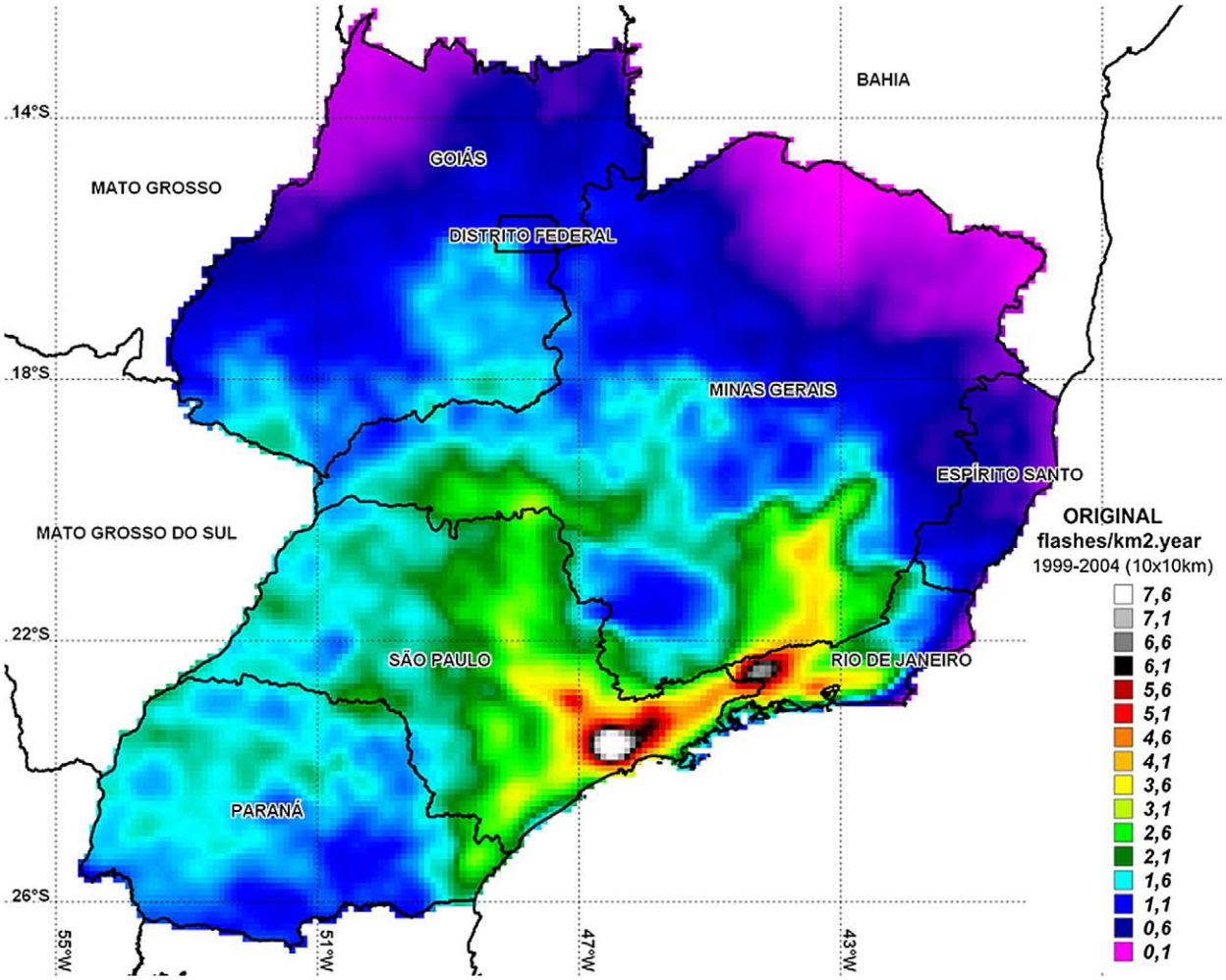


**Fig. 12.** CG flash density map (flashes $km^{-2}$ $yr^{-1}$) for a 6-year dataset (1999–2004) without correction regarding the RINDAT network RFDE. The grid resolution is 10 × 10 km.

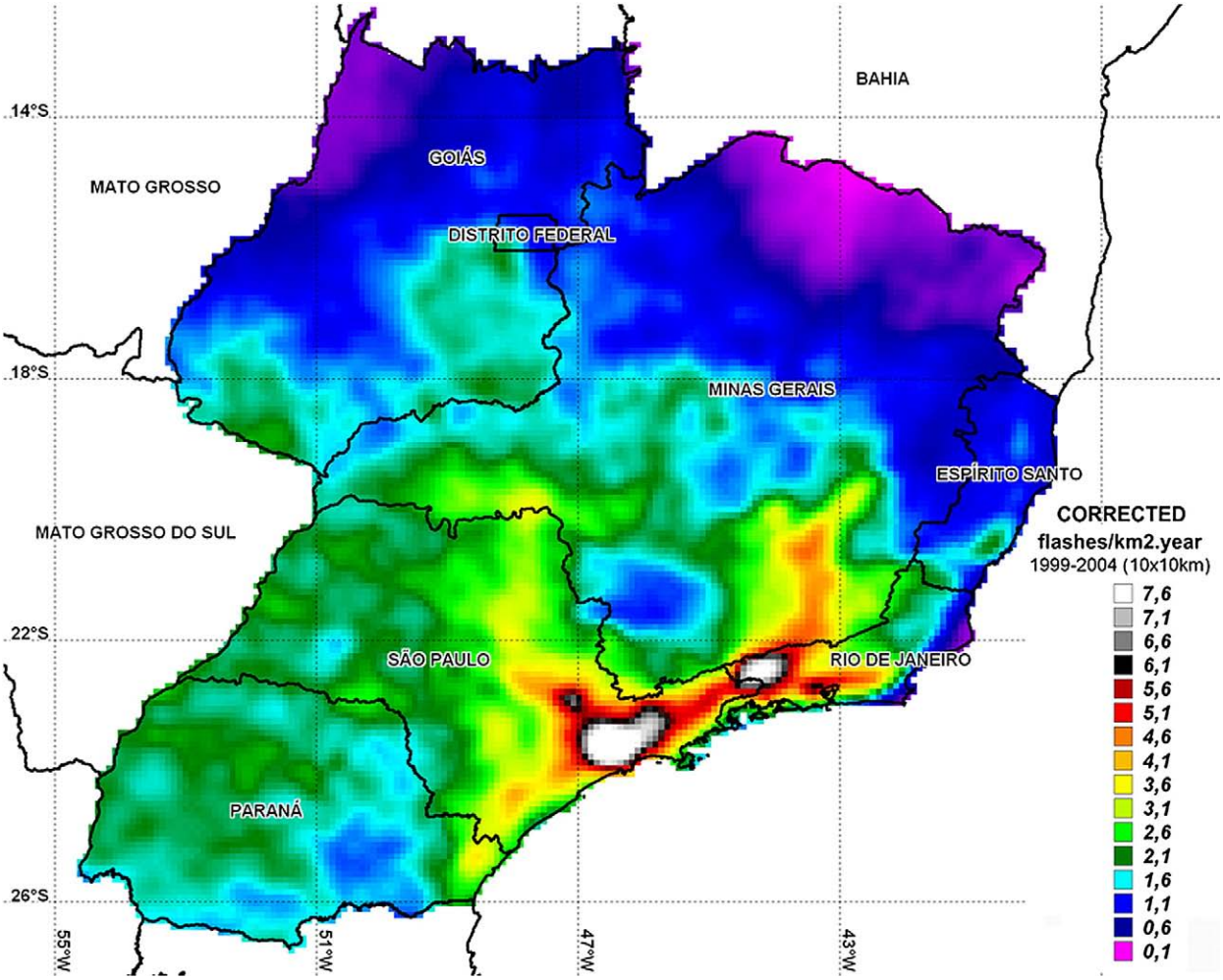


**Fig. 13.** Same as Fig. 12, for the corrected CG flash density values.

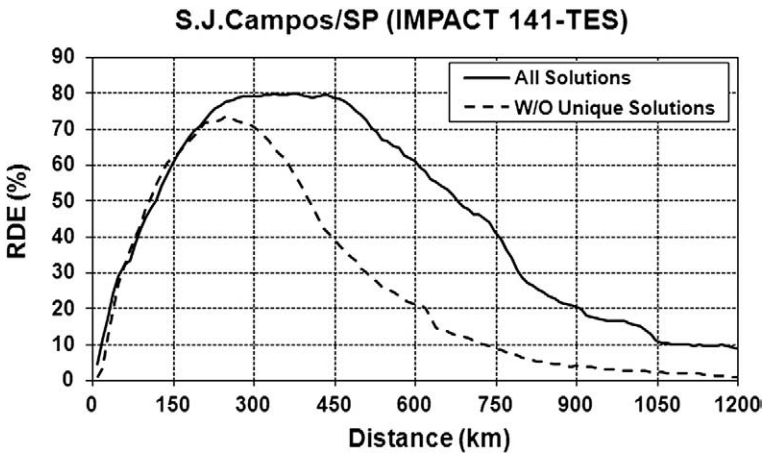


**Fig. 14.** The effect of removing the unique CG lightning solutions in the calculation of the sensor RSDE probability function. This new approach reduces the unrealistic high DE far from the sensor (responsible for the "border effect") without affecting significantly the performance closer to the sensor (inside the network). The curves were integrated for the entire peak current distribution. W/O = without.

and 80%. Below 60% RFDE, the correction is not able to counteract the reduced number of CG strokes detected by the network, leading to CG flash densities smaller than expected, when compared with the *Lightning Imager Sensor* data presented by Naccarato et al. (2008). On the other hand, above 80% DE, the model correction does not increase appreciably the number of CG flashes, which prevents it from recovering the actual values of CG flash densities, according to the LIS data (Naccarato et al., 2008).

## 4. The BrasilDAT Network RFDEM

### 4.1. Overall description

As discussed previously, the RINDAT network RFDEM presented very interesting results, showing that the model can reproduce several features of the LDN spatial performance. However, the results still show an unrealistic "border effect" closer to the network boundaries (where most of the sensors are essential) that causes an artificial increase of the DE over these outermost areas. A sensor is called essential for a particular CG lightning solution when this solution is computed with a minimum number of reporting sensors. Thus, without that sensor, this so-called unique solution will not exist. In order to overcome this limitation, the BrasilDAT network RFDEM employs a new methodology to calculate the sensor RSDE distribution functions. As described in Section 3.1, the sensor RSDE curves used by the previous model are computed simply by the ratio of the number of CG strokes detected by the sensor divided by the number of events detected by the network for a specific peak current $I_p$ and distance $d$ (refer to Eq. (1)). In this new approach, the sensor curves are assessed neglecting the CG stroke unique solutions, i.e. for which that specific sensor is essential. The resulting effect can be seen in Fig. 14, which shows the RSDE curves for the São José dos Campos IMPACT sensor considering all solutions, and neglecting the unique solutions. The RSDE values were integrated for all peak current distribution to simplify the analysis. It can be noticed that the new methodology effectively reduces the unrealistic high DE of the sensor over 300 km caused by the distant CG strokes that are detected only by the minimum number of reporting sensors. On the other hand, for regions closer to the sensor (distances lower than 300 km), it can be inferred by the sensor RSDE curve that the DE inside the network is not significantly affected. Thus, the expected effect in the overall network RSDE is exactly the decrease of the "border effect" in the outermost areas (which prevents the model from estimating rational CG flash

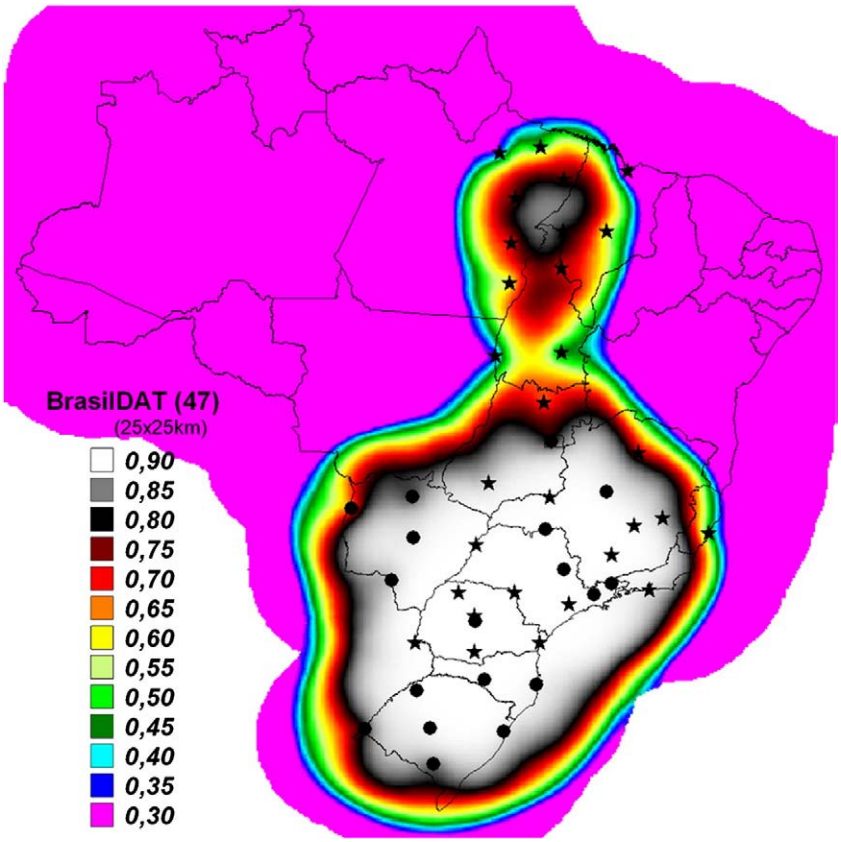


**Fig. 15.** The BrasilDAT network RFDE computed by the new model using the original sensor RSDE curves (for all solutions). The resolution is 25×25 km.

density values) without removing the low-current strokes inside the network, which would certainly alter its estimated performance.

### 4.2. Results and discussion

In order to test how the new methodology is really able to decrease the "border effect", the individual sensor RSDE curves without the unique solutions and integrated for the entire peak current distribution (similar to Fig. 14) were used to compute the overall network RSDE that was then converted to RFDE by Eq. (9).

Fig. 15 presents the BrasilDAT network RFDE computed by the RFDEM using the sensor RSDE curves (similar to Fig. 14) that include all solutions (previous approach). Fig. 16 shows the BrasilDAT network RFDE considering the curves neglecting the unique solutions (new approach). The magenta represents RFDE values up to 30%. The white color represents RFDE values up to 88%. From both figures, it can be observed that the network has a very high performance in the mid-southern Brazil, decreasing significantly towards the north due to the small network composed of only LPATS sensors. In general, almost 40% of the country is actually covered by a network with about 80–90% RFDE.

Comparing Figs. 15 and 16, it can be observed that the "border effect" is clearly decreased since the RFDE values calculated by the new methodology are lower through all the network boundaries. On the other hand, as expected, the estimated RFDE inside the network was not affected by the removal of the unique solutions in the sensor RSDE curves calculation. Thus, it can be stated that the model reliability was improved, allowing a better reproduction of the natural network spatial performance, particularly closer to the outermost sensors. Therefore, the new BrasilDAT RFDEM presented now a reasonable sensibility that allows testing any LDN for unfavorable sensor geometries and/or looking for regions with bad or insufficient sensor coverage.

### 4.3. Correction of the CG flash densities

Fig. 17 shows the CG flash density values (flashes $km^{-2}$ $yr^{-1}$) based on a 2-year CG flash data (from Jun/2005 to May/2007) provided by BrasilDAT network without the correction regarding the FDE variations. As already discussed, the CG flash density maps must be corrected in terms of the network RFDE in order to minimize the effect of its performance over the lightning spatial distribution. Hence, Fig. 18 presents the corrected CG flash density values. As expected, the larger variations are concentrated in the northern edge of the country (compared to Fig. 17), where BrasilDAT presents a lower performance (showed in Fig. 16).

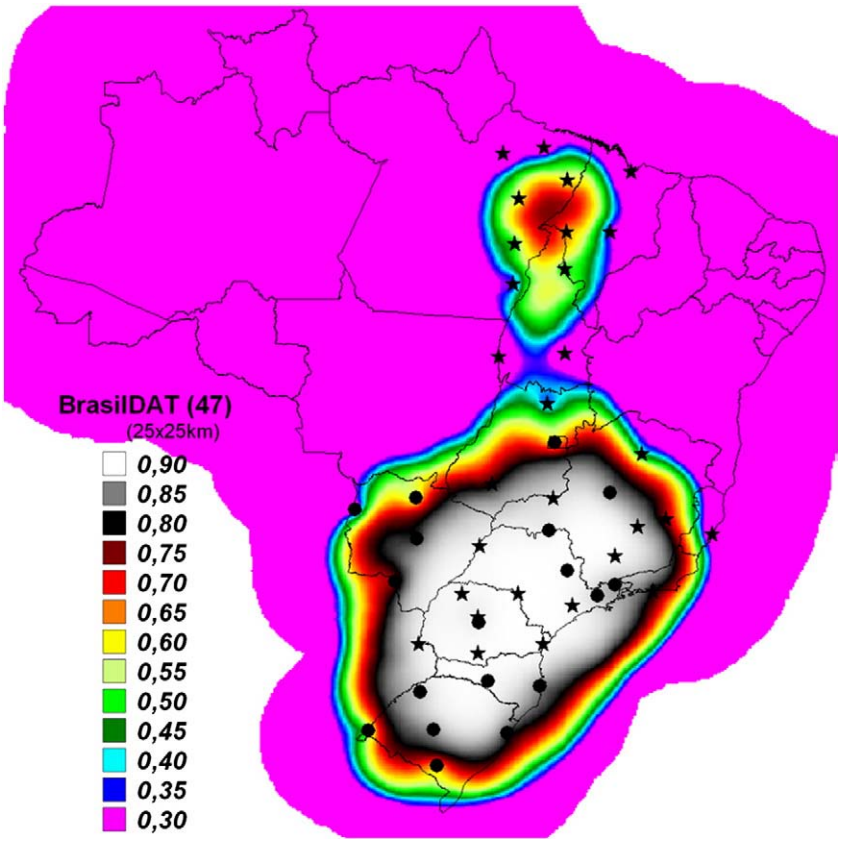


**Fig. 16.** Same as Fig. 15, but using the new sensor RSDE curves (neglecting the unique solutions).

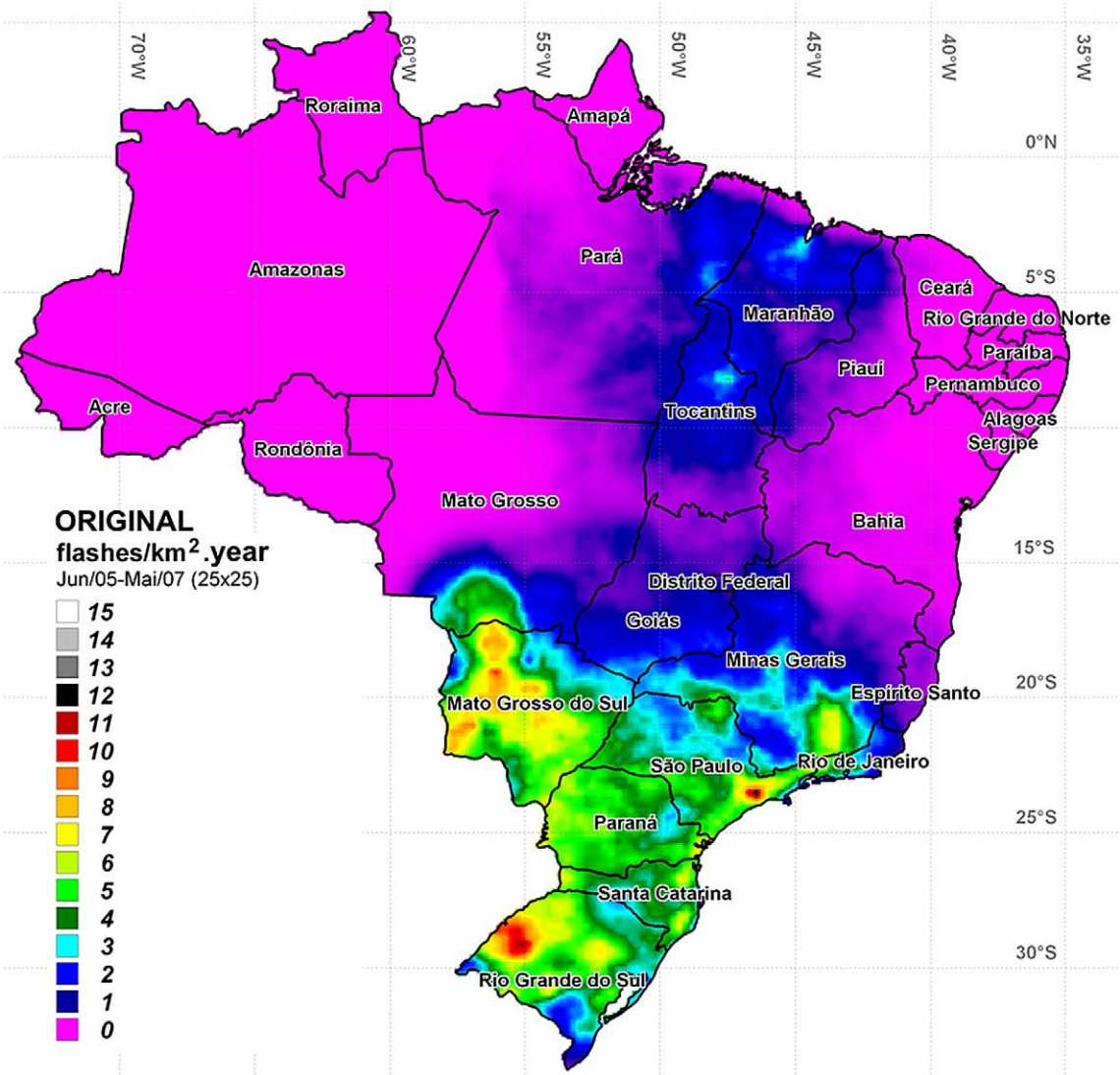


**Fig. 17.** CG flash density values (flashes $km^{-2}$ $yr^{-1}$) for a 2-year BrasilDAT dataset (Jun/2005 to May/2007) without any correction regarding the variations of the network RFDE. The grid resolution is 25×25 km.

Additional effort is now required to verify whether the very high CG flash density regions observed in southern Mato Grosso and western Maranhão (Naccarato et al., 2008) are caused by the process of RFDE correction or if they really represent a physical phenomenon. Alternatively, some areas with higher CG flash densities are well reproduced, e.g. western Paraná and states of Rio Grande do Sul and Tocantins.

## 5. Summary and conclusions

The main purpose of correcting CG flash density maps due to the LDN RFDE is to minimize (preferably remove) the fraction of the geographical variation in the lightning data that is directly related to the network spatial performance. In Brazil, due to the continuous expansion of the BrasilDAT network, this is particularly important to integrate the CG lightning data provided by the different regional networks: RINDAT, SIDDEM and SIPAM.

A comprehensive review of several techniques for developing a RDEM is presented. All of them use a set of CG lightning data reported by the network to compute its relative detection efficiency (RDE). The first work of Naccarato et al. (2004b) combined the Murphy et al. (2002) and Rompala et al. (2003) methods to produce a quite simple technique to assess the RFDE of a LDN without the use of an explicit physical model. Due to its limitations, a RFDEM for the RINDAT regional network was developed in 2004. This model computes the RSDE distribution function for each sensor, which depends on the peak current and the distance from the stroke (propagation effects), using the data provided by the same network. The results show

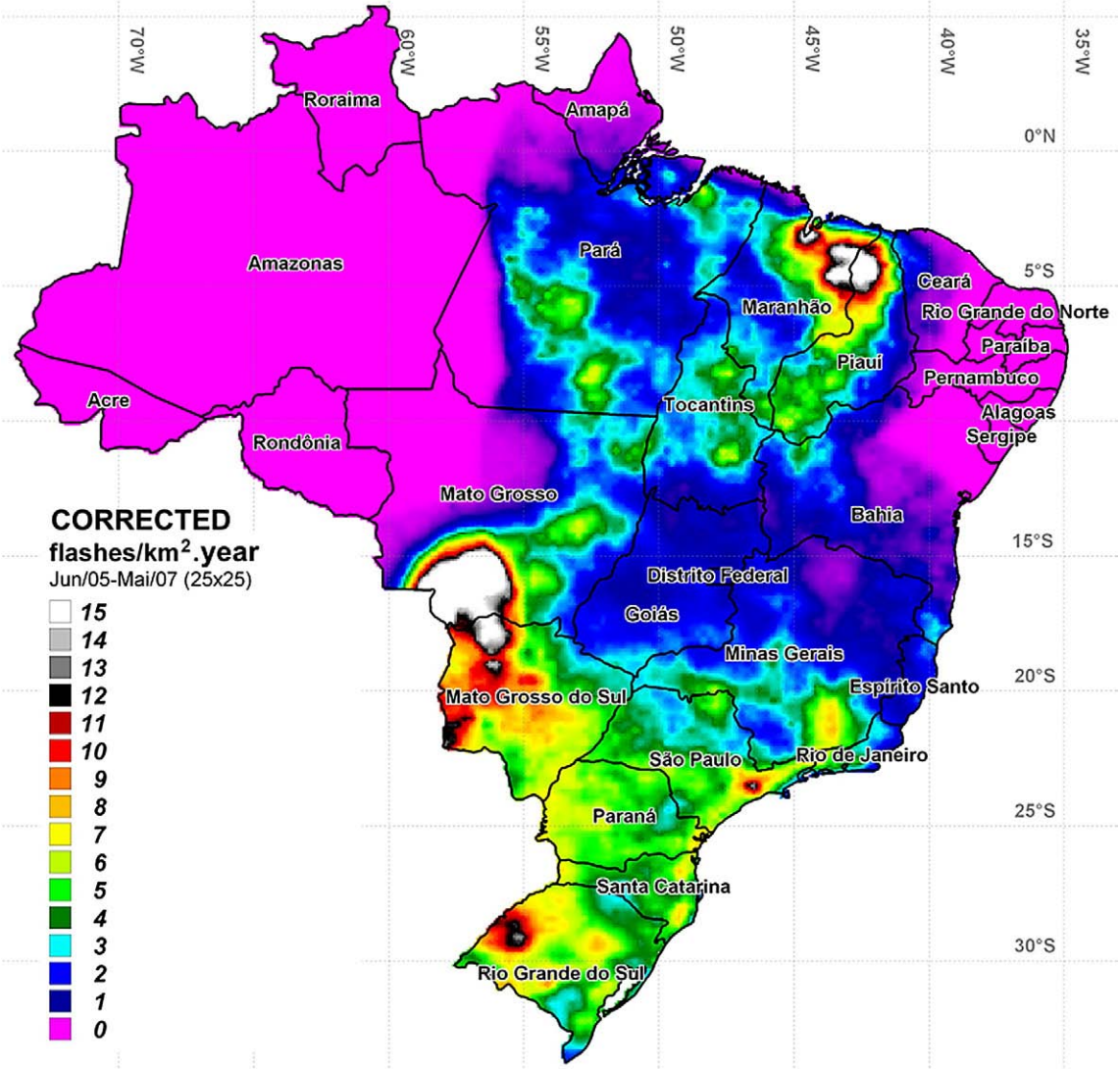


**Fig. 18.** Same as Fig. 18, but for corrected CG flash density values.

that the RINDAT RFDEM had enough sensitivity to reproduce these important aspects of the LDN behavior: (1) variations in the network RSDE as a function of the peak current distribution; (2) the occurrence of SDE anomalies closer to the outermost network sensors for lower peak current ranges; (3) the distinct effect of LPATS and IMPACT sensors in the overall network RSDE (represented by Eq. (7)).

The RINDAT network RFDEM presented very interesting results, but it still shows an unrealistic "border effect" closer to the network boundaries depicted by an artificial increase of the network DE. In order to overcome this limitation, the BrasilDAT network RFDEM employs a new methodology to calculate the sensor RSDE distribution functions that neglects the CG stroke unique solutions (provided by the sensor when it is essential). The new approach was able to reduce the "border effect" without affecting the performance estimation inside the network. Thus, the new BrasilDAT RFDEM presents a reasonable sensitivity that allows testing any LDN for unfavorable sensor geometries and/or looking for regions with bad or insufficient sensor coverage.

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