# Insights into Brazilian microphysical convective clouds observed during SOS-CHUVA

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# Abstract.

Although Hydrometeor Classification Algorithms (HCAs) exist since several decades, their potential uses such as an additional tool for nowcasting issues related to high-impact weather events are relatively

- 25 limited. Here, an unsupervised technique is firstly used to retrieve the dominant hydrometeor types associated with stormy days of the SOS-CHUVA field experiment thanks to an X-band dualpolarization research radar. With this regard, stratiform echoes are composed of five microphysical species (light rain, rain, wet snow, aggregates and ice crystals), whereas convective regions have eight (light/moderate/heavy rain, hail, low/high density graupel, aggregates and ice crystals). Then the
- 30 dominant microphysical life cycle of 23 severe convective cells is investigated with particular emphasis 30 on their maximum activities in relation to lightning information (mature stage). It is shown that heavy 31 rain, hail, graupels, and aggregates increase in terms of volumes as the SOS-CHUVA convective cells 32 grow up. The time evolution of those four hydrometeor types, and especially graupels and ice crystals 33 which are key microphysical species for thunderstorm electrification, are closely related to lightning
- 35 rate and could help to prevent subsequent natural hazards associated to severe convective cells.

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**Keywords:** hydrometeor classification, tropical microphysics, dual-polarization radar, lightning, nowcasting

# **1. Introduction**

Although worldwide meteorological weather services have made considerable advances over past

- 45 decades, forecasts accuracy associated to potential high-impact weather events for very short time periods (nowcasting) are still not yet enough at both space and time scales to avoid or at least sufficiently mitigate socio-economical disasters (Wilson et al, 1998). Convective storms manifest through various meteorological systems ranging from isolated thunderstorm to complex Mesoscale Convective Systems (MCSs). Associated damages caused by those meteorological events can be
- <sup>50</sup> numerous over very short periods (hail, downburst, flash floods, lightning) and directly may affect human activities (road safety, flight assistance, power utilities). Therefore, a better understanding of physical processes at play within these intense events is required in order to improve forecast capabilities and also to provide objective procedures to meteorologists for anticipating their rapid evolution.
- <sup>55</sup> Dual-polarimetric (DPOL) weather radar is one of the most widely and reliable used instruments nowadays for nowcasting by the research community and the national weather services. By using the high sensitivity resulting from the combination of two orthogonal polarized microwaves, numerous benefits have been learned from polarimetric radars for the detection of hazards in convective clouds over the last 30 years. For instance, the exploitation of polarimetric variables has allowed to improve
- 60 the detection of damaging hail (Bringi et al, 1986), whereas Ryzhkov et al (2013) have proposed a method to differentiate the size of hail regardless of the DPOL radar wavelength. Recently, studies have suggested that precursors of hail could be associated to specific polarimetric radar signatures such as low coefficient correlation  $\rho_{HV}$  or even high specific differential phase  $K_{DP}$  for temperatures lower than

- 0 °C (Picca and Ryzhkov, 2012; Kumjian and Lebo, 2016). Another interesting feature deduced from 65 polarimetric radars is the presence of positive differential reflectivity  $Z_{DR}$  columns above ambient 0°C 65 isotherm, which are directly related to convective storm updrafts (Kumjian et al, 2014). With this 65 regard, Snyder et al (2015) have developed an algorithm based on the detection of  $Z_{DR}$  columns in order 66 to detect initiation of new intense convective storms and to examine the evolution of related updrafts. 67 Closely spaced to positive  $Z_{DR}$  columnar regions, positive  $K_{DP}$  columns above the melting level (T < 0
- <sup>70</sup> °C) have also shown to be good proxies of deep convection updrafts (Hubbert et al, 1998; Kumjian and Ryzhkov, 2008; Van Lier-Walqui et al, 2016). Finally, the exploitation of polarimetric radar variables has allowed to improve the forecast of tornadoes by focusing on the low level signatures and especially the Z<sub>DR</sub> and K<sub>DP</sub> footprints (Romine et al, 2008; Kumjian and Ryzhkov, 2008).

One of the most important advantages from DPOL radars is their high sensitivity to hydrometeors and

their related ability to discriminate between them (e.g. Vivekanandan et al, 1999; Ryzhkov et al, 2005). To date, various Hydrometeor Classification Aglorithms (HCAs) have been developed by using the synergy of the dual-polarimetric observables (horizontal reflectivity, Z<sub>H</sub>; Z<sub>DR</sub>; K<sub>DP</sub>; ρ<sub>HV</sub>) along with external temperature information (Park et al, 2009; Dolan and Rutledge, 2009; Al-Sakka et al, 2013; Dolan et al, 2013; Bechini and Chandrasekar et al 2014; Grazioli et al, 2015; Ribaud et al, 2018; among others). Such HCAs have already demonstrated their utilities by improving quantitative precipitation estimation and helped to prevent flooding (Giangrande and Ryzhkov, 2008; Boodoo et al, 2015). For instance, Météo-France's meteorologists have started to used hydrometeor identification as an complementary reliable nowcasting tool for anticipating potential high-impact severe weather related to specific convective storms.

- Microphysical characteristics deduced from polarimetric radar in conjunction with lightning information have also demonstrated potential benefits in order to better understand convective clouds. For instance, Schultz et al (2015) have noticed that lightning jumps (rapid increase in lightning activity) are especially correlated to increases in graupel volume and updrafts characterized by vertical motion higher than 10 m/s within the [-10°C; -40°C] layer. According to Ribaud et al (2016), graupel volumes are good proxies for lighting initiation, whereas wet hail growth processes may have negative impact on lightning occurrences. Also, graupel intrusion within ice crystals layer can disturbed lightning activity by producing significantly higher lightning activity (Ribaud et al, 2016). Polarimetric signatures along with hydrometeor identification have also shown appealing capabilities to diagnose the evolution of different storm electrification stages in Brazil (Mattos et al, 2016; Mattos et al, 2017). Fuchs et al
- 95 (2018) have also noticed that anomalous electrical charge structures are mainly associated with larger and stronger updrafts.

Most of the aforementioned results are, or could be, used by forecasters in their decision-making to track and put more emphasis on potential hazards in a severe storm. To date, the time evolution of dominant hydrometeor relative to convective storms is not available in terms of a nowcasting tool. By

statistically following the microphysical evolution of convective storms could led to another objective diagnose for nowcasting purposes. The present study aims at investigating the temporal evolution of each hydrometeor type volumes for sets of convective storms that occurred during the SOS-CHUVA project in Brazil, an extension of CHUVA project applied to nowcasting (Machado et al, 2017). With this regard, section 2 provides a brief overview of the SOS-CHUVA project and a description of the radar dataset. Section 3 deals with the HCA technique and retrieved hydrometeor types for the São

Paulo region, while section 4 presents the microphysical life cycle of convective cells in terms of volumes and altitudes. Finally, the main conclusions of this study are provided in section 5.

#### 2. Field experiment and datasets

- The present study is based upon data collected in the state of São Paulo during the SOS-CHUVA project which was conducted during intensive Operation Periods from 2016 to 2018. SOS-CHUVA is a multi-institutional research program focusing on nowcasting of severe weather events that occurred in South-East of Brazil during the wet season (November March). To achieve this goal, the development of nowcasting tools for improving the forecasts capabilities and providing objective procedures for meteorologists is expected to rely on meaningful results learned from the CHUVA research program
- (Machado et al, 2014). The ability to get access to the microphysical structures of precipitating systems represents also an important objective of the SOS-CHUVA project. Among all the instruments deployed during this research program, a DPOL X-band weather radar was located in Campinas in complement of pre-existing operational Doppler radar network. Concurrently, dense ground-based observations via
   raingauges measurements have also been set up in the cities of Piracicaba and Jaguaríuna to document

intense rain events. Figure 1 shows the map of the facilities used in this particular study.

The DPOL X-band radar was operated in Simultaneous Transmission And Reception (STAR mode) and provided  $Z_{H}$ ,  $Z_{DR}$ , the differential phase  $\Phi_{DP}$ , and  $\rho_{HV}$ . The polarimetric Campinas radar was designed to perform full volumetric scans every 10 minutes, each cycle was composed of 17 elevations ranging

from  $0.5^{\circ}$  to  $50^{\circ}$  with a  $1.3^{\circ}$  beam width at -3 dB. In addition, a vertical pointing scan for calibration purposes along with a 180° RHI scan over the Jaguaríuna raingauges network were performed.

The radar raw dataset has been pre-processed according to the procedure presented in Ribaud et al (2018). The processing chain consists in: (i)  $Z_{DR}$  calibration by removing offset deduced from vertical pointing in precipitation; (ii) discrimination between nonmeteorological and meteorological echoes; (iii)

130 correction of  $\Phi_{DP}$  offset and filtering; (iv) estimation of  $K_{DP}$  (Hubbert and Bringi, 1995); and (iv) attenuation correction applied to both  $Z_H$  and  $Z_{DR}$  (Testud et al, 2000). To mitigate as much as possible potential bias or errors, dataset has been restricted to precipitation events wherein the radome was dry. In addition, a high Signal-Noise-Ratio  $\geq 10$  dB along with a reduced radar coverage ranging from 5 to 60 km have been considered. Finally, the stratiform-convective separation described in Steiner et al 135 (1995) has been applied to the radar dataset from horizontal reflectivity field at a constant altitude plan

position indicator (CAPPI) generated at 3 km (T >  $0^{\circ}$ C).

# 3. Hydrometeor classification for São Paulo region

#### **3.a) methodology**

140 As mentioned in the introduction, there is plenty of HCAs proposed in the literature at all wavelengths and based on the combination of DPOL radar observables (Z<sub>H</sub>, Z<sub>DR</sub>, K<sub>DP</sub>, ρ<sub>HV</sub>) and temperature data inferred from radio-soundings or model outputs. In this study one makes the use of two particular hydrometeor identification techniques: (i) the clustering approach, and (ii) the fuzzy logic.

The core of the hydrometeor classification presented in this paper relies on an Agglomerative

145 Hierarchical Clustering (AHC) method, which aims at identifying similar polarimetric observables signatures and gathering them into clusters. This technique is a bottom-up algorithm that considers each observation as a singleton cluster at the outset. Based on their similarities, pairs of clusters are then iteratively aggregated until all clusters form an unique cluster containing all observations at the end. Finally, a posteriori analysis is performed by the user to determine the optimal number of clusters. With

- this respect, the reader is referred to Grazioli et al (2015) for background on clustering techniques, and Ribaud et al (2018) for the analysis of the clustering scheme sensitivity. Note that only relevant information that are needed for the understanding of the present analysis are detailed hereafter, while the entire description of the methodology is described in Grazioli et al (2015; hereafter G15) and have been taken over by Ribaud et al (2018; hereafter R18).
- 155 The AHC method relies on the definition of objects which are five-dimensional vectors defined for each valid radar resolution volume as follows:

$$x = \{Z_H, Z_{DR}, K_{DP}, \rho_{HV}, \Delta z\}$$

and where ∆z is the difference between the radar resolution height and the isotherm 0°C deduced either from sounding balloons or NCEP reanalysis. Objects are standardized in order to not mislead the clustering method with the different order of magnitude of each object's components. With this regard, polarimetric radar observations are concatenated into a [0; 1] common space thanks to minimummaximum boundaries rule, whereas the temperature information is mitigated into a [0; 0.5] range based on a soft sigmoid transformation where 0? (0.5) corresponds to altitude below (over) the brightband. In order to evaluate similarities/dissimilarities between clusters, the Ward linkage rule is considered along with the euclidean distance as metric (R18). As described in G15, the AHC algorithm do not only avaluate similarities/discimilarities between clusters at each iteration step, but also check the spatial

evaluate similarities/dissimilarities between clusters at each iteration step, but also check the spatial homogeneity of the clustering distribution by assuming a smooth spatial transition between clusters (i.e. hydrometeor types). Once the present setup is complete, the AHC method is applied to a subset of 25

000 observations randomly chosen from the SOS-CHUVA database and before being assigned to the 170 remaining dataset using the nearest clustering rule due to time consuming issues when dealing with very large dataset.

Concurrently, the X-band fuzzy logic algorithm of Dolan et al (2009; hereafter DR09) has been used to evaluate the clustering outputs from the AHC method. Initially it allows the discrimination between:

175 Light Rain (LR), Rain (RN), Aggregates (AG), Low Density Graupel (LDG), High Density Graupel (HDG), Ice Crystals (IC), and Vertical Ice (VI). This classification has been slightly enriched of the Wet Snow (WS) and Melting Hail (MH) microphysical species by Besic et al (2016) through scattering simulations. In total, the adapted fuzzy logic allows to distinguish between 10 hydrometeor types and will refer as DR09 algorithm hereafter.

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#### 3.b) Hydrometeor classification

According to the AHC method described in section 3.a, the algorithm has been conducted on the DPOL radar dataset for 13 case studies of intense rainfall events. Initially the AHC method randomly picked 25 000 radar observations considering each of them as a singleton cluster. A simple hierarchical aggregation has been conducted until to reach 50 clusters (i.e. far from the final partition), whereas the following iteration step has also considered the analysis of the spatial smoothness. This setup has been separately conducted over both stratiform and convective regions. Here, the clustering outputs retrieved by the AHC method are identified and associated with their corresponding microphysical species. With this respect, the choice of the best trade-off about the optimal number of clusters have been manually

190 investigated beforehand, due to the intrinsic high complexity of representing all clustering partitions in this paper. Note that the complete SOS-CHUVA cluster centroids are given in Appendix A.

#### 3.b.1) Stratiform echoes classification

Figure 2 exhibits clustering outputs extracted from an RHI presenting typical stratiform echoes on 3
December 2016 in the region of Campinas. Overall, clustering outputs are consistent with hydrometeor types retrieved by the fuzzy logic and DPOL radar signatures. For positives temperatures, clusters 3S and 5S (# referred to the cluster's number and S stands for Stratiform clouds) are in agreement with the DR09 Rain and Light Rain microphysical species, respectively. Nevertheless, one can notice that the fuzzy logic Light Rain (x[25; 35 km]) ?? is more pronounced that the cluster 5S, whereas the clustering outputs present a more homogeneous region according to cluster 3S. The melting layer, characterized by very low (high) ρ<sub>HV</sub> (Z<sub>H</sub>-Z<sub>DR</sub>) values, is well represented by the cluster 4S. Note that the DR09 algorithm is mainly driven by temperature information within this specific layer, whereas the clustering algorithm allows to closely follow the DPOL signatures (x[3; 20km]). Finally, negatives temperatures are characterized by clusters 1S-2S which appear to correspond to Aggregates and Ice Crystals regions

205 retrieved by the DR09 algorithm.

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To further investigate clusters' characteristics, the  $Z_H$ ,  $Z_{DR}$ ,  $K_{DP}$ ,  $\rho_{HV}$  and  $\Delta z$  distributions are represented through violin plots in Figure 3, while the contingency table between the clustering outputs and the microphysical species retrieved by the DR09 algorithm is presented in Table 1. With this regard, clusters 1S and 2S are defined for negative temperatures and are associated with low  $Z_H$  and  $K_{DP}$ values together with a high coefficient correlation. One can see from the contingency Table 1 that cluster 1S is mostly divided into Aggregates (47 %) and Ice Crystals (35 %), whereas cluster 2S is related to Aggregates (55%) and Wet Snow (30 %). The main discrepancy between both clusters 1S and 2S relies on  $Z_H$  distributions which spread around 17 dBZ and 25 dBZ, respectively. In this respect, R18 has retrieved similar DPOL values for ice crystals and aggregates hydrometeor types associated with

- stratiform regions in Manaus and one can consider hereafter that cluster 1S correspond to Ice Crystals and cluster 2S to Aggregates. As noticed previously in Figure 2, cluster 4S exhibits all the melting layer characteristics on corresponding violin plots with low  $\rho_{HV}$  values (~ 0.91) and high Z<sub>H</sub> (~ 40 dBZ) and Z<sub>DR</sub> (2.9 dB) values. With 75% of agreement with DR09 algorithm cluster 4S is thus associated with Wet Snow hydrometeor type. Finally, only clusters 3S and 5S remain for positive temperatures. Cluster
- 220 5S is characterized by lower  $Z_H$  and  $Z_{DR}$  distributions than cluster 3S, and is mainly associated with Drizzle (95 %) from contingency Table 1. With this regard, one considers that cluster 5S stands for Drizzle and cluster 3S for Rain.

#### 3.b.2) Convective echoes classification

- Figure 4 shows a RHI of a convective cell that occurred on 29 November 2016 in the vicinity of Campinas. Overall the cell is characterized by a deep convective "tower" (x[26; 31 km]) that exhibits horizontal reflectivity up to 55 dBZ, high Z<sub>DR</sub> and K<sub>DP</sub> values for positive temperatures along with low coefficient correlation. With this respect, one can see that the clustering outputs are in agreement with DPOL signatures. While the DR09 retrieves three hydrometeor types for positive temperatures (Light
- 230 Rain, Rain, and Melting Hail), the AHC method finds four different clusters (9C-10C-11C-13C). Those clusters seem to gradually follow the gradient of horizontal reflectivity until to define cluster 9C (#

referred to the cluster's number and C stands for Convective clouds) as highly correlated to  $Z_H$  up to 50dBZ,  $Z_{DR}$  up to 4dB,  $K_{DP}$  up to 3°/km, and low  $\rho_{HV}$  values (< 0.92). Around the isotherm 0°C, the fuzzy logic scheme exhibits a melting layer defined by the Wet Snow hydrometeor type, whereas either

235 radar observables do not present a bright band signature or clustering outputs. Finally, negative temperatures are characterized by clusters 6C-7C-8C-12C. Clusters 7C-8C seem to correspond to a mix of Low and High Density Graupel from the DR09 algorithm, whereas clusters 6C and 11C are in relation with Aggregates and Ice crystals, respectively.

The violin plots in Figure 5 and the contingency Table 2 allow to fully characterize and identify clustering outputs for the convective regions. With this regard, one can notice that cluster 13C is defined for low  $Z_H$  (~ 17dBZ) and high  $\rho_{HV}$  values (~ 0.98), and shares more than 85% with the Drizzle hydrometeor type (Table 2). The main differences between clusters 10C-11C rely on the  $Z_H$  and  $K_{DP}$ distributions. From the contingency Table 2, cluster 11C is divided into Drizzle (29%) and Rain (57%), while 90% of the cluster 10C correspond to Rain hydrometeor type. Thus, one consider hereafter that

- clusters 13C-11C-10C stand for Light, Moderate and Heavy Rain, respectively. Cluster 9C is characterized by very high  $Z_H$  (~51 dBZ),  $Z_{DR}$  (4 dB) and  $K_{DP}$  (3°/km) distributions along with quite low  $\rho_{HV}$  values (~0.97). Although it mainly corresponds to Rain, 12% is in agreement with Melting Hail. Note that in the region of Campinas-São-Paulo it is not rare to observe hail during very convective events. Although hail falls have been noticed several times during the SOS-CHUVA, none of the
- 250 hailpads deployed have unfortunately detected once. Therefore, one let the possibility to discriminate between purely liquid Heavy Rain (cluster 10C) and Melting Hail (cluster 9C). For negative temperatures, half of cluster 6C is associated with Aggregates, ~ 25% with Low Density Graupel and ~

20% with Wet Snow. Also, polarimetric signatures agree well with the Aggregates DR09 T-matrix microphysical features and the work of R18. Although cluster 12C presents similar DPOL distributions,

the main difference with cluster 6C resides in lower ZH values (19 vs 28 dBZ). According to Figure 4 and those polarimetric characteristics, one attributes cluster 6C to Aggregates and cluster 12C to Ice Crystals. Also defined at T < 0°C, cluster 7C is highly in agreement with the Low Density Graupel of DR09 algorithm (~ 68%) and same hydrometeor DPOL signatures retrieved in R18. Finally, cluster 8C exhibits all the brightband characteristics and shares more than 75% with the Wet Snow (Table 2). As</li>
previously noticed on Figure 4, the convective cell do not exhibit a melting layer together with another PPIs and RHIs extracted from the AHC (not shown). With this respect, one might attribute cluster 8C as

High Density Graupel, i.e. as ...(Dolan def ???).

#### **3.b.3) Ground validations**

- Although making differences between different types of rain may be somewhat questionable, Figure 6 presents comparisons of hydrometeor types retrieved from the clustering outputs defined for T > 0 °C in both stratiform and convective regions, with raingauge measurements observed in both Piracicaba and Jaguariuna sites during SOS-CHUVA (cf. Figure 1). The rationale for this approach is that the clustering outputs should be in agreement with ground observations. The analysis has been performed
- 270 by considering the 3x3 neighborhood radar measurements for each raingauge station. Overall, one can notice that clustering outputs are in agreement with ground observations. Indeed, stratiform rains are characterized by rain rates (RR) lower than 5mm/h, whereas convective precipitations are defined for

RR ranging in average from 8mm/h to 15mm/h. Note that both convective Heavy Rain and Melting Hail clusters present large distributions and can sometimes reach more than 40mm/h.

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#### 3.b.4) Discrepancies and similarities with Manaus region

The present hydrometeor classification allows to make a brief comparison with microphysical species retrieved through the work of R18 based on both the same AHC methodology and the DPOL X-band radar deployed during both the Go-Amazon2014/5 (Martin et al; 2017) and ACRIDICON-CHUVA

- (Wendisch et al, 2016) in the region of Manaus in Amazonas (Latitude: -3.21°; Longitude: -60.60°). Note that Manaus is surrounded by an equatorial forest whereas Campinas is located in a deeply urban region, nearly the Tropic of Capricorn. Overall, one can notice that the stratiform regions exhibit the same hydrometeors in terms of number and types, whereas the convective echoes associated with Manaus wet (dry) season do not show Melting Hail and High Density Graupel (Melting Hail) in comparison to Campinas region cloud microphysics.
- Nevertheless, the hydrometeor type presenting the highest difference with Manaus region is the Wet Snow that characterized the melting layer. The Amazonas region is characterized by horizontal (differential) reflectivities around 30 dBZ (1dB) against 40 dBZ (2 dB) in São Paulo. Also, the coefficient correlation is lower in São Paulo than Manaus region (0.91 vs 0.93). This is probably related
- 290 to the larger ice size and concentration in Campinas region where deep convective processes are stronger than the monsoon convective clouds.

Independently of the region between Campinas and Manaus, the cluster exhibiting the highest similarities in terms of DPOL signatures is the Heavy Rain category associated with convective regions.

This hydrometeor type is always characterized by mean Z<sub>H</sub> [43; 47 dBZ], Z<sub>DR</sub> [2; 3 dB], K<sub>DP</sub> [2; 3 °/km]

and  $\rho_{HV}$  [0.97; 0.98]. Although the convective region can be affected by different kinematic and microphysical processes, it appears the dominant hydrometeor types for both Manaus and Campinas regions are very similar whereas the discrepancies are more related to how they are distributed inside the cloud.

#### 300 4. Microphysical life cycle of convective cells

Getting access to the microphysical structure of severe weather events that occurred in the vicinity of Sao Paulo is part of the SOS-CHUVA objectives and is essential for assessing the severity of storm's potential. As discussed previously, the development of nowcasting tools for meteorologists is needed to improve weather warnings.

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#### 4a. Cell tracking and lightning selection

The Forecasting and Tracking the Evolution of Cloud Clusters (ForTraCc, Vila et al; 2008) has been used in order to put emphasis on microphysical life cycle of convective cells. This automated cell tracking algorithm has been adapted to work onto convective-stratiform outputs extracted from the Steiner et al (1995) methodology initially conducted on CAPPIs of  $Z_H$  at 3 km (T < 0°C) with a grid resolution of 1km x 1km. By using geometrical overlapping in successive time steps, the ForTraCc system aims at identifying each convective cell (via the center of mass) and following them in both space and time. With this regard, the reflectivity threshold employed was 40 dBZ, and the minimum size considered has been set up to 36 pixels in order to get geometrical overlapping in the 10 minutes 315 time step. Figure 7 presents 23 convective cell trajectories retrieved by the ForTraCC algorithm during the studied period. Overall, one can noticed that convective cells are associated with meteorological events crossing the radar domain from Northwest to Southeast.

According to the identified convective cells, lightning information have been extracted from the BrasilDAT network, which is based on Earth Netwoks technology. The signals radiations associated with lightning discharges are received in the very large frequency band (1 Hz – 12 MHz), and lightning events (flashes) are retrieved by the Time of Arrival technique. Naccarato et al (2012) assessed the performance of the BrasilDat Network in the vicinity of São Paulo, which is composed of a higher number of sensors than elsewhere in Brazil. The authors found that the network efficiency was up to 88% for cloud-to-ground flashes.

- In order to gather all the convective cells and explore the general microphysical evolution of the SOS-CHUVA events, lightning information have been considered here to set a  $t_0$  time (synchronizing). With this respect, one assumed that the maximum of lightning activity (normalized by the convective area) corresponds to the maximum convective stage of the convective cell ( $t_0$ ). Then a time-window of one hour has been considered to put emphasis onto the microphysical life cycle from time evolution ranging
- from 0 to  $\pm$  30 minutes behind/ahead the t<sub>0</sub> time. The choice of one hour interval has been motivated by previous results from TITAN project (Dixon et al, 1993) along with May and Ballinger (2007) which showed that the majority of convective cells exhibit a lifetime less than 60min, although global lifetimes associated to the parent cloud can be longer.

#### 4b. Microphysical evolution of convective clouds

The first microphysical aspect that has been investigated relies on the time evolution of volumes of hydrometeor types (Figure 8). With this regard, radar pulse volume has been associated with each hydrometeor type retrieved by the AHC method for the 23 convective cells. Results are presented in terms of "equivalent height", hereafter referred to as H\* and defined as:

$$H_i(n) = \frac{V_i}{S(n)}$$

where V refers to the volume associated to the hydrometeor type *i*, and S corresponds to the surface area of the convective cell n. Overall the time evolution of the volumes associated with each hydrometeor type agree quite well with the representation of microphysical life cycle within convective cells (Figure 8a). With this regard, volumes associated with Heavy Rain, Low and High Density Graupel, 345 Aggregates, and to a lesser extent Melting Hail, sharply increase from t-30min before reaching their peaks at t<sub>0</sub>, and progressively decaying afterwards. Those hydrometeor types are well correlated with the time evolution of the convective cell structure which can be divided into initiation, mature, and dissipitating stages. Although the evolution of Ice Crystals volumes are similar to those previous 350 hydrometeor types, it presents a delayed by 20 minutes. This is due to the mature-dissipitating transition, which acts to die out the storm from the bottom to the top and allows the growth of Ice Crystals for a longer time. Finally, both light and moderate rains exhibit the same signatures with low increase of weak precipitations until  $t_0$  before to sharply strengthen as the storm tends to dissipate. These results indicate that the microphysical life cycle is in agreement with the general representation associated with convective cell in terms of dynamics and model parametrization. 355

In order to assess the potential from monitoring hydrometeor type volumes for nowcasting perspectives, Figure 8b shows the first time derivative of microphysical volumes in relation to the "mean" convective cell. With this respect, one can noticed that the best precursors are Low and High Density Graupel along with the Aggregates hydrometeor types. They present variations of about 4 m/min between t-20min and t<sub>0</sub>, and thus could be considered to put more emphasis onto convective cells that present high positive volume variations of Graupels and/or Aggregates. Nevertheless, one should underline that the microphysical cloud representation is highly constrained by radar time resolution to complete an entire volume scan (i.e. 10 minutes here). For instance, microphysical processes may be affected and subject to quicker variations driven by dynamical effects.

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The time evolution of the mean altitude associated to the solid hydrometeor types (T < 0 °C) is presented in Figure 9 from the same 23 convective cells extracted from the SOS-CHUVA dataset. While the mean altitude of High Density Graupel does not vary with height significantly and oscillate around 6 km, the Low Density Graupel hydrometeor type raises from 6.5 km to ~ 7.5 km between the initiation to the mature stage of the convective cell. This elevation of Low Density Graupel is particularly in agreement with the electrification processes at play for separating charge within the storm (and known as non-inductive mechanism, Takahashi et al 1978). Indeed, by lifting from 6.5 to 7.5 km this microphysical type reaches cloud environment presenting negative temperatures of about [-15; -20°C] and according to Krehbiel et al (1986), "strong electrification does not occur until the cloud and precipitation develop above 7-8 km above MSL in the summer, corresponding to air temperature of -15 to -20°C". Finally, both Aggregates and Ice Crystals follow the same evolution, presenting mean altitude differences between the initiation and 10min delayed from t0 of about 1 km.

#### 5) Conclusion

380 The dominant microphysical species associated with convective systems that occurred during the SOS-CHUVA field experiment have been investigated through combining X-band dual-polarization radar measurements and lightning information.

According to the methodology initially developed by GR15 and the study of R18, an unsupervised HAC method has been developed to retrieve the dominant hydrometeor types of high-impact weather events.

- With this regard, it has been shown that SOS-CHUVA precipitating systems are composed of five hydrometeor types for stratiform regions (light rain, rain, wet snow, aggregates, and ice crystals), whereas convective echoes are defined by height microphysical species (light/moderate/heavy rain, hail, low/high density graupel, aggregates, and ice crystals). Although the validation of such HCA is a difficult task, it has been shown that ground observations via raingauges are in agreement with the
- 390 different intensity of convective rains retrieved by the hydrometeor classification. Finally it has been noticed that the diversity of dominant hydrometeor types are quite similar between the tropical city of Campinas located in southeast of Brazil and the equatorial city of Manaus, suggesting that potential microphysical discrepancies may be more related to their own distribution within the cloud through dynamical processes.
- <sup>395</sup> In a second step, a particular emphasis has been placed on 23 convective cells that occurred during the wet season of the SOS-CHUVA project. Microphysical aspects associated to the critical one hour period

focused on the mature stage of the convective systems have been investigated thanks to retrieved hydrometeor data and lightning information. With this regard, the time evolution of hydrometeor volumes and their respective first time derivative has reveal that heavy rain, low/high density graupel, aggregates and to a lesser extent hail are correlated to the development of the convective cell, making them good precursors for nowcasting tasks. As expected the height evolution related to low density graupel and ice crystals which are key microphysical species in relation to electrification processes, are also a good indicator to the convective cell development and potential resulting lightning.

- The present study could be extended by making use of extensive polarimetric radar measurements to reinforce retrieved microphysical properties associated to each hydrometeor type but also by investigating more severe convective cells. Results presented in this paper could be used to constrain and/or validate information derived by high-resolution numerical weather prediction suites, such as microphysical parametrization schemes. Finally, hydrometeor classification and the time evolution of
- 410 heavy rain, low/high density graupel, and ice crystals volumes will be used by Brazilian forecasters in a near future.

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TYPE	DZ	RN	MH	WS	AG	LDG	HDG	VI	CR
18	0.01 %	0.00 %	0.00 %	13.49 %	47.37 %	0.82 %	0.00 %	3.55 %	34.76 %
28	0.02 %	0.17 %	0.00 %	29.9 %	55.39 %	8.59 %	0.01 %	0.29 %	5.64 %
38	42.49 %	47.92 %	1.06 %	8.52 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
<b>4</b> S	0.04 %	3.44 %	0.05 %	75.14 %	1.01 %	16.98 %	3.05 %	0.00 %	0.29 %
<b>5</b> S	95.2 %	0.01 %	1.73 %	3.06 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %

**Table 1:** Confusion matrix comparing the clustering outputs from the stratiform region and hydrometeor species retrieved from the adapted fuzzy logic.

ТҮРЕ	DZ	RN	MH	WS	AG	LDG	HDG	VI	CR
6C	0.09 %	0.10 %	0.00 %	19.19 %	53.33 %	26.88 %	0.02 %	0.16 %	0.24 %
7C	0.00 %	0.68 %	0.28 %	21.76 %	0.00 %	67.82 %	9.47 %	0.00 %	0.00 %
8C	0.37 %	0.61 %	0.05 %	75.33 %	4.49 %	15.01 %	3.70 %	0.15 %	0.29 %
9C	0.00 %	87.88 %	11.94 %	0.18 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
10C	0.01 %	90.33 %	5.41 %	4.25 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
11C	29.42 %	57.30 %	0.44 %	12.84 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %
12C	0.08 %	0.00 %	0.00 %	20.00 %	49.49 %	1.23 %	0.00 %	4.33 %	24.87 %
13C	85.38 %	0.34 %	2.26 %	12.01 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %

 Table 2: Same as Table 3, but for the convective region



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# Appendix A: SOS-CHUVA cluster centroids

Cluster	Label	Z <sub>H</sub> [dBZ]	Z <sub>DR</sub> [dB]	K <sub>DP</sub> [deg/km]	ρну [-]	Δz [km]
15	Ice Crystals Small Aggregates	16.88	2.42	0.23	0.98	+ 2.33
28	Aggregates	24.83	2.1	0.23	0.99	+ 1.85
38	Rain	35.77	2.94	0.27	0.98	- 2.11
48	Wet Snow	39.83	2.91	0.29	0.91	+ 0.69
58	Drizzle	11.59	1.94	0.06	0.97	- 2.66
6C	Aggregates	28.08	1.45	0.15	0.99	+ 2.13
7C	Low Density Graupel	41.4	1.24	0.47	0.98	+ 2.09
8C	High Density Graupel	39.48	2.9	0.36	0.92	+ 0.68
9C	Melting hail	51.32	4.39	2.85	0.97	- 2.32
10C	Heavy Rain	43.56	2.88	1.65	0.98	- 2.33
11C	Moderate Rain	30.23	2.88	0.31	0.98	- 2.08
12C	Ice Crystals Small Aggregates	19.14	2.1	0.15	0.98	+ 2.11
13C	Light Rain	17.45	2.28	0.11	0.98	- 2.13

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Table A.1: Cluster centroids for the SOS-CHUVA project.