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Cloud and rain liquid water statistics in the CHUVA campaign

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ABSTRACT

The purpose of this study is to present statistics related to the integration of cloud and rain liquid water and the profiles for different cloud types and regimes. From 2010 to 2012, the CHUVA project collected information regarding cloud and rain characteristics in different precipitation regimes in Brazil. CHUVA had four field campaigns between 2010 and 2011, located in the North, Northeast and Southeast regions of Brazil, covering the semi-arid, Amazon, coastal and mountain regions. The synergy of several instruments allowed us to classify rain events and describe the cloud processes regionally. Microwave radiometers, LiDAR, radar, and disdrometers were employed in this study. The rain type classification was made using vertical profiles of reflectivity (VPR) and polarimetric variables from dual polarization radar (XPOL). The integrated liquid water (ILW_C) for non-precipitating clouds was retrieved with a microwave ground-based radiometer using a neural network. For rainy conditions, the profiles from the rain liquid water content (LWC_R) and their integrated (ILW_R) properties were estimated by Micro Rain Radar (MRR) and XPOL VPRs. For non-precipitating clouds, the ILW_C values were larger for the sites in tropical regions, in particular near the coast, than for Southeast Brazil. For rainy cases, distinct LWC_R profiles were observed for different rain classifications and regions. The differences are small for low rain rates and a distinction between different rainfall regimes is more evident for high rain rates. Vale and Belém clouds present the deepest layers and largest convective rain rates. The clouds in the Southeast region of Brazil (Vale do Paraíba) and North region (Belém) showed the largest reflectivity in the mixed and glaciated layers, respectively. In contrast, the Northeast coastal site (e.g. Fortaleza) showed larger values in the warm part of the clouds. Several analyses are presented, describing the cloud processes and the differences among the cloud types, rain rates and regions.

1. Introduction

Clouds cover approximately 68% of the Earth; therefore, it is essential to understand the physical properties of clouds in order to diagnose the Earth's energy and water balance (Rossow and Shiffer, 1999). Atmospheric water is found as vapor (gas phase), cloud and rain liquid water (liquid phase) and different types of ice, such as snow and hail (solid phase). The significant variability of hydrometeors is due to the complex atmospheric physical processes that directly impact the weather conditions and climate. For example, the quantity of water in the clouds influences the amount of latent heat and, consequently, the upward and downward motions within the cloud (Zhao and Carr, 1997). The energy balance is also strongly dependent on the amounts of water and ice in the clouds (Crewell and Löhnert, 2003; Zhao and Weng, 2002), which directly influence the climate. However, as mentioned by Löhnert et al. (2001), the lack of information concerning these complex processes, especially with respect to cloud microphysics, has limited the available parameterizations in high-resolution numerical models. Unlike other meteorological parameters, the liquid water content of clouds is not measured operationally, and there is little information about the variability of the average properties. The importance of this knowledge goes beyond forecasting and climate modeling, to the nowcasting of severe events (Greene and Clark, 1972).

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According to Pruppacher and Klett (1997), liquid water content varies considerably among clouds, from approximately 0.2 g m^{-3} in the initial stage of cumulus cloud development up to 14 g m^{-3} during severe storms. Cotton et al. (2010) list a series of characteristics associated with different cloud types, showing that liquid water content varies significantly. For example, stratus cloud liquid water presents values of approximately 0.05 to 0.25 g m^{-3}, although cases exist in which these values range up to 0.6 g m^{-3}. This is in agreement with Hogan et al. (2005), based on the synergistic use of many active sensors, although the maximum found for ordinary cumulus clouds was 1 g m^{-3}. However, Lawson and Blyth (1998) found a large variability. Nonetheless, this value is easily exceeded by systems with large vertical development, such as cumulonimbus, which can have values above 1.5 g m^{-3}.

Atmospheric remote sensing by weather radar is one of the most applicable methodologies for determining those quantities around the world, since the high cost of in situ measurements (e.g. aircraft) is limited to short periods for some specific regions of the world. Atlas (1954) and Donaldson (1955) were among the first to use active remote sensing to study cloud liquid water content and precipitation. Even so, according to Hagen and Yuter (2003), relationships between radar reflectivity and liquid water content (Z–LWC), a very useful type of parameterization, are not as frequently considered as Z–R relations (radar reflectivity (Z) and rain rate (R); Michaelides et al., 2009). Recently, Zhao et al. (2013) showed different relationships based on polarimetric variables to estimate the rainwater content, as well as the effects of attenuation on X-band radar retrievals, also described by Eccles and Mueller (1971). Meywerk et al. (2005) showed several techniques that allow the estimation of liquid water content, in addition to the synergy between the various collocated instruments. As reported by Ebell et al. (2010), the use of a ground-based radiometer may assist in the estimation performed by cloud radar. The use of passive microwave radiometers to estimate the integrated liquid water (ILW_C) for non-precipitating clouds has been widely applied (Peter and Kämpfer, 1992; Liljegren et al., 2001; Ware et al., 2003; Westwater et al., 2005; Mätzler and Morland, 2009; Karmakar et al., 2011). Following Crewell and Löhnert (2003), the accuracy of these ILW_C retrievals by radiometers can achieve 16 g m^{-2}, depending on the calibration and weather conditions (e.g. non-rainy events). Nonetheless, the major difficulty is the partitioning of cloud and rain water content within the same cloud. Based on studies of the polarization difference signal in raindrops performed by Czekala and Simmer (1998) and Czekala et al. (2001), Saavedra et al. (2012) found mean squared errors of 0.144 mm for cloud and 0.052 mm for rain liquid water content during precipitation events using active and passive sensors.

The goal of this study is to determine the water content of precipitating and non-precipitating clouds and the liquid water profiles for different cloud types and regions in Brazil. The data employed in this study were acquired during four field experiments throughout Brazil during the CHUVA[1] [*C*loud process of t*H*e main precipitation system in Brazil: a contrib*U*tion to cloud resol*V*ing Modeling *A*nd to the Global Precipitation Measurement (GPM, Smith et al., 2007)] project. This work discusses the main differences among the profiles of liquid water content and the corresponding integrated liquid water for the various precipitation regimes over the continental and coastal regions in tropical or subtropical latitudes. Also, this study discusses differences among measurements from different sensors and the limitations and errors associated with each type of measurement.

2. Data and methods

2.1. The CHUVA project

The field campaigns of CHUVA focused on understanding the radiative and microphysical processes of continental clouds over Brazil. For a detailed description of the CHUVA project see Machado et al. (in press). The CHUVA field experiments were conducted in different places with different weather patterns, using the same measurement strategy (described below) and instruments to study the precipitation regimes. During the experiments, polarimetric and vertically pointing radars, microwave radiometers, disdrometers, GPS, radiosondes and various other instruments were used. One of the main objectives was to minimize the uncertainties in satellite rainfall estimation as reported by Stephens and Kummerow (2007). Precipitation from warm clouds, based on scattering algorithms, is not retrieved. Besides, information about the atmospheric states as well as the cloud and precipitation structures is very important to improve precipitation estimation. The characterization of different rainy clouds in different regions of Brazil would assist the development or improvements of satellite-based rainfall estimation algorithms.

2.2. Measurement strategy

The data used in this study were obtained from field experiments of the CHUVA project, conducted between March 2010 and December 2011, over four regions of Brazil. Two experiments focused on the characterization of warm clouds, the first of which was performed in Alcântara in the state of Maranhão from March 3 to April 15, 2010, and the second of which was held in Fortaleza in the state of Ceará from April 4 to May 1, 2011. Both are located on the coast of Northeast Brazil. The third field experiment was conducted during the month of June in Belém, in the state of Pará in the North region of Brazil. From November 1 to December 21, 2011, the CHUVA project was held in Southeast Brazil in Vale do Paraíba in the state of São Paulo. Fig. 1 shows the geographical position of each field experiment in the CHUVA project. A schematic representation of the instrument distribution was described by Machado et al. (in press). This study uses the data from three sites, as described below:

- *Main site*: This site had instruments to measure clouds and rainfall in high temporal resolution. The following instruments were employed in this study: PARSIVEL (PARticle SIze and VELocity) and Joss–Waldvogel (JWD) disdrometers, tipping bucket rain gauges, MP-3000A microwave radiometer, LiDAR and Micro Rain Radar.
- *RADAR site*: X-band dual polarization radar was run with two scan strategies including a volume scan and Height Indicator Range (RHI) every 6–10 min. The latter was oriented over the

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[1] Meaning *rain* in Portuguese.