# Robust Observational Quantification of the Contribution of Mesoscale Convective Systems to Rainfall in the Tropics

R. ROCA AND J. AUBLANC

*Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France*

P. CHAMBON

*Centre National de la Recherche Météorologique–GAME, Météo-France and CNRS, Toulouse, France*

T. FIOLLEAU

*Centro Nacional de Monitoramento e Alertas de Desastres Naturais (CEMADEN), Cachoeira Paulista, São Paulo, Brazil*

N. VILTARD

*Laboratoire Atmosphères, Milieux, Observations Spatiales, UVSQ, IPSL/CNRS, Vélizy, France*

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ABSTRACT

Satellite estimation of precipitation and satellite-derived statistics of mesoscale convective systems (MCS) are analyzed conjunctively to quantify the contribution of the various types of MCS to the water budget of the tropics. This study focuses on two main mesoscale characteristics of the systems: duration and propagation. Overall, the systems lasting more than 12 h are shown to account for around 75% of the tropical rainfall, and 60% of the rainfall is due to systems traveling more than 250 km, a typical GCM grid. A number of regional features are also revealed by factoring in the convective systems' morphological parameters in the water budget computation. These findings support the challenging effort to account for such mesoscale features when considering the theory on the future evolution of the water budget as well as the physical parameterizations of climate models. Finally, this analysis provides a simple metric for evaluating high-resolution numerical simulations of the tropical water budget. Furthermore, results are shown to be robust to the selection of the satellite rainfall products.

## 1. Introduction

The water and energy cycle in intertropical regions is critical to the energy budget of Earth's climate and by consequence to its future evolution. Despite its importance, we still lack understanding of the underlying driving processes of the precipitation portion of the water budget (e.g., Sherwood et al. 2010). The radiative convective equilibrium theory seems to hold on a global scale and provide some guidance for the evolution of the planetary precipitation under increasing greenhouse gas concentrations (Stephens and Ellis 2008). Its applicability on a regional—in our case tropical—scale is nevertheless not fully warranted (Takahashi 2009). There are ongoing efforts to include large-scale dynamics in this theoretical framework (Chou and Neelin 2004; O'Gorman et al. 2011), but they have mitigated success when confronted with the recent climate observations of the Walker's circulation over the tropical Pacific Ocean (e.g., Sohn et al. 2013; Chadwick et al. 2013). Simple conceptual models of the interaction between deep convection and precipitation where precipitation is roughly the product of the mean convective mass flux by the mean boundary layer humidity have been proposed (e.g., Held and Soden 2006). While offering interesting thermodynamical scaling, these models are nevertheless likely to be too simple to accurately describe the processes operating in the tropics.

*Corresponding author address:* Dr. Rémy Roca, Observatoire Midi-Pyrénées, Laboratoire d'Etudes Géophysiques et d'Océanographie Spatiale, 14 Av Edouard Belin, 31000 Toulouse, France.
E-mail: roca@legos.obs-mip.fr

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In the tropics, deep convection occurs in a complex environment, where a number of mesoscale features (rear inflow, downdrafts, density currents, anvils, etc.) play an overwhelming role in determining the precipitation at the surface (e.g., Redelsperger 1997). The individual deep convective cells are embedded in organized mesoscale convective systems (MCS). An MCS typically scales between 100 and 1000 km and is composed of convective and stratiform cloudiness. An MCS usually shows a multihour life cycle composed of initiation, mature, and dissipation phases delineated through distinct thermodynamical, microphysical, dynamical, and precipitating states (Houze 1982). Depending on its large-scale environment, some of these MCS can remain stationary or can propagate over significant distance. The West African fast-moving, long-lasting squall lines that can travel thousands of kilometers are a well-known example of propagating systems (Desbois et al. 1988; Lafore and Moncrieff 1989). While there is a large body of literature on the MCS (Houze 2004; Tao and Moncrieff 2009), a thermodynamical and/or dynamical scaling of the MCS effect onto precipitation would be helpful to enrich the actual theoretical discussions. Such scaling is being explored in idealized climate change numerical experiments with focus on extreme rain rates (Muller et al. 2011). The main features of the systems are also tentatively incorporated into climate models (Grandpeix and Lafore 2010; Del Genio 2011; Mapes and Neale 2011). One additional difficulty for both idealized simulations and climate models is the propagation of the systems: in particular, across distances larger than the model grid cell. Recent work on this issue suggests that successful simulations of the propagation of MCS in a climate model is based on surrogate mechanisms (Pritchard et al. 2011) and confirms that accounting for these MCS features is a challenging effort (Moncrieff 2010; Roca et al. 2010b). Few, if any, observationally based studies are available to help guide the abovementioned modeling developments (Nesbitt et al. 2006). A number of regional investigations using observations have resulted in local estimations of the contribution of MCS to the precipitation often based on locally adapted definition of mesoscale convection (e.g., Laurent et al. 1998; Durkee et al. 2009). While these studies suggest that such developments are indeed likely to be worthwhile, still, a global perspective of the importance of these MCS to the water budget of the tropical regions has yet to emerge. How important are the long-lasting systems to the water budget? Are the propagating systems significant contributors to tropical precipitation? How does this contribution depend upon the duration and the propagation distance of the MCS?

In this short paper, we attempt to address these questions by quantifying the effects of the MCS on the precipitation budget over the intertropical belt by analyzing, in conjunction, satellite-derived mesoscale convective system statistics and satellite estimates of precipitation. The study focuses on two major characteristics of the MCS: duration and propagation distance as keen features of mesoscale organized convection. The paper is organized as follows: The data and methodology are reviewed in section 2. Section 3 presents the results of the investigation, and the findings are discussed in a final section of the manuscript.

## 2. Satellite data and methodology

### a. *Rainfall estimates*

Daily accumulated rainfall estimates from the Tropical Amount of Precipitation with an Estimation of Errors–Bayesian Rain Algorithm including Neural Networks (TAPEER–BRAIN) product are used for the period of June–September (JJAS) 2009. The TAPEER–BRAIN product is a multiplatform algorithm where instantaneous rain rates derived from microwave imagers are merged with the thermal infrared imagery from geostationary operational satellites (Chambon et al. 2013a). The microwave estimates are provided by the BRAIN retrievals (Viltard et al. 2006; Kirstetter et al. 2013; Kacimi et al. 2013). The same retrieval is applied on to the imagers of Advanced Microwave Scanning Radiometer (AMSR), Special Sensor Microwave Imager (SSM/I) from *F-15* and *F-16*, and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). Furthermore, full-resolution IR data are processed together with the BRAIN retrievals via a universally adjusted Geostationary Operational Environmental Satellite (GOES) precipitation index technique (Xu et al. 1999) to build the daily accumulation at the resolution of $1° \times 1°$ [see the algorithm theoretical basis document (ATBD) for more details; Chambon et al. 2012]. The 2009 configuration of the microwave imager constellation is good enough to ensure the performances of the $1° \mathrm{day}^{-1}$ product (Chambon et al. 2013b). The product has been compared extensively to rain gauges in West Africa and is shown to perform well over this tropical location (Chambon et al. 2013a), providing the same range of agreement as found with the TRMM Multisatellite Precipitation Analysis (TMPA) 3B42 version 6 (v6) products (Roca et al. 2010a). The present study has been replicated with the TMPA 3B42 v7 products (Huffman et al. 2007) and the Global Precipitation Climatology Project (GPCP) version 1.2 (v1.2) products (Huffman et al. 2001) as a mean of evaluating the sensitivity of the results, if any, to the selection of the satellite products. The absolute amount of rainfall slightly differs among the

TABLE 1. Statistics for rainfall and MCS occurrence and contribution to rainfall over the 30°S–30°N region during JJAS 2009 included for all regions (A), oceanic points (O), and land points (L).

| | Rainfall Mean (mm day$^{-1}$) | | | All MCS | | | | | | MCS with duration <15 h | | | | | | MCS with propagation >250 km | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Occurrence (%) | | | Rain fraction (%) | | | Occurrence (%) | | | Rain fraction (%) | | | Occurrence (%) | | | Rain fraction (%) | | |
| | A | O | L | A | O | L | A | O | L | A | O | L | A | O | L | A | O | L | A | O | L |
| TAPEER v1.0 | 3.1 | 3.3 | 2.5 | 34 | 32 | 39 | 93 | 93 | 92 | 22 | 19 | 30 | 40 | 36 | 54 | 15 | 15 | 15 | 53 | 53 | 50 |
| TMPA 3B42 v7.0 | 3.5 | 3.7 | 2.9 | | | | 92 | 92 | 94 | | | | 43 | 39 | 58 | | | | 49 | 50 | 47 |
| GPCP v1.2 | 3.2 | 3.4 | 2.9 | | | | 93 | 92 | 96 | | | | 45 | 41 | 57 | | | | 51 | 51 | 50 |

three products (Table 1). The results (based on the normalized distribution of daily rain accumulation) are shown to be insensitive to the products' differences.

The main features of the tropical climatology (monsoons, oceanic ITCZ, etc.) are easily spotted as well as the regional maxima of the Bay of Bengal and the Myanmar coast, with seasonal mean rain rates of around 20–25 mm day$^{-1}$ on the map of the TAPEER–BRAIN precipitation for summer 2009 (Fig. 1, top).

### *b. Mesoscale convective systems*

The morphology of MCS is here characterized by their duration (hours) and their distance of propagation (kilometers) from genesis to lysis. All of this information is readily derived from geostationary satellite infrared imagery and the use of a tracking algorithm. In the present study, the geostationary IR (geo-IR) dataset consists in full space/time-resolution thermal infrared measurements obtained from the operational fleet of geostationary satellites at work in summer 2009: *GOES-10*, *GOES-11*, *GOES-12*, *Meteosat-9*, *Meteosat-7*, and *Multifunctional Transport Satellite-1* (*MTSAT-1*). Quality control information and details about this dataset are described at length in Fiolleau and Roca (2013b). The identifying and tracking algorithm used here is the tracking of organized convection algorithm through 3D segmentation (TOOCAN) approach (Fiolleau and Roca 2013a). The TOOCAN method can be seen as an extension of the detect-and-spread technique (Boer and Ramanathan 1997; Roca and Ramanathan 2000; Roca et al. 2002) to three dimensions. Seeds of convective systems are identified within a volume of IR imagery (the image space and time) and are grown to the usual threshold limit of 235 K using a multiple step computation. This technique offers an improvement on former approaches usually based on overlap assumption between consecutive images to track the clusters through time. More specifically TOOCAN provides a better description of the MCS, starting earlier and ending later in the life cycle and preventing artificial mergers/splitters (Fiolleau and Roca 2013a).

### *c. Rationale for the cross analysis of the two databases*

Performing the joint analysis of the two databases requires pairing information of different natures: Eulerian for the rainfall and Lagrangian (or object oriented) for the MCS. To this end, we have regridded the MCS information on the 1° day$^{-1}$ grid. Using the full resolution segmented imagery, all the MCS cloud shields have been projected on the regular grid. The number of IR pixels of a given MCS over a grid box during the day is stored. The morphology parameters for up to 25 individual MCS are kept for each grid box. The statistics are then built accounting for each grid box and day, with the parameters of the system contributing most to a grid box defined as the system with the highest amount of IR pixels in the grid box. It is then possible to associate each 1° day$^{-1}$ grid to the morphology of the most representative system of that region that day. In practice, there are only few cases where more than one system provides significant and comparable contributions. The results shown below are not sensitive to this simplification. In the following, we refer to the morphology parameters of the most representative system simply as the morphology of the MCS. Note that it is possible that an MCS that contributes significantly to the cold cloudiness of a grid box contributes less significantly to daily accumulated precipitation.

Each grid box either did experience MCS activity, if some cold IR pixels were present, or did not if no cold cloud shield was encountered during the day over the degree. While only a third of the grid boxes population are flagged with such MCS activity (slightly more over land), it corresponds to 93% of the total rainfall (Table 1). Note that this overall fraction is not sensitive to the selected satellite rainfall products.

## 3. Results

### *a. Geographical distribution*

The MCS that last less than 15 h contribute between 40% and 45% to the total rain (36%–41% and 54%–58%

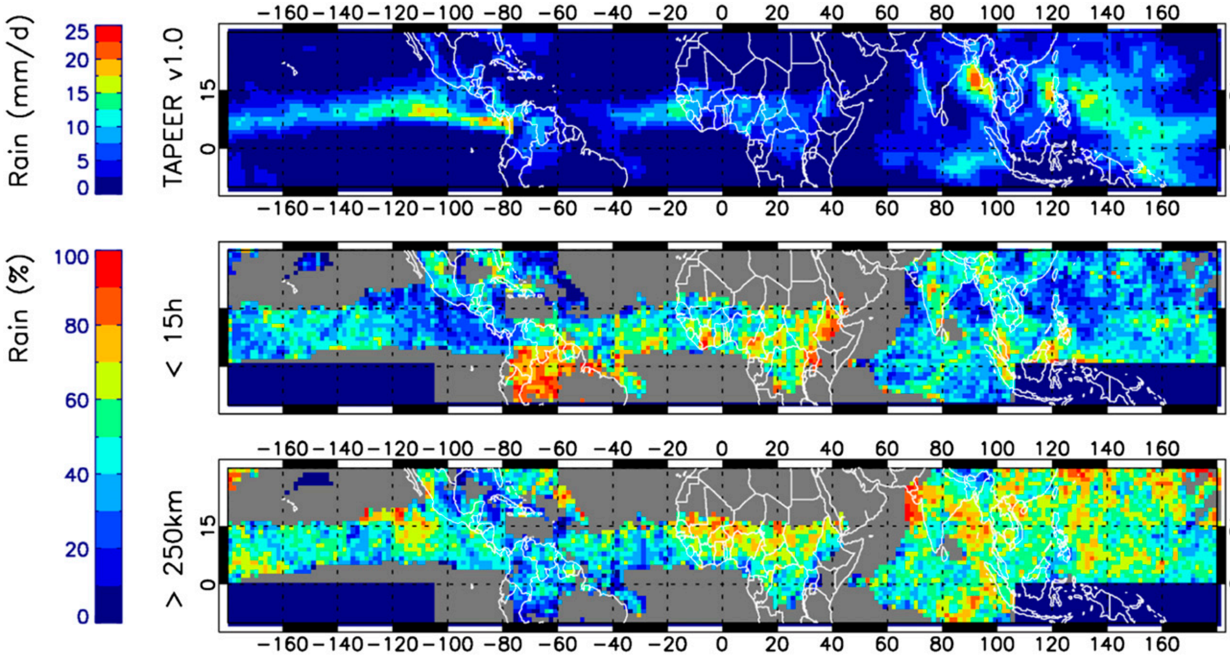


FIG. 1. (top) Seasonal mean daily rainfall (mm day$^{-1}$) for JJAS 2009. Fraction of the seasonal rainfall accumulation (%) resulting from (middle) the MCS with duration less than 15 h and (bottom) MCS propagating more than 250 km. In (middle) and (bottom), regions for which the seasonal rainfall accumulation is less than 1.5 mm day$^{-1}$ have been colored in gray for clarity. Note that no tracking data are available over the Southern Hemispheric sector of *GOES-11* (180°–108°W) since the 30-min IR images were not available to us at the time of processing. No tracking data are available over the Southern Hemispheric sector of *MTSAT-1* (108°E–180°) either because they are not acquired by the satellite. See Fiolleau and Roca (2013b) for more details on the geostationary imagery. These regions have been colored in dark blue.

over ocean and land, respectively), depending upon the satellite rainfall products (Table 1). The systems propagating more than 250 km yield 49%–53%, with a similar contribution over land and over ocean. Furthermore, the contribution of the short-lived systems is characterized by strong regional variations (Fig. 1). Over the Amazon–north Brazil region, these systems account for a large portion (>80%) of the rain that is consistent with the MCS duration distribution there, which is skewed toward a short lifetime compared to other tropical regions (e.g., Machado and Laurent 2004). Similarly, rainfall from the East African Rift region is mainly due to these short-lived storms, which are very frequent in this area (Jackson et al. 2009). These short-lived systems also contribute significantly to the totals of the coastal regions of West Africa, which is consistent with the distribution of the MCS population (Fiolleau et al. 2009). On the contrary, no particular oceanic region stands out of the analysis and overall the short systems do not seem to contribute heavily to the oceanic rains. The propagating systems contribute strongly to the rainfall accumulation over the Sahel as found in previous local studies in Niamey, Niger (Mathon et al. 2002). These traveling systems provide only a weak contribution to the Brazilian rains. Over the Bay of Bengal, as well as over large part of the Indian continent, the propagating systems contribute largely to the seasonal amount of precipitation. Over the eastern Pacific, at the core to the ITCZ, these propagating systems are the main contributors to rain accumulation. This is not as clear over the western Pacific sector, where propagating systems exhibit a wide range of contributions, even if it can be locally large.

### b. *Contribution to the water budget*

Figure 2 presents the cumulated distribution functions of the total MCS precipitation for various MCS durations and propagation distances. The systems that last less than 12 h only contribute to an overall 25% of the precipitation totals when considering the TAPEER product. Around 80% (75%) of the MCS (total) rainfall can be accounted for by the systems lasting up to 24 h. A few systems lasting more than 1 day provide a significant 20% of the tropical amount of rain resulting from MCS. Note that when land only is considered a slight shift of the distribution is observed (90% of the rain resulting from systems lasting up to 24 h) that express the slight shift of the system duration toward shorter life cycle over land compared to the

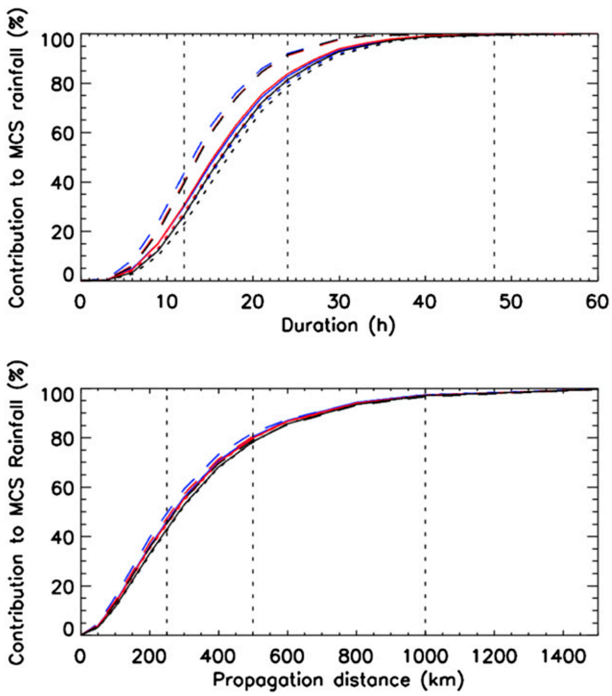


FIG. 2. Cumulated distribution function of tropical precipitation amount (%) as a function of (top) the MCS duration in hours and (bottom) propagation distance in kilometers. The solid line is for all of the 30°S–30°N region, the long dashed line is for the continent, and the dotted line is for oceanic conditions. TAPEER version 1.0 (v1.0) is in black, TMPA 3B42 v7.0 is in blue, and GPCP v1.2 is in red. The vertical short dashed lines represent 12-, 24-, and 48-h marks in (top) and 250-, 500-, and 1000-km marks in (bottom).

ocean as anticipated from the sustainability concept (Yuter and Houze 1998).

The stationary systems that travel less than 250 km (a typical GCM grid box) overall contribute to roughly 50% (60%) of the MCS (total) rainfall. The systems propagating up to 500 km contribute up to 80% of the MCS precipitation. A very small fraction of the rain is contributed by the systems crossing more than 1000 km during their life cycle. Note that, unlike for duration, no significant difference between land and oceanic conditions is observed. Acknowledging the vertical tropospheric shear as a key element for mesoscale systems to propagate in the tropics (e.g., Moncrieff 1992), no obvious land and/or ocean dependency is indeed expected.

Figure 2 also reveals the already mentioned (Table 1) robustness of our results for the selection of the satellite products.

## 4. Discussion

Cross analysis of the Lagrangian (or object oriented) MCS database, together with the Eulerian, gridded satellite estimation of precipitation has been performed using 4 months of data that dealt with more than 160 000 systems. The study reveals a number of regional features that stand out during the analysis when the duration of the mesoscale convective systems or its distance of propagation is factored in the water budget computation. Overall, the systems lasting more than 12 h account for 75% of the tropical rainfall and the systems traveling more than 250 km account for 60%. Sound differences in the contribution of the short-lived systems between land and sea have been shown to be in line with the expected boundary layer moisture and energy supply difference between land and sea environments. These results are robust to the selection of the rainfall products, but the uncertainties in rainfall estimation remain to be characterized in more detail.

These results have consequences at various levels. On the water and energy cycle theoretical front, unlike global precipitation, the lack of energetic controls at the regional scale makes it difficult for simple scaling arguments to describe the observational record. The present analysis provides useful data to scale the precipitation accounting for the various underlying categories of MCS (propagating or stationary, long or short lived, etc.). Concerning the climate model and convective parameterization problem, the scale separation paradigm makes it difficult to account for propagating systems in a simple manner. Evaluation of climate models can benefit from our study by separating the rainfall induced by unrepresented propagating systems and the rainfall due to more stationary/local convective systems. Such an approach provides more physically sound comparisons between observations and simulations (Sane et al. 2012). Finally, large-domain cloud-resolving model simulations are becoming more readily available and exhibit realistic detailed morphological features of MCS (Beucher et al. 2014; Hagos et al. 2013). Our study provides a simple metric that could be replicated on these simulations in order to validate the contribution of the various MCS flavors to the simulated water budget.

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