A Simple Model of the Life Cycle of Mesoscale Convective Systems
Cloud Shield in the Tropics

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ABSTRACT

Mesoscale convective systems (MCSs) are important to the water and energy budget of the tropical climate and are essential ingredients of the tropical circulation. MCSs are readily observed in satellite infrared geostationary imagery as cloud clusters that evolve in time from small structures to well-organized large patches of cloud shield before dissipating. The MCS cloud shield is the result of a large ensemble of mesoscale dynamical, thermodynamical, and microphysical processes. This study shows that a simple parametric model can summarize the time evolution of the morphological characteristics of the cloud shield during the life cycle of the MCS. It consists of a growth–decay linear model of the cloud shield and is based on three parameters: the time of maximum extent, the maximum extent, and the duration of the MCS. It is shown that the time of maximum is frequently close to the middle of the life cycle and that the correlation between maximum extent and duration is strong all over the tropics. This suggests that 1 degree of freedom is left to summarize the life cycle of the MCS cloud shield. Such a model fits the observed MCS equally well, independent of the duration, size, location, and propagation characteristics, and its relevance is assessed for a large number of MCSs over three boreal summer periods over the whole tropical belt. The scaling of this simple model exhibits weak (strong) regional variability for the short- (long-) lived systems indicative of the primary importance of the internal dynamics of the systems to the large-scale environment for MCS sustainability.

1. Introduction

Mesoscale convective systems (MCSs) in the tropics connect the low atmospheric levels to the free troposphere, through the vertical transport of mass, water, and momentum. Their extended upper-level cloud decks have a strong impact on the tropical radiative budget (e.g., Ramanathan and Collins 1991; Machado and Rossow 1993; Wilcox and Ramanathan 2001; Del Genio and Kovari 2002; Roca et al. 2005b; Del Genio et al. 2005). These convective systems also dominate the water budget of the intertropical belt by producing most of the rainfall accumulation (Roca et al. 2014). The vertical distribution of net heating and momentum associated with the systems influences the tropical large-scale circulation (e.g., Schumacher et al. 2004) as well as its variability at different time scales (e.g., Mapes 1993; Seo and Son 2012).

Owing to their central role in the tropical energy and water budget, the study of MCS benefited from a large corpus of previous research efforts using campaign measurements [e.g., GATE, Monsoon Experiment (MONEX), TOGA COARE, the TRMM Large-Scale Biosphere–Atmosphere Experiment in Amazonia (TRMM-LBA), and DYNAMO], satellite observations, and model developments that have been synthetized in many reviews (e.g., Houze and Betts 1981; Houze 1982; Redelsperger 1997; Houze 2004; Houze et al. 2015). From these efforts emerged a well-accepted conceptual model of the MCS internal dynamics and a stage model that describes the time evolution of these components of a MCS and of its upper-level cloud shield. The MCS cloud shield envelops a convective core, a stratiform rain anvil region, and a nonprecipitating stratiform anvil region. The convective core is characterized by intense rainfall, prevailing strong ascending motions, and a convective-scale circulation. The larger stratiform rain anvil part is...
characterized by less intense rainfall, mesoscale circulations, and one order of magnitude weaker vertical motions compared to the convective region (Houze 1997). The nonprecipitating stratiform anvil is composed of ice particles aloft and mixed phase depending on its depth (Li and Schumacher 2011). The convective–stratiform fraction evolves along the MCS life cycle, bringing and removing condensates aloft and allowing for a well identified and consistent life cycle of the upper-level cold cloud shield of the MCS readily observed in the geostationary satellite imagery. Following Houze (1982), the life cycle of the MCS, and of its cloud shield, can be schematically summarized in three phases:

- First, during the initiation phase, individual deep convective cells are triggered and bring the condensate aloft.
- Second, deep convection cells still exist, and the stratiform anvil and associated mesoscale circulation builds up. The stratiform precipitating anvil is composed of cloud material originating from previously active deep convective cells. The condensate is removed from the upper level via precipitation. It is usually referred to as the mature phase of the MCS life cycle.
- Finally, deep convection stops, and the anvil cloud fades out during the so-called dissipation phase, where eventually stratiform rain also stops, and the remnant anvil dissipates on a longer time scale. Microphysical processes influence the evolution of the cloud particles and constrain their dissipation time scale and/or terminal fall velocity.

The factors controlling the time evolution of the characteristics of the cloud shield hence span a large variety of scales, including processes ranging from convective scales to mesoscales and microphysical aspects. These factors depend on the internal dynamics and organization of the MCS and exhibits sensitivity to the large-scale thermodynamical and dynamical environment in which they occur and which is thought to vary widely across the tropics (Del Genio et al. 2012). The time evolution of the spatial extent of the cloud shield results from the complex interplay of these processes. Nevertheless, at the life cycle scale, the cloud shield exhibits significant consistency and a number of simple features that have been highlighted over various regions of the world. McAnelly and Cotton (1989) composited a mesoscale convective complexes cloud shield over the central United States that exhibits linear and symmetrical patterns of a growing and decaying life cycle. Machado and Laurent (2004) showed simple patterns of MCS cloud-shield evolution of smoothly growing and decaying shield for a subset of MCSs with no splits or merge events over Amazonia. Kondo et al. (2006) also show the symmetrical cloud-shield life cycle over the western Pacific and the Maritime Continent for another class of MCS. A few studies have attempted to provide tropical wide statistics of MCS characteristics. Machado and Rossow (1993) focused on the radiative properties of the clusters. Tsakraklides and Evans (2003) summarize the diurnal cycle of various MCS subcategories. A number of studies explore the relationship between MCS duration and precipitation (Liu 2011; Roca et al. 2014; Esmaili et al. 2016). Fiolleau and Roca (2013b) focused on the precipitation life cycle of MCSs and identified a symmetrical time evolution of the MCS cold cloud shields, although it is not quantified any further. A tropical wide homogeneous perspective on the MCS cloud-shield life cycle is nevertheless lacking.

The main objective of the present study is hence to fill this gap and to establish the robustness of these previously highlighted regional features of the life cycle of the cold cloud shield for a large population of MCSs at the tropical wide scale: (i) Are the MCS cloud shields growing and decaying or revealing more complex time evolution of their upper cloud decks? (ii) Is this time evolution linear? (iii) Is such a simple pattern relevant for any type of MCS (independent of their size, duration, and propagation characteristics)? (iv) What fraction of the MCS is concerned; is it a subset of the MCS? (v) If there is any such pattern, does it exhibit regional variability?

Similarly, at larger scales, high correlation is observed between the morphological parameters of the systems (maximum cluster size and MCS duration). It indicates that the largest cloud shields are associated with long-lasting mesoscale convection that injects enough water condensate in the upper levels during enough time to allow the growth of the shield to its largest value [Houze (2004) and references therein]. This relationship is reported over the warm pool (e.g., Chen and Houze 1997), over the Bay of Bengal (Zuidema 2003), over equatorial Africa (Laing et al. 2011), and over the continental United States (Feng et al. 2012). The other objective of this study is to assess at the tropical scale such a relationship and document, if any, its regional variability.

A secondary objective of the study is to provide a simple statistical tool to ease the future exploration of both the dynamics of the convective, stratiform, and nonprecipitating part of the storm along the life cycle of the MCS using compositing techniques (Kondo et al. 2006; Futyan and Del Genio 2007; Fiolleau and Roca 2013b; Bouniol et al. 2016), including the relationship of the simple statistical model parameters with the large-scale environment of the MCS.

To fulfill these objectives, a homogeneous processing of the geostationary satellite fleet infrared imagery...
with a recently developed tracking technique is performed to document the time evolution of the cold cloud shield of MCS over the entire tropics. The analysis of these observations is performed through the elaboration of a simple parametric model for the time evolution of the cold cloud shield of MCS. The satellite data we used are presented. Then in section 3 the statistical model is introduced, and its relevance is discussed in detail. Section 4 further simplifies the parametric model by investigating the correlation among the morphological parameters of the systems. A discussion and conclusions section ends the paper.

2. Data and method

a. Infrared geostationary imagery

Thermal channel brightness temperature (BT) images obtained by the operational meteorological geostationary satellite fleet at full space and time resolution are used over the 30°S–30°N latitude belt during the boreal summer months of June–September. Three years of data have been processed: 2012, 2013, and 2014. Table 1 summarizes the characteristics of the data. The satellite fleet exhibits a relatively high degree of homogeneity with spectrally similar window channels, similar temporal resolution, and slight variability in the spatial resolution of the captors during our period of interest. Overall, the availability of the data exceeds around 90% of the time with the highest availability for the Meteosat Second Generation-2 (MSG-2) and the lowest for the Multi-functional Transport Satellite-2 (MTSAT-2). Meteosat-7 is impacted during the boreal summer by solar eclipses, and data are not disseminated during a couple of hours daily from early August to mid-September explaining the lower statistics when interruptions are considered. The overall availability of the data is well suited to document the deep cloudiness in the tropical regions.

b. Mesoscale convective systems

**DEFINITION**

Mesoscale convective systems correspond to the aggregation of numerous individual convective storms for which the storm anvils merge in a single cirriform cloud shield (Redelsperger 1997). The organization of convection within the MCS can take a large variety of shapes, making it delicate to classify from the resulting cloud shield. As a consequence, previous studies have proposed numerous definitions and terminology for these systems or for a subset of the whole population [see review in Fiolleau and Roca (2013a) and references therein]. Some of these definitions are based on the use of multiple criteria based on thresholds applied to the size, duration, and depth of the cold cloud shield readily computable from the IR imagery. On the other hand, radar-based nomenclature often requires a continuous precipitation area to be reached at some point in the life cycle, generally corresponding to the mature phase of the system, with a typical dimension of 100 km in order to account for the setup of an associated mesoscale circulation (Houze 2004). Any area estimate depends upon the threshold used to delineate it and can express significant sensitivity to small variations of the threshold in IR imagery (Machado et al. 1992) or radar data (Guilloteau et al. 2016). In the following, we refer rather loosely to MCSs as a cloud object defined by a cluster continuous in space and time. We do not enforce any size-based criteria since the systems of interest here do reach out to large dimensions at some point in their life cycle (see section 3).

**Selection of the infrared threshold**

The upper-level cloudiness is here defined with an arbitrary threshold of 235 K, commonly used to define upper cold cloud in the tropics from infrared thermal...
imagery (Duvel 1989). This includes deep convective and precipitating stratiform regions as well as non-precipitating anvils (Liu et al. 2007). The use of colder and warmer thresholds has been also reported in the literature. The use of colder thresholds prevents including the whole stratiform anvil (both precipitating and nonprecipitating), while warmer thresholds can add unrelated midlevel cloudiness to the convective cluster (Sherwood and Wahrlich 1999; Yuan et al. 2011). The 235-K threshold is hence considered as the best compromise to characterize the MCS cloud shield (Bouniol et al. 2016). A sensitivity study (not shown) to the threshold selection using 225- and 245-K values showed that the findings and conclusions of this study are fully robust to this choice. Hence, in the following, any pixel with BT colder or equal to 235 K is considered to belong to a cold space–time cluster.

c. Tracking of the cloud systems

1) METHOD

The attribution of these cold pixels to various individual convective systems is performed by applying the recently developed technique named tracking of organized convection algorithm using a 3D segmentation (TOOCAN) on the thresholded images. This method is described at length in Fiolleau and Roca (2013a), and here only a short summary is provided to highlight its salient features. Former approaches for convective systems identification and tracking are based on, first, a cluster delineation using a thresholded image and, second, overlapping statistics to track the clusters in time (Williams and Houze 1987; Mathon and Laurent 2001). Unlike these techniques, TOOCAN operates in the infrared “volume” (space and time). First, seeds are identified at a cold threshold and grown via successive dilatation operations thanks to a 10-connectivity operator (8 pixels in space and 2 in time) to a warmer BT value. This process is repeated until each of the pixels colder than 235 K is associated to an individual system. This multistep, multithreshold technique can be seen as a 3D extension of the detection and spread approach (Boer and Ramanathan 1997). Compared to previous approaches based on the overlap technique, the TOOCAN approach yields to smoother evolution of the size of the cloud shield of the system along its life cycle mainly because of the suppression of the split or merge artifacts (Fiolleau and Roca 2013a).

2) IMPLEMENTATION ASPECTS

The tracking is performed separately for each geostationary platform over wide longitudinal areas to minimize edge effects, and only a restricted useful area is kept for the analysis (Table 1). The lack of homogeneity of the geostationary fleet spatial and temporal resolution (Table 1) over the tropical belt is accounted for by performing the tracking: (i) with 30-min resolution for MSG satellites to avoid oversegmentation as a result of the original 15-min resolution compared to other platforms and (ii) with a pixel-resolution-independent configuration for the seeds identification. Note that the scanning pattern of MTSAT-2 does not provide half-hourly sampling of the Southern Hemisphere region, and, as a consequence, in order to avoid inhomogeneity with other satellites, this region is not considered in the study.

For up to five consecutive missing or low-quality images in the time series, images are replicated, and the tracking is performed nominally. If more than five consecutive images are missing the tracking is stopped, and a fresh start is operated at the end of the interruption. The interrupted systems as well as the one initiated from a fresh start are flagged. In practice, the interruptions concern mainly the Meteosat-7 satellite during the eclipses (Table 1). In the following, these flagged systems are removed from the statistics.

3) CLASSIFICATION OF THE CLOUD SYSTEMS

Like other tracking algorithms TOOCAN gives access to various morphological parameters of the cloud system integrated life cycle like the location and time of genesis or lysis, the duration of the system, the overall propagation distance, the maximum size reached, the timing of this maximum size within the life cycle, etc. These integrated parameters are derived from the raw tracking algorithm data, which document, with a resolution of 30 min along the life cycle, the trajectory of the cloud cluster centroid, the size of the cloud cluster of the system, and a suite of elaborated statistics like the brightness temperature distribution and other morphological parameters that are not all used here.

To permit the comparison among the cloud systems with different life duration, all the time-resolved properties of the system are normalized with respect to the life duration, leading to a life cycle index based on 10 stages ranging from 0% to 100% of the life cycle. Such a normalization approach has already been used in various forms (e.g., McAnelly and Cotton 1989; Fiolleau and Roca 2013b). Note that, in the following, for sake of simplicity, the terminology “the life cycle of the MCS” will be used in place of “the duration-normalized life cycle of the cold cloud shield of the MCS as defined by the TOOCAN algorithm.”

Three classes of systems are introduced following Fiolleau and Roca (2013b). Owing to the normalization procedure (10 half-hourly steps), only the systems with duration longer than 10 images every 5 h are considered for further classification. The systems shorter than 5 h
are labeled as class 1. The remaining population is further split into two classes depending on the occurrence of a single maximum in the time evolution of the system’s shield extension. Such an approach permits us to filter the systems with complex shield life cycle, including regeneration, or a long plateau, etc., which are labeled class 2b. The remaining systems are hence defined to exhibit a single growing phase followed by a single decaying phase and are labeled class 2a. Note that, while both class 2a and 2b systems last longer than 5 h, no upper limit on system duration is introduced. The application of such classification is principally an outcome of the TOOCAN results that provide a smooth enough life cycle to grant such an approach. Applying the present classification onto the results of other algorithms is nevertheless possible at the cost of heavy filtering out of the systems with split and merged events and associated loss of representative statistics (Fiolleau and Roca 2013b).

d. The population of MCSs in the tropics

The maps of mean seasonal cold cloud cover and occurrence of all the cloud systems (Fig. 1) exhibit the well-known features of the boreal summer climate of the tropics. The present results are overall in line with previous atlases of MCSs, based on other definitions, algorithms, and satellite observations, either from local (Fiolleau et al. 2009) or global studies (e.g., Mohr and Zipser 1996; Liu et al. 2007). The maxima of occurrence of the MCSs correspond generally with the region with high cold cloudiness. Over the Atlantic Ocean, a very zonal and homogeneous structure spread from the Guinean coast up to 40°W (Machado et al. 1992). Over the Indian Ocean, three distinct well-known features are seen: the local maximum is located on the western flank of the Ghats, the Bay of Bengal exhibits a large number of MCSs occurring on its eastern coast (Zuidema 2003), and the open ocean shows a broad region, mainly zonally structured corresponding to the ITCZ (Roca and Ramanathan 2000). On the continent, the MCSs and rainfall distributions show the classical monsoon features: the West African rain and systems belt does not extend farther north to 17.5°N, and the Indian Ocean pattern reaches up to the foot of the Himalayas around 27.5°N. The strong link between orography and MCSs is also well observed with local maxima over the Guinean mountains, Mount Cameroon, and the Ethiopian Plateau for West Africa. Only a few systems are found on the eastern side of the Great Rift range (Jackson et al. 2009). The MCSs are also found numerous over the western half of the Maritime Continent (Williams and Houze 1987) with occurrence similar to that of Southeast Asia and the Philippines. The eastern Pacific ITCZ also shows a large population of MCSs.

The distribution of the MCS duration over the tropics is lognormal (Fig. 2). The mode of the PDF is between 4 and 5 h. Systems are overall more frequent over ocean than over land. Land-based systems are, on average, a bit shorter (8 vs 9 h) than over the oceans. Systems can last up to 50 h over land, although the systems longer than 36 h are very infrequent. Oceanic systems can last longer than over land, up to 70 h. These results suggest that very long systems (~150 h) are not found with the present tracking technique and that this previously noted extreme population could be an artifact of the previous overlap-single-threshold tracking technique (Fiolleau and Roca 2013b) and the use of 3-hourly observations in previous studies (e.g., Machado et al. 1992; Gambheer and Bhat 2000). While the short systems dominate the occurrence statistics, their contribution to the total cold cloud cover is not overwhelming. For instance, the systems with duration up to 12 h correspond

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**Fig. 1.** (top) Seasonal mean cold cloudiness (%) and (bottom) seasonal mean number of MCSs averaged over 2012, 2013, and 2014.
to 80% of the occurrence of the systems (Fig. 2b) but only to 40% of the cold cloud cover (Fig. 2c). Similarly, the systems lasting more than 24 h only represent 5% of the cold cloudiness while they hardly account for the total number of systems. Similar scaling is also evident in rainfall (Roca et al. 2014).

The maximum extent statistics indicates that, while systems can reach up to $1.4 \times 10^6$ km$^2$, they are mainly characterized by a maximum area between $1 \times 10^3$ and $2 \times 10^5$ km$^2$ (Fig. 2d). When contribution to the cold cloudiness is factored in, the systems below 5000 km$^2$, corresponding to a typical scale of about 100 km, represent only a small fraction of the total. Indeed 97% of the cold cloudiness is associated to systems with the maximum attained size $S_{\text{max}}$ larger than 5000 km$^2$. The CDFs are similar over land and ocean.

The overall statistics of occurrence and of contribution to the cold cloudiness for the tropics indicates that, while numerous, the class 1 systems hardly contribute to the cold cloudiness (Table 2). The class 2a systems account for around 13% of the population and account for around 13% of the total cold cloudiness. The class 2a systems account for 60% of the population but 84% of the cloudiness. Similar results hold for land and oceanic regions separately. Class 1 systems are found ubiquitously over the tropical continents with enhanced population in East Africa and along the Burma coasts (Fig. 3). The frontier between the regions observed by Meteosat-7 and MTSAT-2 can be guessed on the occurrence map of the class 1 systems, which are the systems that are more affected by the eclipses. The class 2a systems map indeed shows no such dependency. As expected, locations of class 2a systems follow that of the cold cloudiness and highlight the same climatological features. The class 2b systems are found in the same regions as the class 2a systems but less frequently.

The geographical distribution of the relative contribution to the cold cloudiness (Fig. 4) confirms these integrated statistics and further reveals no local dependency of the overall respective role of each class. Since 84% of the upper cloudiness is due to class 2a
systems that are characterized by a simple growth–decay time evolution of the cloud-shield extension, a simple parametric model is introduced, and only class 2a systems are further analyzed.

3. A simple model of the life cycle of the mesoscale convective systems cloud shield

a. A growth–decay model

TIME OF MAXIMUM IN SIZE

The first parameter characterizing the growth–decay model is the moment within the entire life cycle at which the maximum extension of the cloud shield is reached. The time of maximum extent will be denoted as $T_{\text{max}}$ in the following and expressed in percent of the system’s duration.

(i) Overall statistics and dependency on various MCS characteristics

The $T_{\text{max}}$ is distributed normally with an average value of 52% and a 10% standard deviation (Fig. 5). Oceanic and continental systems exhibit the same distribution. The analysis of the $T_{\text{max}}$ dependency upon the various MCS characteristics reveals no particular tendency for $T_{\text{max}}$ to vary along with the duration of the system, the maximum extent, or with their propagation distance (Fig. 6). A very small trend is seen nevertheless in the standard deviation of $T_{\text{max}}$ with the systems reaching larger maximum extension exhibiting a slightly narrower distribution than the one reaching small extension. The geographical distribution of the local mean $T_{\text{max}}$ (Fig. 7) further reveals no obvious dependency of the distribution of this parameter. Overall, the analysis indicates that most of the systems over the tropical belt are characterized by a strong symmetry in the time evolution of their cold cloud-shield area.

(ii) Discussion

The heavy symmetry in the IR cold cloud-shield evolution revealed here at the entire tropical belt–scale appears to be independent from the details of the tracking algorithm (Fiolleau and Roca 2013b). This has also been previously noted in other parts of the world. Over Amazonia, MCSs observed from GOES data also exhibit a symmetrical life cycle of the cold cloud shield (Machado and Laurent 2004). McAnelly and Cotton (1989) studied

### Table 2. Mean Seasonal statistics for 2012, 2013, and 2014.

<table>
<thead>
<tr>
<th>Contribution to the total occurrence (%)</th>
<th>Contribution to the total cold cloudiness (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Land</td>
</tr>
<tr>
<td>No.</td>
<td>884 063</td>
</tr>
<tr>
<td>Class 1</td>
<td>27</td>
</tr>
<tr>
<td>Class 2a</td>
<td>60</td>
</tr>
<tr>
<td>Class 2b</td>
<td>13</td>
</tr>
</tbody>
</table>

**Fig. 3.** Seasonal mean fraction of the time with (top) class 1, (middle) class 2a, and (bottom) class 2b systems averaged over 2012, 2013, and 2014.
the mesoscale convective complexes (MCCs) over the central United States, and their average composite life cycle of these MCCs at 240 K exhibits strong symmetry. Similarly, Sherwood and Wahrlich’s (1999) analysis of the warm pool systems indicates rather symmetrical cold cloud-shield evolution along the life cycle of the averaged system using 235 K as a threshold. The reasons for having growth and decay phases of the MCS size with similar duration are not obvious. It is primarily a characteristic associated with the 235-K threshold and the corresponding cloud underlying microphysics. It is likely that inclusion of a larger amount of nonprecipitating cirrus cloudiness in the delineation of the MCS edges, by growing the cloud shield to a much warmer threshold, for instance, would modify the probability distribution function of the cluster extension (e.g., Roca et al. 2002) and by consequence the time evolution of the full upper-level cloudiness because of the MCSs (Sherwood and Wahrlich 1999). Extending the cloud cluster to a much warmer threshold is nevertheless not straightforward and can yield to misclassification of some low- or midlevel cloudy pixels as upper-level thin cirrus (Yuan et al. 2011; Sèze et al. 2015). The lack of dependency of the symmetry to the location and characteristics of the MCS points to the convective system’s internal dynamics as a prime explanation for it rather than environmental conditions.

b. Linearity of the growth–decay model

Previous investigations of the time evolution of the areal extent of the cold cloud shield of tropical MCSs have relied upon a variety of shapes to characterize the growth and decay of the cloud shield ranging from third- and fourth-order (Feng et al. 2012) to sixth-order polynomial fit (Futyan and Del Genio 2007) and second-order (Machado and Laurent 2004; Vila et al. 2008) or linear fit (McAnelly and Cotton 1989). In the following, the relevance of using a linear implementation of the growth–decay model is quantitatively assessed.

1) THE LINEAR MODEL

(i) Construction

The normalized linear growth–decay (LGD) model is constructed for each system based on the time of maximum. It is composed of a linear growth from a null size

![Fig. 4. Seasonal mean of the relative contribution to cold cloudiness for (top) class 1, (middle) class 2a, and (bottom) class 2b systems averaged over 2012, 2013, and 2014.](image)

![Fig. 5. Distribution of the time of maximum (%) for the class 2a system for the entire tropical belt (solid), continent (short dashed), and ocean (long dashed).](image)
at the beginning of the life cycle of the system to a size of 1 at the time of maximum is used, followed by a linear decrease toward a null size at the end of the system. The linear model is discretized over 10 steps in a similar way to the observed life cycle.

(i) Examples

Figure 8 exemplifies the relevance of the LGD model for a few actual cases, ranging from well fit to loosely linear time evolution of the cloud shield. The root-mean-square difference (RMSD) between the actual MCS life cycle and the ones predicted by the LGD model quantifies this agreement and is reported for the examples. In the lower range (RMSD < 0.06), the LGD clearly appears to be well suited to describe the time evolution of the cold cloud shield for various MCS durations and maximum extents. In the midrange (0.06 < RMSD < 0.15), one can still see some linearly evolving cloud shields, although the match with the model is not as strong. Finally, when RMSD (RMSD > 0.15) increases, the departure from a linear model can be substantial, as shown in Fig. 8, bottom. At the scale of the intertropical belt, RMSD varies between 0.02 and 0.44. The mean value is 0.12, and the mode of the PDF is around 0.1. More than 80% of the MCS population is characterized with an RMSD less than 0.15 (Fig. 9), a value indicative of a reasonable agreement between the observations and the model. It corresponds to 81% of the class 2a cold cloudiness. A similar result holds when land and oceanic systems are considered separately.

2) Parametric Relevance

(i) Dependency upon various MCS morphological characteristics

The analysis of the RMSD distribution shows little to no dependencies on the MCS main morphological characteristics. The relevance of the LGD model is not restricted to any particular subset of systems. A slight increase of the RMSD as a function of duration is nevertheless observed (Fig. 10a). Land-based systems lasting more than 20 h exhibit a stronger increase in RMSD with duration than oceanic systems. While statistically significant, this trend is well within a single standard deviation of the sample. Hence, the assessment of the lesser goodness of fit of the linear model for long-lived land systems compared to the oceanic regions is still difficult and deserves further scrutiny. Similarly, the systems with the largest maximum extent seem to be relatively slightly less well fit with the LGD model, although this concerns few systems. The LGD model agreement with the data also reveals a tendency to slightly worsen as the system propagation distance increases.
increases. No difference is observed between oceanic and land systems (Fig. 10).

(ii) Growing and decaying phase

To further show that the overall LGD model relevance does not arise from a spurious behavior, the RMSD is now computed over each growing and decaying phase separately. Figure 11 shows the resulting statistics for all the systems with $T_{\text{max}}$ greater than 20% and lower than 70% owing to the distribution of $T_{\text{max}}$ (see section 3) and the lack of cases for the extreme $T_{\text{max}}$ value. Again, the computations indicate no significant dependency of the model behavior. The longest relative duration of each phase, with $T_{\text{max}}$ between 20% and 30% for the decaying phase (between 70% and 80% for the growing phase), exhibit a not as good agreement between the model and the observations.

In summary, once properly normalized, it is hence possible to describe the full life cycle of the most important system category, with a simple linear growth–decay model characterized by three parameters: $T_{\text{max}}$, $S_{\text{max}}$, and duration. The growing phase corresponds to an increasing stratiform region fed by active convective cells with lifetime larger than the stratiform materials dissipation rate. Conversely, the decaying phase is characterized by a faster dissipation of the MCS stratiform elements than the new active convection is able to cope with. Hence, under these assumptions, the whole time evolution of the MCS cloudiness is fully determined by three parameters: the duration of the MCS, $S_{\text{max}}$, and $T_{\text{max}}$. The duration of the MCS and the maximum extent are linked to the sustainability of the environment in which the MCS occurs (Houze 2004). Assuming linear growth–decay in the relative time frame (0%–100%) further means that the rate of stratiform materials “replacement” is constant in each phase. This model is considerably simpler than the various conceptual models of MCS that typically include initiation, intensification, mature, and dissipation phases with various evolution rates. Unlike the more elaborated description of the MCS life stages, usually based

![Fig. 8. Examples of time evolution of the size of the cloud shield for the class 2a systems. Various RMSDs, durations, and maximum sizes are considered. The thin line is the actual cloud shield data, and the thick line corresponds to the linear model. See text for details.](http://example.com/fig8.png)

![Fig. 9. CDF of the root-mean-square error between the observed class 2a MCS size evolution and the linear growth–decay model prediction for the entire tropical belt (solid), continent (short dashed), and ocean (long dashed).](http://example.com/fig9.png)
on the internal dynamics and moist processes in the system, the present one aims at characterizing the time evolution of the cold cloud shield. It does not preclude from incorporating a more detailed description of the precipitation life cycle of the MCS (e.g., Futyan and Del Genio 2007; Fiolleau and Roca 2013b).

c. Further simplifications

1) RELATIONSHIP BETWEEN THE PARAMETERS OF THE MODEL

As identified in many previous studies (e.g., Mapes 1993), the linear correlation between the duration and the maximum extent of the system is significant and indicative of a strong relationship between the parameters of the model. Note that here the scale, defined as the square root of the area, is used to characterize the extent of the MCS in line with previous studies. This correlation further shows no geographical dependency and is high all over the tropical belt (Fig. 12). One important consequence of the strong link between the maximum extent and the duration of the convective systems is that the morphological life cycle of the MCS is determined by fewer parameters. The quantitative relationship between life duration and the maximum extent of the MCS shield indicates a robust relationship all across the tropics (Fig. 13). For the shorter systems the spread in observed scale is small for a given duration and is slightly larger for systems with longer duration.

2) GEOGRAPHICAL DISTRIBUTION

Maps indicate that 7–9-h-duration systems, while frequently encountered over some continental regions and in the oceanic ITCZ region, exhibit a narrow range of scale at maximum extension (~100 km), independent of the regions where they occur (Fig. 14b). On the other hand, the 20–24-h-duration systems, observed over the Pacific Ocean, the Bay of Bengal, and West Africa show a significant regional variability in the absolute magnitude of the maximum extent they reached (Fig. 14d). The boreal summer monsoon affected regions (North America, West Africa, India, Southeast Asia, and associated oceanic basins), are characterized by larger scales than the Pacific and Atlantic ITCZ regions. The Bay of Bengal is the oceanic region with the largest observed scale for a 20–24-h system with magnitude up to 450 km similar to observed Sahelian and continental Indian systems.

4. Summary and discussion

Using a new tracking technique and the observed infrared imagery from the fleet of operational meteorological geostationary satellites, the characteristics of the cloud shield of the MCS are documented in a homogeneous way over the entire tropical belt during the boreal summer season. A simple morphological model of the

![Fig. 10](image-url) Root-mean-square error between the observed class 2a MCS size evolution and the linear growth–decay model prediction as a function of (a) system duration, (b) system maximum extent, and (c) propagation distance of the system for the entire tropical belt (solid), continent (short dashed), and ocean (long dashed). The thin curve corresponds to the standard deviation for the entire tropical belt systems.

![Fig. 11](image-url) Root-mean-square error between the observed class 2a MCS size evolution and the linear growth–decay model prediction as a function of the time of maximum (%) for the entire growth phase (dashed) and decay phase (solid).
MCS is put forth whereby the life cycle of the MCS cloud shield can be described by a linear growing and a decaying phase that can be summarized with three parameters: the maximum extent, the timing of this maximum extension along the system life cycle, and finally the duration of the system. The simple model is shown to represent well the life cycle of the individual systems, with more than 80% of the population and associated cold cloudiness being qualified by a good RMSD between the observed and parametric life cycle. The model further performs equally well over land and ocean and exhibits steady good fit independent of the location and morphology of the storms. Out of the three parameters of the model, $T_{\text{max}}$ is almost constant and equal to 50%, and the two other parameters are strongly correlated. Our results suggest that the evolution of the cold cloud shield from start to end can therefore be simplified down to a single degree of freedom.

This simple statistical model will help the analysis of other observations by providing a first-step characterization of the MCS life cycle (growth or decay). The reduced perspective can guide the development of simplified convective schemes useful to satellite-based precipitation estimation (Bellerby et al. 2009) and help interpret reflectivity profiles (Bouniol et al. 2016). The characterization of the combined effect of a number of physical processes yielding to a growth or decay of the cloud shield along its time evolution offers a new simple integrated constraint on emerging object-oriented validation efforts of high-resolution atmospheric models (Pearson et al. 2010; Beucher et al. 2014; Hagos et al. 2013). The linearity of the time evolution of the cloud shield during each of the growing and decaying phases, even over long life cycles, is supportive of a relatively constant rate of production of ice particles in the anvil during the growing phase and similar rate of removal during the decaying phase and should benefit parameterization efforts (Zender and Kiehl 1997; Elsaesser et al. 2016) by, again, providing a scaling in both space and time of the integral results of the various microphysical processes at play.

The symmetry of the life cycle is a strong characteristic of the MCS population, independent of duration, size, and geography. This suggests that the primary driver for this is the internal dynamics of the systems with weak to no sensitivity to environmental factors. In particular, the upper-level shear or the tropical easterly jet would be expected to influence the symmetry of the time evolution of the cloud shield by spreading ice particles away from the convective cores. It is most likely that the shear strongly affects only lighter ice particles than the ones found within the 235-K delineated shield and could explain the previously reported weak relationship between shear and nonprecipitating anvils (Li and Schumacher 2011). While a major fraction of MCSs are indeed found here to have a symmetrical time evolution of their cloud shield, one-third of the population exhibits significant departures from symmetry (Fig. 5). A detailed investigation of the large-scale shear conditions for a subset of nonsymmetrical systems could shed some light on this process and is left for future work. The time evolution of the intensity, height penetration, and mass flux of deep convection, the transport of the ice particles from the convective region to the stratiform regions, and the subsequent microphysical processes are important characteristics of the internal MCS dynamics that are not directly documented by the infrared imagery by itself (e.g., Diongue et al. 2002; Nesbitt et al. 2006; Liu et al. 2007). The merging of multiple datasets from

![Fig. 12. Map of the correlation between the duration and the maximum extent of the MCSs.](image-url)
various sources, including active sensors, with the geostationary derived morphological characteristics of the MCS is one way to overcome this important limitation. Recent advances based on TRMM and CloudSat satellite data have been shown to be very promising (Kondo et al. 2006; Futyan and Del Genio 2007; Inoue et al. 2009; Fiolleau and Roca 2013b; Bouniol et al. 2016) and will be pursued in the future to explore in more detail the physics behind the symmetrical cloud-shield behavior.

The results reported here over the entire tropics between duration and maximum extent of the cloud shield confirm previous regional investigations. The longer the system lasts, the larger maximum extent the shield can reach. The role of the large-scale environment on the scaling of this relationship remains to be clarified. The sustainability concept (Yuter and Houze 1998; Houze 2004) has been proposed as a framework to discuss the life cycle of MCS within their large-scale environment. This states that the more the environment is sustainable to formation of deep convective cells, the more solid water materials will be available at upper levels to form the shield of the MCS, the longer the system will exist, and a larger extent it will reach. Consequently, a warm moist boundary layer over the ocean is likely to provide an almost infinite reservoir of moisture and energy to sustain deep cell formation that would continuously feed the stratiform region of the MCS. This would yield to large cloud shields that would take a long time to dissipate. Conversely, the continental low-level environment is strongly dependent on the diurnal cycle and is not likely to sustain any deep convective cells after sunset, and therefore, the cold cloud shield would not be fueled by new deep cells and would terminate quickly before reaching large extent. Our results show that, for systems lasting 7–9 h, the maximum shield scale is around 100–150 km without large regional variability. Such systems' maximum growth is similar over continent or ocean, although these relatively short-lived systems are much more frequent over land than ocean. Very-long-lived systems, like those in the 20–24-h population, are more frequently observed over the oceans, especially in the very moist Bay of Bengal and eastern Pacific region.

![Fig. 14](http://journals.ametsoc.org/jcli/article-pdf/30/11/4283/4672293/jcli-d-16-0556_1.pdf) Multiyear statistics of occurrence of MCS lasting (a) 7–9 and (c) 20–24 h and mean scale of the maximum extent for MCS lasting (b) 7–9 and (d) 20–24 h.
with the exception of the West African and Indian continental monsoon exposed regions. Unlike for the shorter MCS, the distribution of the maximum extent of the long-lived systems exhibits large regional variability. The 20–24-h systems of the Sahel, continental India, and Bay of Bengal have maximum extents that are twice as large as those of the 20–24-h systems of the Pacific and Atlantic ITCZ. These results indicate that the sustainability concept, while useful to interpret the frequency of occurrence maps of the MCSs, fails to actually link the cold cloud shield extent to the MCS duration. It is likely because such an energy-based concept alone cannot discriminate between three 7-h-long systems and one 21-h-long system.

The major difference between short-lived and long-lasting systems is the coupling between the stratiform and deep convection regions of the system that eventually controls its duration and morphology (Redelsperger 1997). While this physical process is internal to the MCS dynamics, it is nevertheless influenced by the large-scale environment of the storm. Low-level wind shear has been identified as an important element of propagating squall lines over tropical oceans (LeMone et al. 1998) and could favor the lifting of new convective cells at the cold pool edge (Weisman and Rutan 2004) that contribute to the system’s longevity. Upper-level wind shear can lead to contradictory effects upon the duration and extension of the system. Strong shear can transport ice away from the stratiform precipitating region of the storm toward the nonprecipitating part of the anvil (Li and Schumacher 2011), limiting the production of stratiform rain and the associated feedback onto deep convection (Houze 2004). Stratiform rain production is favored in nonsheared or weakly sheared upper-level environments that are conducive to larger extension of the systems (Schumacher and Houze 2006). While over the tropical oceans boundary layer relative humidity is not a limiting factor for the MCS (Houze 2004), the distribution of humidity at the midtropospheric level can influence deep convection and its organization in a complex way (Sherwood and Wahrlich 1999; Roca et al. 2005a; Del Genio et al. 2012). Either it can inhibit the development of deep cells mainly at the beginning of the life cycle, or it can favor the squall lines by enhancing the evaporation of hydrometeors during the mature phase of the MCS, fueling the cold pools and new convective cells. Future investigation will be directed toward aggregating vertical distributions of horizontal wind shear and relative humidity with the life cycle morphology parameters to explore the possible contributions of these physical processes on the geographical variability of the maximum shield extension reported here. The simple life cycle model will be used to guide such a statistical aggregation of the environmental data.

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