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Multifractal properties of evolving convective systems over tropical South America

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[1] This paper examines variations in multifractal properties of evolving mesoscale convective systems over tropical South America using infrared satellite images and a tracking technique. It is shown that multifractal coefficients have diurnal variation and seem to be modulated by intraseasonal low-level circulations. This remote sensing approach has potential application to infer convective-scale processes occurring in individual mesoscale systems. *INDEX*

TERMS: 1854 Hydrology: Precipitation (3354); 3250 Mathematical Geophysics: Fractals and multifractals; 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3329 Meteorology and Atmospheric Dynamics: Mesoscale meteorology; 3360 Meteorology and Atmospheric Dynamics: Remote sensing

1. Introduction

[2] Convection manifests in the atmosphere within a broad range of spatial and temporal scales. Cumulonimbus clouds often occur in large and long-lasting organized groups, generically referred to as Mesoscale Convective Systems (MCS) [e.g., Houze, 1993]. MCS are recognized for their key role for the distribution of energy, momentum and water in the atmosphere, particularly over the tropics. Large MCS can be easily identified in infrared (IR) satellite images due to their near tropopause-level cloud tops. They appear in radar images as a leading convective line (≤ 10 km) with trailing stratiform precipitation region (≥ 100 km) [Houze, 1993]. Heavy precipitation and lightning are some physical processes that can be observed in association with convective lines. Although IR images have been continuously used to identify and track MCS cloud-shields, they have limited application to describe convective-scale processes that occur in spatial-scales less than 20 km and time-scales less than 1 hour. Nonetheless, the long-term availability of IR images with temporal resolution up to 30 min over large areas of the globe, make them a unique alternative to investigate convection, particularly over areas with scarce *in situ* observations such as tropical South America. Evidence of scaling in space and time of clouds and precipitation has been demonstrated in many previous studies [see Harris *et al.*, 2001 and references therein]. The objective of the present work is to apply spatial scaling properties of clouds observed with IR

satellite images to identify convective scale processes in MCS.

2. Data Sets and Case Studies

[3] Multifractal coefficients of MCS cloud shields that propagate over tropical South America during the 1999 wet season, were investigated with Geostationary Operational Environmental Satellite (GOES-8) IR images. In this study, hourly IR images with 4 km resolution were examined in two periods: 31 January–02 February and 14–16 February. Recent observations have suggested that easterly and westerly anomalies in the low-level wind regime over tropical South America have an implication upon large, meso and convective scales activity [e.g., Petersen *et al.*, 2002; Carvalho *et al.*, 2002]. January 31–Feb 02 was characterized by *westerly anomalies*, whereas 14–16 February was related to *easterly anomalies*.

3. Methodological Approach

[4] Satellite Maximum Spatial Correlation Tracking Technique (MASCOTTE) [Carvalho and Jones, 2001] was applied to monitor MCS life cycles over tropical South America. MCS cloud shields are defined in satellite images according to a threshold criterion (brightness temperature $T_b \leq 235$ K). Only MCS cloud features with equivalent radius ≥ 100 km are analyzed. The underlying hypothesis is that meso to convective-scale vertical movements inside clouds modify the spatial variability of T_b [e.g., Houze, 1993]. This variability can be estimated by the absolute value of the MCS cloud shield T_b gradient, $|\nabla T_b|$, which in turn can be approximated by a multifractal field φ_λ , where $\lambda \geq 1$ is the scale ratio. For multifractal processes $\varphi_\lambda \sim \lambda^\gamma$ (γ is the order of singularity when $\lambda \rightarrow \infty$), the statistical moment of order q follows the power law: $\langle \varphi_\lambda^q \rangle \propto \lambda^{K(q)}$. Assuming that cascade phenomenology [Monin and Yaglom, 1975] is the generic mechanism responsible for φ_λ , and that γ belongs to a stable distribution than the scaling exponent $K(q)$ is given by [e.g., Schertzer and Lovejoy, 1987; Gupta and Waymire, 1990]:

$$K(q) = \begin{cases} \frac{C_1}{\alpha - 1} (q^\alpha - q), & \alpha \neq 1 \\ C_1 q \ln(q), & \alpha = 1. \end{cases} \quad (1)$$

[5] The stable distribution is characterized by the parameters α , β , C_1 and μ [Uchaikin and Zolotarev, 1999]. The Lévy exponent α ($0 < \alpha \leq 2$) controls the rate of fall off of the tail of Probability Density Function (PDF). Large α implies less probability to find random fluctuations far away from a central value. The parameter μ describes the translation of PDF with respect to q

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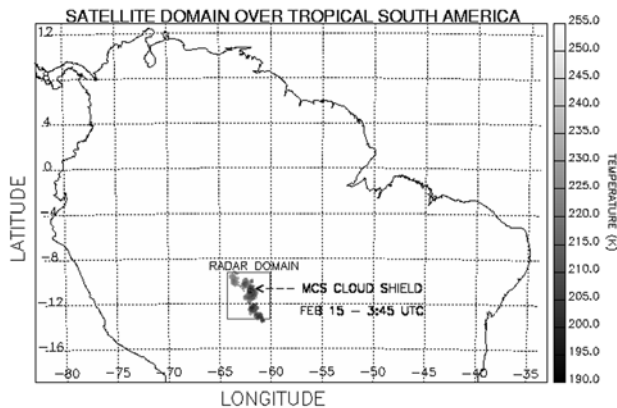


Figure 1. Satellite and radar domains.

whereas β controls the departure from the symmetry. In cascade models, β is set to -1 to ensure the existence of low order statistical moment of the field φ_λ . C_1 is related to the width of PDF and has been associated to the “sparseness” of the mean field [Schertzer and Lovejoy, 1987] or the intermittency of field [Davis et al., 1996]. Therefore, the scaling behavior and statistical properties of a given multifractal field is properly described by α and C_1 . Variations in these coefficients can be potentially useful to identify scaling processes in φ_λ that could be related to the enhancement of convective-scale processes in MCS. Using equation (1), Lavallée [1991] demonstrated that C_1 and α can be estimated independently by considering the following relations:

$$C_1 = dK(q)/dq|_{q=1} \quad (2)$$

and

$$dK(q_{min})/dq = 0, \text{ for } q_{min} = (1/\alpha)^{1/(\alpha-1)} \quad (3)$$

[6] In the present work, the multifractal coefficients C_1 and α are computed as the MCS evolves. For each time, the MCS $|\nabla T_b|$ (φ_λ) is determined. Multifractal properties of φ_λ are obtained after considering a window of 128×128 pixels collocated with the MCS center of gravity. The determination of scaling exponents of clouds as a function of the scale length over a regular 2D grid may include the effects of the background. One can assume that the scaling exponent of the entire scene (i.e., cloud plus background) $K_{tot}(q)$ is the sum of two scaling exponents, that is, $K_{tot}(q) = K_{mcs}(q) + K_{mask}(q)$. The scaling exponent $K_{mcs}(q)$ is the actual scaling exponent of the MCS cloud shield whereas $K_{mask}(q)$ is the scaling exponent of the same scene masked according to a binary classification (clouds and no-clouds). The scaling exponent $K_{mcs}(q)$ has the functional behavior predicted by equation (1) and characterizes the multifractal properties of φ_λ . This is equivalent to consider that the MCS cloud shield lays on a grid with fractal dimension $D \leq 2$.

4. Multifractal Coefficients and MCS Cloud Features

[7] Figure 1 shows the satellite domain where MCS have been monitored. A typical MCS propagating as observed by

satellite ($T_b \leq 235$ K) across the S-Pol and TOGA radars domain is indicated in the same figure to illustrate its horizontal dimension. Multifractal coefficients were analyzed along with other MCS cloud shield characteristics, including Gaussian properties of $|\nabla T_b|$ (that is, mean, variance and skewness). The goal is to infer the physical (linear) correspondence between Lévy exponents and IR parameters frequently used to estimate convective activity [see Carvalho and Jones, 2001]. Results are summarized in Table 1.

[8] The linear correlations in Table 1 indicate that C_1 increases when a large fraction of MCS cloud shield reaches heights above 13 km (that is, $T_b \leq 210$ K) in an environment where the tropopause was often near 16.0 km. Intense convective-scale upward movements ($w_{cs}\uparrow$) are necessary to transport hydrometeors up to these levels. Likewise, C_1 increases with the increase of maximum magnitude and spatial variability of $|\nabla T_b|$. Positive temporal trends of MCS IR properties such as fraction of cold (high) tops and maximum $|\nabla T_b|$ have been incorporated in many satellite techniques to estimate intensity of convection and precipitation [see examples in Kidder and Haar, 1995]. The rationale is that tight $|\nabla T_b|$ and high variable cloud tops are observed near regions with enhanced $w_{cs}\uparrow$. Low linear correlations are observed between α and the MCS IR properties shown in Table 1. Local or environmental conditions may play an important role in determining variations in α , which are not simply extracted from linear statistics with the field $|\nabla T_b|$. However, the similar statistical relationships between α and C_1 versus the mean $|\nabla T_b|$ suggest that both parameters have an equivalent weight in describing the variation of the mean $|\nabla T_b|$.

5. Diurnal and Intraseasonal Variations

[9] Carvalho et al. [2002] demonstrated the existence of strong diurnal variation in the number of MCS over tropical South America, with an afternoon maximum (18:00–23:00 UTC) and a pre-dawn minimum (4:00–9:00 UTC). Petersen et al. [2002] showed a diurnal cycle of lightning flash count consistent with that observation. In addition, as discussed in both studies, there is strong evidence that intraseasonal variations in the low-level wind regime over tropical South America modulate convective activity, and therefore lightning and precipitation. During easterly regimes, relatively dry atmospheric conditions were linked to the enhancement of cloud-to-ground lightning activity, and existence of deeper and more intense convective systems [Petersen et al., 2002]. In contrast, the westerly

Table 1. Linear Correlation Between MCS IR Properties and Lévy Exponents

MCS IR Properties	C_1	α
Area	0.02	-0.14
Fraction MCS with $T_b < 210$ K	0.49	-0.21
Maximum $ \nabla T_b $	<u>0.56</u>	-0.08
Mean $ \nabla T_b $	<u>0.31</u>	0.26
Variance of $ \nabla T_b $	<u>0.63</u>	-0.05
Skewness of $ \nabla T_b $	<u>0.33</u>	-0.17

Underlined correlations are significant at the 95% confidence level ($N = 1203$ observations).

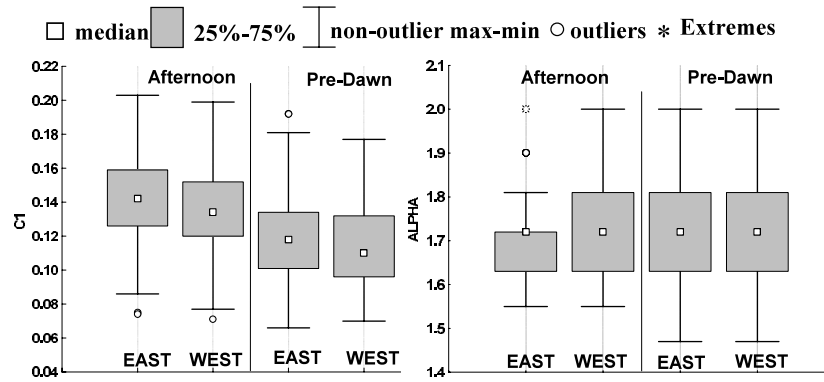


Figure 2. Representation of statistical properties of C_1 (left) and α (right). “Outliers” are data point values ≥ 1.5 times the interquartile range. “Extremes” are data point values ≥ 3.0 times the interquartile range.

regimes were related to less lightning activity and relatively shallower convection. Differences are more relevant in the afternoon. However, monitoring MCS IR properties to investigate convective-scale processes is not straightforward. Multifractal or scaling exponents obtained from IR images, on the other hand, contain important information to infer downscaling processes occurring in the MCS cloud shield.

[10] The diurnal distributions of C_1 and α in different wind regimes (Figure 2) illustrate these aspects. The shifting in C_1 distribution towards higher values in the afternoon and decrease pre-dawn is consistent with the diurnal cycle of lightning activity discussed in *Petersen et al.* [2002]. Indeed, these differences in C_1 can be interpreted as the result of changes in the spectrum of the random fluctuations of φ_λ , which in turn has been hypothesized here to be linked to changes in the spatial variability of $w_{cs}\uparrow$. During the afternoon, the relative increase in the number and/or extent of convective cells may have decreased the spectrum of random fluctuations in φ_λ . In the pre-dawn period, most MCS are decaying and the convective-scale processes are weaker and/or possibly restrict to some few cells. Decaying convective activity decreases the range of fluctuation of φ_λ , which is reflected in lower values of C_1 . Similar rationale can be applied to understand the differences in the distributions observed along with changes in wind regimes. The Mann-Whitney

U non-parametric test with 0.05 significance level indicated that the two samples of C_1 could not be considered as originating from the same population in different regimes in the afternoon. Larger values of C_1 during the easterlies seem to indicate the enhancement of MCS convective cells comparatively to the westerlies.

[11] Diurnal changes in α populations are statistically significant only during the easterly regime. The decrease of α values in the afternoon during the easterlies simply indicates an increase in the probability of occurrence of φ_λ of larger magnitude. Therefore, if one assumes that fluctuations in φ_λ are linked to the enhancement of convective-scale processes in MCS, the coefficient α can be physically related to extreme magnitudes of $w_{cs}\uparrow$. Similar distributions of α values in the pre-dawn period for both regimes and in the afternoon for the westerlies indicate that very large magnitudes of φ_λ random fluctuations are observed with the same probability in the three MCS populations, which is still consistent with the observation of shallower convection during the westerlies [*Petersen et al.*, 2002, and *Carvalho et al.*, 2002].

6. Signal in the Convective Precipitation

[12] An example to illustrate the correspondence between C_1 and α and the convective precipitation area (number of radar pixels) and average intensity (mm/h) associated exclu-

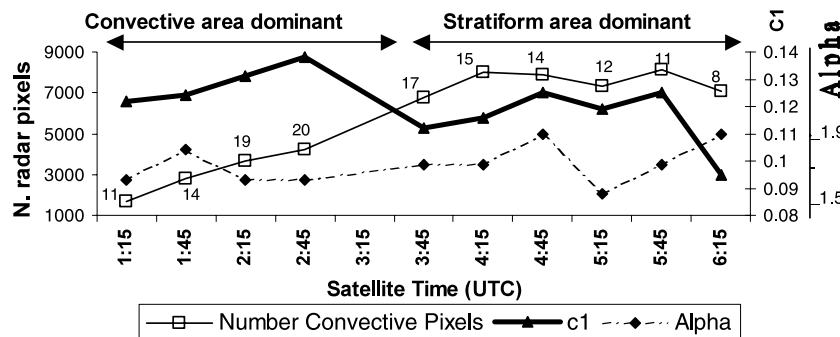


Figure 3. Time evolution of C_1 and α and number of pixels with convective rainfall observed for an MCS propagating over the radar domain on February 15 (easterly regime). Numbers inside the graphic indicate the average convective rain-rate (mm/h). Matching is considered only when satellite and radar images are less than 5 min apart. The Colorado State University provided rainfall data.

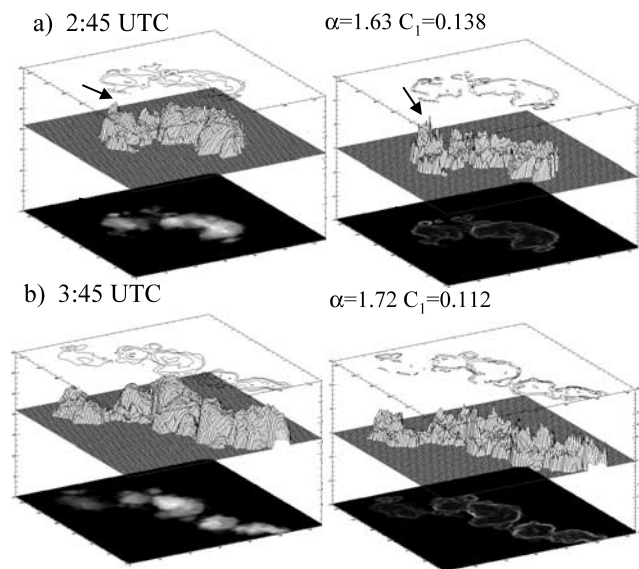


Figure 4. Tri and bi-dimensional projections of the MCS cloud shield (left panels) and respective φ_λ field (right panels) obtained for the event shown in Figure 3. The center of the image is collocated with the center of the gravity of the MCS (and not with the radar). Vertical scale is arbitrary.

sively with a single MCS that propagated over the radar domain is shown in Figures 3 and 4. During the first stage of development of the MCS (1:45–3:45 UTC), convective precipitation area dominates the stratiform one and a peak in the average convective rain-rate is observed. C_1 increases concomitantly and reaches its maximum when the difference in convective and stratiform area and the average convective rain-rate are maxima (2:45 UTC). A decrease in C_1 is observed along with the weakening of convective precipitation and dominance of stratiform area. Note that the number of convective pixels increases but the average rain-rate decreases after 3:45 UTC. Nonetheless, C_1 trend follows the respective trend of convective area. The lowest magnitude of C_1 is observed about 6:15 UTC during minimum average convective rain-rate and maximum stratiform rain-rate (not shown). Corresponding variations of the coefficient α indicate that high magnitudes in the φ_λ fluctuations may not always be related to the mean rain-rate and/or total number of convective pixels, particularly when high fluctuations are confined to a small fraction of the MCS.

[13] Figure 4 provides additional information to interpret these results. At 2:45 UTC, during the time of maximum convective rain-rate, one can observe enhanced cold tops and the existence of high magnitudes in the φ_λ fluctuations, which corresponds to an increase in C_1 and decrease of α . Note that the extreme fluctuations in φ_λ are observed near to a small but very prominent cold top indicated by arrows, which is likely associated with intense upward movement. At 3:45 UTC the MCS area increases as well as the convective and stratiform rain-area. However, a large part of the MCS cloud feature flattens or collapses. The decrease in C_1 coupled to an increase in alpha suggests that not only

the range of fluctuations has decreased but also fluctuations of larger magnitude are less frequent. These observations characterize the transitioning from convective to stratiform features of the MCS, evidenced by a decrease in the mean convective rain-rate and increase in the stratiform rain area.

7. Summary and Conclusions

[14] The present study demonstrated that monitoring multifractal coefficients of MCS cloud shields, as part of satellite tracking technique can be a useful tool to identify convective-scale processes in MCS and have potential application for climatological studies. In addition, it provided evidence that cascade generator models that use spatial and/or temporal scaling properties to simulate precipitation in tropical areas should incorporate information on the diurnal cycle and variations in large-scale regimes.

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