Testing Taylor’s hypothesis in Amazonian rainfall fields during the WETAMC/LBA experiment

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Abstract

Taylor’s hypothesis (TH) for rainfall fields states that the spatial correlation of rainfall intensity at two points at the same instant of time can be equated with the temporal correlation at two instants of time at some fixed location. The validity of TH is tested in a set of 12 storms developed in Rondonia, southwestern Amazonia, Brazil, during the January–February 1999 Wet Season Atmospheric Meso-scale Campaign. The time Eulerian and Lagrangian Autocorrelation Functions (ACF) are estimated, as well as the time-averaged space ACF, using radar rainfall rates of storms spanning between 3.2 and 23 h, measured at 7–10-min time resolution, over a circle of 100 km radius, at 2 km spatial resolution. TH does not hold in 9 out of the 12 studied storms, due to their erratic trajectories and very low values of zonal wind velocity at 700 hPa, independently from underlying atmospheric stability conditions. TH was shown to hold for 3 storms, up to a cutoff time scale of 10–15 min, which is closely related to observed features of the life cycle of convective cells in the region. Such cutoff time scale in Amazonian storms is much shorter than the 40 min identified in mid-latitude convective storms, due to much higher values of CAPE and smaller values of storm speed in Amazonian storms as compared to mid-latitude ones, which in turn contribute to a faster destruction of the rainfall field isotropy. Storms satisfying TH undergo smooth linear trajectories over space, and exhibit the highest negative values of maximum, mean and minimum zonal wind velocity at 700 hPa, within narrow ranges of atmospheric stability conditions. Non-dimensional parameters involving CAPE (maximum, mean and minimum) and CINE (mean) are identified during the storms life cycle, for which TH holds: CAPE mean/CINE mean = [30–35], CAPE max/CINE mean = [32–40], and CAPE min/CINE mean = [22–28]. These findings are independent upon the timing of storms within the diurnal cycle. Also, the estimated Eulerian time ACF’s decay faster than the time-averaged space and the Lagrangian time ACF’s, irrespectively of TH validity. The Eulerian ACF’s exhibit shorter e-folding times, reflecting smaller correlations over short time scales, but also shorter scale of fluctuation, reflecting less persistence in time than over space. No significant associations (linear, exponential or power law) were found between estimated e-folding times and scale of fluctuation, with all estimates of CAPE and CINE. Secondary correlation maxima appear between 50 and 70 min in the Lagrangian time ACF’s for storms satisfying TH. No differences were found in the behavior of each of the three ACF’s for storms developed during either the Easterly or Westerly zonal wind regimes which characterize the development of meso-scale convective systems over the region. These results have important implications for modelling and downscaling rainfall fields over tropical land areas.

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1. Introduction

1.1. The significance of Taylor’s hypothesis

Understanding the space–time dynamics of rainfall fields constitutes one of the most challenging topics of geophysics. An important observation that has guided the research refers to the validity of “Taylor’s hypothesis of the frozen field”, in the space–time correlations of rainfall fields [45,5], which was originally stated in the study of turbulence of fluid flows [41,24]. To understand the hypothesis, let \( \zeta(t, x) \) denote the space–time rainfall intensity at some time \( t > 0 \), and some location \( x \) in a two dimensional region, and assume that rainfall is homogeneous in space and stationary in time. Let the two dimensional region, and assume that rainfall is homogeneous in space and stationary in time. Let the space–time correlation be denoted by, 

\[
\rho(\tau, s) = \text{Cov}(\zeta(t, x), \zeta(t + \tau, x + s)) .
\]

Then Taylor’s hypothesis states that

\[
\rho(\tau, 0) = \rho(0, U\tau),
\]

where \( U \) is some characteristic speed vector. It connects the spatial correlation at two points at the same instant of time with temporal correlation at two instants of time at some fixed location. The hypothesis implies that spatial fluctuations are carried past a fixed point by the mean flow speed without undergoing any essential change. Zawadzki [45] studied radar rainfall data of mid-latitude convective storms, and concluded that Taylor’s hypothesis holds in rainfall intensity fields for time periods shorter than 40 min, and then it breaks down. Zawadzki’s results showed that at time lag \( \tau > 40 \) min, the temporal correlation falls below the spatial correlation. This time scale roughly corresponds to the life cycle of mid-latitude convective rainfall cells. His results also indicated that correlation in space exhibits more memory than correlation in time, since the tails of the temporal correlations fit well to exponential functions, whereas the spatial correlation tails fit well to power laws. Subsequently, Crane [5] using spectral analysis of rapid-response gages located in the Rhine valley (Germany), observed that Taylor’s hypothesis holds in rainfall data up to a cutoff time of 30 min and for spatial scales less than 20 km, and then it breaks down. At the microscale, Lovejoy and Scherzer [22] reports lidar observations of raindrops in which Taylor’s hypothesis does not hold, within a range of spatial scales 3–500 m, and timescales from 0.1 s to 500 s.

The validity of Taylor’s hypothesis and its cutoff time reflects important dynamical features of rainfall fields, and therefore it provides a test for models of the space–time dynamics of rainfall fields, including those based on the stochastic theory of point random fields [19,43,9,11,17,4,14]. The breakdown of Taylor’s hypothesis is caused by the presence of anisotropy between space and time in the advection of rainfall cells across the Earth’s surface, because the life cycle of rainfall cells themselves destroy the space–time isotropy. This explains why Taylor’s hypothesis does hold infinitely in isotropic space–time theories of rainfall, [43,13,32]. The role of dissipation in the cutoff in Taylor’s hypothesis for rainfall correlation was generalized to a wide class of possible stochastic short-memory rainfall models [11]. In fact, lack of evidence for scaling in time, which translate into a finite scale of fluctuation [42], does not preclude scaling properties in space. For time lags for which Taylor’s hypothesis holds, one can expect that scaling in space is reflected in time scaling [46].

The validity of Taylor’s hypothesis is also used as a test for scale-independent models of rainfall fields, including fractal, multi-scaling, and random cascade models [20–22,12,31,33,8,15,29]. For instance, [32] indicate that Taylor’s hypothesis is valid up to a correlation time of the generator process \( W_t \) of a random cascade model of meso-scale rainfall. Other efforts within the context of cascade theories, based on generalizations of Taylor’s hypothesis are discussed in Lovejoy and Scherzer [23].

1.2. Amazonian rainfall and the WETAMC/LBA campaign

The Amazon River basin constitutes a paradigm of complexity in the land surface-atmosphere system, due to its areal extent of more than 6.4 million km² (the largest river basin in the world), its tropical setting, and complex eco-hydro-climatological dynamics, which exert global influence. The hydro-climatic and ecological functioning of the Amazon is currently being investigated by the Large Scale Atmosphere–Biosphere Experiment in Amazonia (LBA) [1,35,28,7]. Modelling results suggest that strong changes may occur in local, regional and global atmospheric circulation patterns associated with deforestation over the Amazon [39,48,49,26,44]. The annual cycle of precipitation exhibits a wet season during November–March and a dry season during May–September, due to the latitudinal migration of the Intertropical Convergence Zone [30], which interacts with the seasonal cycle of moisture advection by the low level winds from the Atlantic Ocean, and through complex interactions of the land surface-atmosphere system, including important precipitation recycling feedback from evapotranspiration [36,10].

At smaller space–time scales, convective rainfall over the Amazon has been investigated during the Wet Season Atmospheric Meso-scale Campaign/LBA (WETAMC/LBA) experiment in Amazonia, developed during the period January–February 1999. The WETAMC/LBA campaign focused on the dynamical, microphysical, electrical, and diabatic heating characteristics of tropical convection in this part of Amazonia.
For a detailed review and results of the experiment, see Silva Dias et al. [37,38] and [25]. During the WETAM/LBA campaign, two main regimes in the convective activity were observed [34,18,3]. These two regimes were closely associated with the zonal wind component in the low tropospheric layer at 850–700 hPa; hence they were coined as Westerly and Easterly regimes.

Using information from a set of 12 storms recorded during the 1999 WETAMC/LBA field campaign, in this paper we intend: (i) to test for the validity of Taylor’s hypothesis and the possible existence of a cutoff timescale in land-based convection-dominated tropical rainfall, and how the results compare with those obtained by Zawadzki [45] for mid-latitude convective rainfall; (ii) to quantify differences in the decay of ACF’s for Amazonian storms, and (iii) to understand how the results in (i) and (ii) are linked to dynamical and thermodynamical characteristics of the atmosphere during the storms, which include their regime, average zonal wind velocity at 700 hPa, and atmospheric stability indices including Convective Available Potential Energy (CAPE), and Convection Inhibition Energy (CINE). Required definitions and theoretical considerations are shown in Section 2, while data sets are described in Section 3, results are provided in Section 4, and conclusions are summarized in Section 5.

2. Definitions and theory

This section uses Zawadzki [45] definitions for the time Eulerian, Lagrangian, and Spatial autocorrelation functions (ACF). Let \( R(x, y, t) \) represents the rainfall rate as a function of space and time, whose scales are defined for an isolated storm in terms of an area \( S \) and a time \( T \), such that

\[
R(x, y, t) \geq 0, \quad (x, y) \in S \text{ and } t \in T,
\]

\[
R(x, y, t) = 0, \quad \text{outside this region.}
\]

A time–space autocorrelation function of \( R \) is therefore given as

\[
A_{S,T}(x, \beta, \tau) = \frac{1}{ST} \int_T \int_S R(x, y, t) R(x + \alpha, y + \beta, t + \tau) \, dx \, dy \, dt,
\]

where \( \alpha, \beta \) and \( \tau \) represent the lag variables, and the normalized ACF defined as,

\[
a'(\alpha, \beta, \tau) = \frac{A_{S,T}(\alpha, \beta, \tau)}{A_{S,T}(0, 0, 0)}
\]

will be independent of \( S \) and \( T \), provided these parameters are large enough to contain the entire storm system. Note that the normalized ACF is an even function varying between 0 and 1, and that the definition of the ACF does not require the assumption of stationarity and homogeneity of \( R(x, y, t) \). Henceforth, we denote time averages with an overbar, and space averages by \( \langle \cdot \rangle \), and thus Eq. (3) becomes

\[
A_{S,T}(\alpha, \beta, \tau) = \langle R(x, y, t) R(x + \alpha, y + \beta, t + \tau) \rangle.
\]

The instantaneous space ACF is defined by

\[
A_{S}(\alpha, \beta) = \langle R(x, y, t) R(x + \alpha, y + \beta, t) \rangle.
\]

The time-averaged space ACF is defined for \( \tau = 0 \) in Eq. (5), as

\[
A_{S,T}(\alpha, \beta, 0) = \langle R(x, y, t) R(x + \alpha, y + \beta, t) \rangle.
\]

And the time Eulerian ACF is obtained from (5), with \( \alpha = \beta = 0 \). Thus,

\[
E_{S,T}(\tau) = A_{S,T}(0, 0, \tau) = \langle R(x, y, t) R(x, y, t + \tau) \rangle.
\]

The cross-correlation function of rain rates at two different times is defined as

\[
\langle R(x, y, t_1) R(x + \alpha_0, y + \beta_0, t_2) \rangle.
\]

There exist values of \( \alpha_0 \) and \( \beta_0 \), which will maximize this expression. These lags represent the linear displacement of the pattern \( R(x, y, t_1) \) with respect to a second pattern \( R(x, y, t_2) \), which gives the optimal matching between them. Thus, a vector displacement of the storm is defined during the interval \( (t_2 - t_1) \) by the pair \( (\alpha_0, \beta_0) \). In general, \( \alpha_0 \) and \( \beta_0 \) depend on \( t_1 \) and \( \tau = t_2 - t_1 \).

The velocity components of the storm system are defined by

\[
U_x(t) = \lim_{t \to 0} \frac{\alpha_0}{\tau}, \quad U_y(t) = \lim_{t \to 0} \frac{\beta_0}{\tau}.
\]

Assuming a constant velocity \( U \) for the storm system, we get \( \alpha_0 = U_x \tau, \quad \beta_0 = U_y \tau \).

Now we define a Lagrangian ACF, by making \( \alpha = \alpha_0 \) and \( \beta = \beta_0 \) in Eq. (5), as

\[
L_{S,T}(\tau) = A_{S,T}(\alpha_0, \beta_0, \tau) = \langle R(x, y, t) R(x + \alpha_0, y + \beta_0, t + \tau) \rangle.
\]

It is worth noting that the Eulerian ACF is dependent on the motion of the storm, while the time Lagrangian ACF is defined relative to the storm local coordinates, and therefore it is independent of the storm’s motion. For clarity,

\[
A_{S,T}(0, 0, 0) = \overline{A_{S,T}(0)} = E_{S,T}(0) = L_{S,T}(0) = \langle R^2 \rangle,
\]

where \( \langle R^2 \rangle \) is the mean square value over \( S \) and \( T \), of \( R(x, y, t) \). The normalized ACF’s are obtained by dividing Eqs. (7), (8) and (12) by \( \langle R^2 \rangle \), and using Eqs. (4) and (13):

\[
\overline{a(\alpha, \beta)} = a'(\alpha, \beta, 0),
\]

\[
e(\tau) = a'(0, 0, \tau),
\]

\[
l(\tau) = a'(\alpha_0, \beta_0, \tau).
\]
The instantaneous space ACF is normalized by dividing Eq. (6) by \( A_S(0,0) = \langle R^2 \rangle \) to obtain
\[
a(x, \beta) = \frac{A_S(x, \beta)}{\langle R^2 \rangle}.
\] (15)

2.1. Taylor’s hypothesis in rainfall fields

For the case in which rainfall rates are expressed in a time-independent coordinate system, i.e. \((x', y')\) are the coordinates of the storm, and \(R(x', y', t)\) is the rainfall rate in such coordinates, then
\[
R(x, y, t) = R(x', y') = R'(x - U_x t, y - U_y t).
\] (16)

Therefore the Eulerian ACF, from Eq. (8) becomes
\[
E_{S,T}(\tau) = \langle R'(x - U_x t, y - U_y t) R'(x - U_x t - U_x \tau, y - U_y t - U_y \tau) \rangle
\] (17)
and the time-averaged space ACF, from Eq. (7), becomes
\[
A_{S,T}(x, \beta, 0) = \langle R'(x - U_x t, y - U_y t) R'(x - U_x t + \alpha, y - U_y t + \beta) \rangle.
\] (18)

Taking \( \alpha = -U_x \tau \) and \( \beta = -U_y \tau \) in Eq. (18), then by comparing (17) and (18), in the direction of motion we get under the assumption of isotropy,
\[
E_{S,T}(\tau) = A_{S}(\tau) = A_{S}(U \tau),
\] (19)
where
\[
U = \sqrt{U_x^2 + U_y^2}.
\] (20)

Therefore, using Eq. (13), we obtain
\[
a(U \tau) = e(\tau).
\] (21)

Taylor’s hypothesis is applicable to precipitation processes if Eq. (21) does hold. That is, the storm is statistically stationary in the sense that the properties of space variations can be obtained from time variations at a point by converting time into space through the velocity of the storm system. [45].

3. Datasets

The state of Rondonia (Brazil) is located in the southwestern part of Amazonia. Its vegetation is dominated mainly by tropical forests, deforested pastures, and spatially forested savannas. The relief averages 300 m, ranging between 50 and 1000 m. Average temperature is 24–25°C, with maxima between 28 and 29°C and minimum around 22°C. Mean annual precipitation ranges between 2000 and 2500 mm, with a monthly average of 250 mm/month during the wet season (October–April), and 50 mm/month during the dry season.

Our data set consisted of radar rainfall rates of storms developed in Rondonia during the WETAMC/LBA experiment, which were recorded by the S-POL (S-band, dual polarimetric) radar located at 61.9982°W, 11.2213°S. Original data consisted of microwave band reflectivity, which is directly related to rainfall intensity at a spatial scale of 2 km × 2 km, over a circular area of ~31,000 km². Surveillance scans were available between 7 and 10 min. The resulting processed rainfall maps were produced by the Colorado State University Radar Meteorology Group, and made available from the URL http://tornado.atmos.colostate.edu/lbadata/radar_main.html. Our data set consisted of 12 storms developed during the WETAMC/LBA campaign, whose main characteristics are shown in Table 1. Fig. 1 shows a sequence of the January 11th 1999 storm, from 13:53 to 17:45, local time.

To estimate the Eulerian time ACF, radar data are used at each time interval, \( \tau \), without spatial displacement (\( \alpha = \beta = 0 \)), while the Lagrangian ACF requires the search of a pair of parameters \( \alpha \) and \( \beta \) that maximize Eq. (12). Such values of \( \alpha \) and \( \beta \) represent the linear

<table>
<thead>
<tr>
<th>Storm date</th>
<th>Start time (LTC)</th>
<th>End time (LTC)</th>
<th>Duration (h)</th>
<th>Time interval (min)</th>
<th>Maximum intensity (mm/h)</th>
<th>1/e Eulerian (min)</th>
<th>1/e Lagrangian (min)</th>
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<tr>
<td>990111</td>
<td>13:53</td>
<td>18:46</td>
<td>3.8</td>
<td>7</td>
<td>183</td>
<td>8</td>
<td>37</td>
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<td>18:45</td>
<td>4.2</td>
<td>11</td>
<td>150</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
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<td>23:46</td>
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<td>163</td>
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<tr>
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<td>14:34</td>
<td>5.5</td>
<td>7</td>
<td>117</td>
<td>12</td>
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<td>10</td>
<td>165</td>
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</table>
displacement of the storm system. The time-averaged spatial ACF is estimated using the averaged values of $a$ and $b$ for all lags, and using Eq. (7), as input values. Thus, there exists an estimated Spatial ACF for each lag, $s$. As we already mentioned, all the estimated ACF’s are divided by $R^2$, to obtain normalized estimates.

Information of zonal wind velocity at 700 hPa during the studied storms was obtained from the Climate Reanalysis project from the National Center for Atmospheric Research-National Center for Environmental Prediction (NCEP/NCAR) [16], for the region between $61^\circ$W to $62.8^\circ$W and $10.4^\circ$S to $12.1^\circ$S, corresponding to the S-POL radar coverage region. Data were obtained four times per day at 00, 06, 12 and 18 h. Estimation of thermodynamic indices (CAPE and CINE) was performed using data recorded from radiosondes deployed during the WETAMC campaign inside the ABRACOS project region. ABRACOS is the acronym of the Anglo-Brazilian Amazonian Climate Observation Study; http://www.nwl.ac.uk/ih/www/research/babracos.html, which is located inside the S-POL radar coverage region. Values of CAPE and CINE were estimated according to definitions given by Curry and Webster [6, p. 199].

4. Results and discussion

Analysis of estimated ACF’s indicates that 9 out of 12 storms exhibit different decaying autocorrelation functions, meaning that Taylor’s hypothesis does not hold. Those storms are identified in the first column of Table 1 as 990113, 990115, 990114, 990116, 990201, 990220, 990228, 990126b, and 990225. Fig. 2 shows the normalized Lagrangian, Eulerian and Spatial ACF’s, and the space–time trajectories of two selected storms. The remaining 3 storms (990111, 990112 and 990126a) do satisfy Taylor’s hypothesis. Fig. 3 shows the ACF’s for two of the storms which exhibit similar decay for the time Eulerian and the time-averaged space (Spatial) ACF’s. It turns out that Taylor’s hypothesis is valid up to a certain cutoff time lag of approximately $\tau = 10–15$ min. Results (not shown) indicate that the timing of the storms during the diurnal cycle does not affect the validity of these conclusions.

A detailed analysis of the storm paths suggests that Taylor’s hypothesis is valid depending upon the type of storm trajectory. Taylor’s hypothesis is not valid for storms showing erratic (space-filling) trajectories. One of Taylor’s hypothesis fundamental assumptions is that the velocity field advects the storm properties, thus making it possible to interchange time for space in the ACF’s. On the other hand, storms undergoing smooth, linear and constant velocity trajectories, as shown for the second set of storms (Fig. 3), do satisfy the underlying assumptions and therefore Taylor’s hypothesis, within the aforementioned cutoff time scales.

For storms satisfying Taylor’s hypothesis, the identified cutoff timescale of $10–15$ min could be associated with some observed physical characteristics of rainfall cells. Silva Dias et al. [38] describe the organization of convection into precipitating lines, whose convective cells exhibit fairly erect vertical structures (see their Figures 15 and 16), except during the mature phase when the convective vertical structure become tilted as the cells extend to above 9 km. In any case, storm cells exhibit horizontal extents of approximately 4000–4500 m, and horizontal velocities on the order of 6–8 ms$^{-1}$, which means that the timescale of such rainfall cells is

Fig. 1. A sequence of precipitation patterns of the storm of January 11, 1999 from 13:53 to 17:45 local time. Higher intensity rainfall rates correspond to darker colors, and the central point indicates the radar location. Spatial scale is shown on the top left graph.
on the order of 10–15 min. On the other hand, convective activity over the region exhibits pulses of maximum vertical wind velocity, with an average periodicity of approximately 30 min; see Fig. 12 of Silva Dias et al. [38]. One can conjecture that the cutoff time of Taylor’s hypothesis corresponds to half the time interval between such convective activity pulses, during which rainfall cells regenerate in association with the updrafts, and dissipate in association with downwash precipitation.

Also, our results point out that in Amazonian convective storms, either Taylor’s hypothesis does not hold or its validity is restricted to a much shorter time scales than the 40-min threshold identified for mid-latitude convective storms, [45]. Differences between cutoff time

Fig. 2. Time-averaged space ACF, with the scale of space lag converted to time scale, together with the Eulerian and Lagrangian time ACF’s, of two selected storms for which Taylor’s hypothesis does not hold. Storm 990115 (top), and storm 990228 (bottom). Trajectories of the storm centroids are shown on the right, with time ($T$, min) evolution shown at the inset.

Fig. 3. Similar to Fig. 2 for two selected storms satisfying Taylor’s hypothesis. Storm 990111 (top), and storm 990112 (bottom).
scales between Amazonian and mid-latitude storms may be explained in terms of the physical mechanisms governing both tropical and extra-tropical land-based convective storms, including the interaction between highly localized deep convection mechanisms with the large-scale flow, strength of land surface-atmosphere interactions, evapotranspiration and surface moisture convergence rates, diurnal cycle of surface heating, vertical wind speed rates, and atmospheric stability characteristics. Indeed, relevant differences are observed between values of CAPE and wind speed for Amazonian and mid-latitude convective storms. Our results (Table 2) indicate that average CAPE range between 1177 J/kg and 3197 J/kg, whereas for the mid-latitude storms studied by Zawadzki et al. [47], CAPE hardly exceeds the value of 850 J/kg. Such differences in CAPE reflect a much more unstable atmosphere in tropical storms, in comparison to mid-latitude storms. A stronger atmospheric instability contributes to destroy isotropy in space, thus explaining the shorter cutoff time in Amazonian storms. Also, wind speed does not surpass 9 m/s in Amazonian storms, whereas they get 15–20 m/s in mid-latitude storms, as reported by Zawadzki [45, see his Table 2]. Higher wind speeds for mid-latitude storms contribute to maintain the isotropy of the field for a longer time scale, and the validity of Taylor’s hypothesis up to a longer cutoff time.

For the entire set of analyzed storms, the Eulerian time ACF’s exhibit the fastest decaying rates, as they combine both space and time variability. This conclusion is evidenced by a shorter decorrelation or e-folding time, defined as the time lag for which the ACF reaches the value 1/e of its maximum. Our results indicate that the Eulerian time ACF’s exhibit e-folding times that are nearly half of those for the Lagrangian time ACF’s (see last two columns of Table 1). These results can be explained by the very definition of the time Eulerian and Lagrangian ACF’s, due to their dependence with respect to the storm’s motion, as stated before. Another property characterizing the rate of decay of the three ACF’s is the scale of fluctuation, defined as [40,42]

\[ \theta = \int_{-\infty}^{\infty} \rho(\tau,0) \, d\tau, \tag{22} \]

where \( \rho(\tau,0) \) has already been defined in (1). The scale of fluctuation was introduced by Taylor himself to estimate the time interval between independent observations in the study of turbulent flows, but it also quantifies the degree of persistence and the type of memory of stochastic processes [27]. The scale of fluctuation of the time-averaged space ACF’s is longer than the scale of fluctuation of the Eulerian ACF’s, irrespective of Taylor’s hypothesis validity. This result implies that, for Amazonian storms, the time-averaged space ACF’s are more persistent than the time Eulerian ACF’s, in agreement with findings of Zawadzki [45, see his Fig. 15] for mid-latitude convective storms. Another noticeable feature of the estimated ACF’s is the secondary correlation maxima appearing in the Lagrangian time ACF’s for storms satisfying Taylor’s hypothesis. For storm 990111 (Fig. 3, top), the secondary correlation maximum (around 0.4) appears around 50–55 min, whereas for storm 990112 (Fig. 3, bottom), it appears approximately at 70 min. The physics behind this observation requires further investigation.

Taylor’s hypothesis was also tested for storms developed during the Easterly and Westerly zonal wind regimes identified in Amazonian convection by Cifelli et al. [3]. The first one occurred on January 26th (990226b in Table 1), during an Easterly phase, and the second one on February 25th (990225 in Table 1), during a westerly phase. A relevant question refers to statistical differences emerging from physical and dynamical features of both storm generating mechanisms. Fig. 4 shows that differences between the estimated Eulerian, Lagrangian and Spatial ACF’s are

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**Table 2**

<table>
<thead>
<tr>
<th>Storm data</th>
<th>TH</th>
<th>Regime</th>
<th>Uwind</th>
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TH in the second column refers to whether Taylor’s hypothesis holds. Third column refers to Westerly (W), or Easterly (E) zonal wind regimes.
negligible for these storms pertaining to both zonal wind regimes. This result may be explained because of the number of rain cells per day is very similar during the two regimes, and also because the structural characteristics of the convective systems (size and lifetime) are quite similar between the two regimes, although differences have been found in the organization of the convection [18]. Differences between the space–time variability of storms during both regimes also arise in estimates of CAPE and CINE, during the studied storms. Table 2 shows the values of maximum, minimum and mean zonal wind velocity at 700 hPa, and at the same time depending upon atmospheric stability indices. We found narrow ranges of

between CAPE (maximum, mean, and minimum) and CINE (mean), for which Taylor’s hypothesis was identified to hold, as follows: CAPE mean/CINE mean = [30–35], CAPE max/CINE mean = [32–40], and CAPE min/CINE mean = [22–28]. The physical significance of these non-dimensional ratios with regard to Taylor’s hypothesis remains to be investigated.

• Besides these two previous conclusions, there appears to be no clear-cut differentiated values of the studied dynamical and thermodynamical variables during Amazonian storms, with respect to Taylor’s hypothesis validity. Such variables exhibit a large range of values, including maximum zonal wind velocity at 700 hPa $[-9.5 \text{ m s}^{-1} \text{ to } 7 \text{ m s}^{-1}]$, minimum wind velocity at 700 hPa $[-9 \text{ m s}^{-1} \text{ to } 7.25 \text{ m s}^{-1}]$, maximum storm CAPE $[1460 \text{ J kg}^{-1} \text{ to } 3846 \text{ J kg}^{-1}]$, minimum storm CAPE $[645 \text{ J kg}^{-1} \text{ to } 2631 \text{ J kg}^{-1}]$, and average CINE $[31 \text{ J kg}^{-1} \text{ to } 200 \text{ J kg}^{-1}]$, without any significant correlation among them (not shown). Such disparity of atmospheric environments during the studied Amazonian storms may explain their (mostly) erratic trajectories, which in turn contribute to explain why most of the storms do not satisfy Taylor’s hypothesis, but also the short cutoff time of those storms satisfying it.

• No significant association (linear, exponential or power law) was found between estimated values of e-folding time or scale of fluctuation, with respect to all estimates of CAPE and CINE, for the set of studied storms.

5. Conclusions

The validity of Taylor’s hypothesis in rainfall fields is tested using information of radar rainfall rates of storms spanning between 3 and 23 h, at 7–10-min time resolution. Storms were recorded in southwestern Amazonia, at Rondonia, Brazil, during the wet season WETAMC/ LBA experiment, during January–February 1999. Our findings indicate that Taylor’s hypothesis does not hold in most studied storms (9 out of 12), due to their erratic (more space-filling) trajectories, characterized by exhibiting the lowest values of zonal wind velocity at 700 hPa, irrespectively of the values of atmospheric stability indices such as CAPE and CINE, during the studied storms. The identified erratic trajectories of those storms invalidate the underlying assumptions of Taylor’s hypothesis. On the other hand, Taylor’s hypothesis was shown to hold for a small set of 3 storms undergoing smooth, linear trajectories over space, characterized with the highest negative values of zonal wind velocity at 700 hPa, and at the same time depending upon atmospheric stability indices. We found narrow ranges of

Fig. 4. Differences between the three ACF’s for two storms pertaining to the easterly and westerly zonal wind regimes identified in Amazonian convection by Cifelli et al. [3]. The first one developed on January 26th (990226 in Table 1), during an easterly phase, and the second one on February 25th (990225 in Table 1), during a westerly phase.
non-dimensional parameters formed between CAPE (maximum, mean and minimum) and CINE (mean), whose values are associated with the validity of Taylor’s hypothesis, namely: (i) CAPE mean/CINE mean = [30–35], (ii) CAPE max/CINE mean = [32–40], and (iii) CAPE min/CINE mean = [22–28]. Otherwise, have found no more significant correlations between dynamical and thermodynamical values of the studied storms with regard to the validity (or lack thereof) of Taylor’s hypothesis. The identified disparity of atmospheric environments pertaining to these Amazonian storms can be a reflect of their (for the most part) erratic trajectories, which contribute to explain why most of them do not satisfy Taylor’s hypothesis, but also the short time scale for its break down (10–15 min) in those storms satisfying it. Such brief timescale may be explained by observed physical characteristics (size and velocity) during the life cycle of convective rainfall cells in this Amazonian region [38]. For those storms satisfying Taylor’s hypothesis, such cutoff time scale is much shorter than the one found by Zawadzki [45] for mid-latitude convective storms (40 min), due to characteristic life cycles of the tropical storms, but also due to much larger values of CAPE and smaller wind speeds in tropical storms as compared with mid-latitude storms, which contributes to destroy the isotropy of the field. Up to such time lag (10–15 min), one could expect that scaling in space is reflected in time scaling [46]. The timing during the diurnal cycle do not affect the validity of these conclusions.

For our data set, Eulerian time ACF’s decay much faster than the Lagrangian time and the time-averaged space ACF’s, thus indicating that the Eulerian ACF’s exhibit shorter e-folding times, as well as less persistence. Secondary correlation maxima appeared in the Lagrangian time ACF’s for storms which satisfy Taylor’s hypothesis. The secondary correlation maximum (around 0.4) appeared between 50 and 70 min. No significant correlations were found between e-folding time and scale of fluctuation of the storms with thermodynamic stability indices like CAPE and CINE. Also, no differences were found among each of the three ACF’s for storms developed during the Easterly and Westerly zonal wind regimes, in spite of the differences found in the kinematic and microphysical vertical structure characteristics [34,18,3].

Testing Taylor’s hypothesis in rainfall fields is based upon the type decaying features of the ACF’s, which are in turn associated with second-order statistical moments of the probability distribution function of the relevant stochastic processes. Analysis of higher–higher order moments of the space–time scaling of Amazonian storms indeed exhibit significant differences for storms pertaining to both Easterly and Westerly regimes [2]. As it was previously mentioned in Section 1, these results shed light towards linking the physics and statistical characteristics of Amazonian convection, but also they serve as ground truth for model testing and downscaling the results of meso-scale models over tropical land regions.

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References


