CHARACTERIZATION OF COHERENT STRUCTURES IN THE ATMOSPHERIC SURFACE LAYER

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Abstract. The ramplike coherent structures, observed in the temporal series of temperature and humidity in the atmospheric surface layer, are analyzed using the intermittency function and the wavelet transforms, with Haar, D4 and Mexican Hat functions as mother wavelets, in order to find the most efficient conditional sampling technique. It was found that the intermittency function and the wavelet transform, using Mexican Hat as mother wavelet, are the only ones that sample structures that fulfill the ramplike coherent structures definition of a slow rise followed by a sudden drop in the temporal series. The conditionally averaged structures detected by both techniques were similar for temperature, humidity, and vertical velocity at heights of 3, 5, and 9.4 m. Significant discrepancies were found among the conditional averaged structures detected by both techniques for zonal and meridional components of the wind at 11.5 m. Considering both techniques, it was observed that the averaged coherent-structure duration ranged from 23.7 ± 0.5 s to 37.8 ± 3.0 s. Furthermore, the averaged number of events per 20-minute period ranged from 20.0 ± 1.0 to 28.5 ± 1.1, and the averaged intermittency factor from 45.0 ± 0.4% to 59.1 ± 1.3%. It was also observed that the averaged duration of the ramplike coherent structures increases with height, while their intensity, number, and intermittency factor decrease. Despite the good matching obtained for temperature and humidity, the coherent-structure properties did not show the expected variation with wind speed, stability parameter, and friction velocity. The Kolmogorov–Smirnov test indicated that the intermittent function and the wavelet transform did not detect coherent structures belonging to the same population.

Keywords: Atmospheric turbulence, Coherent structures, Conditional sampling, Surface layer, Intermittency, Wavelet transform.

1. Introduction

Coherent structures have been an important subject in atmospheric turbulence research since the 1980s. This interest was intensified by Gao et al. (1989), who demonstrated that these phenomena might be responsible for up to 75% of the turbulent fluxes in the atmospheric surface layer. Later on, other authors showed that these high percentage values were observed only for particular cases. For instance,

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Lu and Fitzjarrald (1994) reported that coherent structures were responsible, on average, for about 40% of the overall turbulent heat and momentum fluxes.

Coherent structures are characteristic of large-scale turbulence in the atmospheric surface layer (Boppe et al., 1999; Paw U et al., 1992). Under convective conditions, coherent structures are recognized in time series of temperature fluctuations as a gradual rise in temperature, followed by a sudden fall (Antonia et al., 1979). Under stable conditions, this pattern inverts and a gradual fall is followed by a sudden rise (Kikuchi and Chiba, 1985). Further investigation revealed that a gradual rise followed by a sudden fall occurs in time series of humidity fluctuations not only for convective, but also stable, conditions (Gao et al., 1989).

The stability effects on the ramplike behaviour are a direct consequence of the spatial distribution of the sources of heat and moisture. For instance, during daytime the warmer air is located near to the surface, so the sudden temperature fall is due to the presence of colder air arriving from above. During the nighttime, the sudden temperature rise is associated with warmer air arriving from above. Since the source of humidity is usually situated only at the surface, the coherent structures present in time series of humidity fluctuations shown a pattern independent of stability.

Observations indicate that ramplike coherent structures are also associated with a specific wind field pattern. Qiu et al. (1995), using ensemble averages of vertical velocity and temperature, showed that the gradual rise of scalar quantities (or fall, for temperature under stable conditions) is associated with slow ascending air motion, while the sudden fall (rise) is followed by a rapidly descending air movement. Katul et al. (1997) claim that these regions of ejection (ascending) and sweep (descending) eddy motions define the spatial extent of the coherent structures.

Despite the observational efforts described above, the definitions of temporal/spatial boundaries of these phenomena are still not established. For instance, some authors such as Qiu et al. (1995), Lu and Fitzjarrald (1994), and Collineau and Brunet (1993 b), included in their definition portions of the ramplike coherent structures that follow the sudden fall. Since the definition of the boundaries is a fundamental step in the analysis of coherent structures, in the present work we decided to use the one proposed by Antonia et al. (1979). The ramp in this definition ends at the sudden fall region. This characterization is quite adequate to the application of the intermittent function sampling technique and it has been successfully used in several works (Wilczak, 1984; Paw U et al., 1992)

There is sufficient evidence indicating that the vertical wind shear is the major factor in the generation of these coherent structures in the surface layer (Antonia et al., 1979; Gao et al., 1989; Paw U et al., 1992). According to Robinson (1991), the surface-layer coherent structures are characterized by 'quasi-streamwise' and 'loop-shaped vortical' vortices. Robinson (1991) claimed that these vortices might be generated and maintained by hydrodynamic instability associated with inflection points in the instantaneous horizontal wind velocity profiles near to the surface. The complexity of these vortices may account for the large dispersion found in the properties of the ramplike coherent structures in the surface layer. For instance, vortices at different stages of development can display different responses as a sensor probes them. Boppe et al. (1999), using measurements in different levels, identified several types of structures near to the surface. They suggested that some large-scale motions, in near-neutral conditions, are associated with transverse vortical arch-like structures. In this work, it will be assumed that the ramplike coherent structures observed in the surface layer are induced by these vortices that, in turn, are generated and maintained by an inflection point instability mechanism.

Ramplike coherent structures are detected in temporal series through conditional sampling techniques, such as intermittency function (Antonia et al., 1983); VITA (Variable Interval Time Average; Schols, 1984), multi-level detection scheme (Gao et al., 1992), quadrant analysis (Boppe et al., 1999), and wavelet transform (Collineau and Brunet, 1993b; Hagelberg and Gamage, 1994). The large variety of detection methods indicates that identifying ramplike coherent structures in the surface layer is a complex task. There is considerable disagreement among these authors concerning the definition of the ramplike coherent structures boundaries. Yuan and Mokhtarzadeh-Dehghan (1994) applied several conditional sampling methods to wind tunnel turbulent data and arrived at the conclusion that 'no two methods detect exactly the same event ensemble'. Sometimes they even detect different parts of the same event. To complicate further this scenario, the capability of detection in most methods relies on subjective thresholds.

The original motivation for our research arose when we used visual identification to detect ramplike coherent structures in the temperature signal observed during a field experiment in Iperó, São Paulo (Targino and Soares, 2002). The impossibility of extending this procedure to the entire data set led us to search for conditional sampling methods and, later on, to compare several different methods (Krusche, 1997). In the search for the most efficient technique to detect ramplike coherent structures, we ended up with four: Intermittency function, and wavelet transform, using Haar, D4 and Mexican hat as the mother wavelet. It should be emphasized here that efficiency means the capability to detect the largest number of *actual* ramplike structures in the time series of temperature and humidity fluctuations.

In this work, the detection capabilities of intermittency function, and wavelet transform, using Haar, D4 and Mexican hat as mother wavelets, are explored and tested by applying these techniques to detect coherent structures in 129 series of temperature, humidity, and the vertical wind component. The dataset corresponds to 43 hours of simultaneous measurements carried out exclusively during daytime. These three parameters were measured at heights of 3.0, 5.0, 9.4 m above the surface, while the horizontal wind components were measured at 11.5 m, with a sample rate of 1 Hz. The measurements are described in Section 2, which is followed by a brief description of conditional methods used here (Section 3). The conditionally average coherent structures are determined and used as criteria to evaluate the detection efficiency of the methods in Section 4. The major properties of the detected coherent structures (event number, duration, intensity, and intermittence factor) and the results of the Kolmogorov–Smirnov test are also discussed in Section 4. Section 5 presents the conclusions.

2. Field Experiment

The data used in this work were obtained by the University of São Paulo at Iperó (23°24′ S, 47°35′ W, altitude 550 m) in Brazil during the observational campaign carried out in March 1993. Iperó is located in the country region of the State of São Paulo about 80 km west of the city of São Paulo. The observations were made at a site located in the central area of the Tiête River valley, which is crossed by the Sorocaba River valley in a north-west to south-east direction. Both valleys are very shallow, so that the main topographic feature is the 300-m high Araçoiaba Hill, located about 5 km to the south-west.

The terrain where the measurements were taken is flat, covered, at the time of the experiment, with 0.50 m high corn in the growing phase (Targino and Soares, 2002). The fetch around the micrometeorological tower was about 1,000 m in the south–east direction and 500 m in all other directions. The sensors were positioned towards the south–east quadrant because prevailing winds in the region are from the south–east. Beyond the immediate area, in the north and south directions, the cornfield was gradually replaced by small bushes and a few buildings sparsely distributed over bare soil. In all directions the terrain sloped gently outwards in such a way that these features did not obstruct the flow upstream of the micrometeorological tower.

Three sets of turbulent sensors for temperature (fine wire thermometer, model CA27, with an accuracy of 0.2 °C), water vapour density (Krypton hygrometer, model KH20, with an accuracy of 2×10^{-5} kg m^{-3}), and vertical velocity (sonic anemometer model CA27 with an accuracy of 0.05 m s^{-1}) measurements were placed on a 12-metre tower, at heights of 3.0, 5.0, 9.4 m. All instruments were manufactured by Campbell Inc. and have a response time smaller than 0.1 s. The horizontal components of the wind were measured at 11.5 m using a propeller anemometer (R. M. Young manufacturers). These wind sensors operate with an accuracy and response time comparable to the sonic anemometers. A more complete description of the sensors and the location of the experiment can be found in Targino and Soares (2002).

The data used in this work were obtained from March 8 to 21, 1993, at frequencies of 1 and 10 Hz. We selected 129 time series, which represent the temporal evolution of temperature, humidity, and wind speed fluctuations, in the surface layer, during convective conditions, corresponding to times between 1000 to 1400 local time. The time series sampled at 10 Hz (about 20% of data) were averaged to give the time series at 1 Hz. According to Gao and Li (1993), this averaging procedure does not alter the characteristics of the coherent structures, and was used here because it reduced the number of variables and, consequently, the computation time. Each time series was composed of 1,200 measurements, equivalent to a period of 20 min, and the 129 time series correspond to a total of 43 hours of measurements.

The period of the year chosen corresponds to the end of summer in the southeast of Brazil. The summer of 1993 was particularly dry, especially in Iperó where no rain was detected during the campaign. As a consequence of the absence of rain, the corn had reached an underdeveloped mature stage. As will be seen in Section 4, this fact may have had a strong impact on the pattern of coherent structures detected for humidity.

3. Methodology

Ramplike coherent structures are detected in temporal series through conditional sampling techniques, such as intermittency function, VITA, multi-level detection scheme, quadrant analysis, and wavelet transform. In this work, two types of conditional sampling, the intermittency function and the wavelet transform, will be applied to analyze the ramplike coherent structures in the surface layer under convective conditions. This choice was based on a large amount of evidence available in the literature about their ability to detect this type of event.

In general, the conditional sampling techniques, used to detect coherent structures, require a selection criterion that is a function of a minimum event duration, τ, and of a threshold level κ that establishes the circumstances under which the event will be considered (Greenhut and Khalsa, 1982). In most of the cases, visual identification is applied as a calibration procedure and as a decisive factor to choose which technique is more efficient (Paw U et al., 1992). In the description presented in the next subsections (3.1 and 3.2), special emphasis is given to how these criteria are defined in the intermittent function and wavelet transform methods.

3.1. Intermittency function

The intermittency function (or indicator function) $I_a(t)$ of a temporal series $a(t)$ is defined as (Hedley and Keffer, 1974):

$$I_a(t) = \begin{cases} 1, & \text{when } a(t) > \kappa_I \text{ during } \tau \\ 0, & \text{otherwise} \end{cases}, \tag{1}$$

where τ is the minimum event duration and κ_I is the threshold level, which is set proportional to the standard deviation σ_a of the series (Lenschow and Stephens, 1980).

This intermittency function has several advantages. It is easy to evaluate and yields not only the duration of coherent structures, but also the location of these events in the series, which is essential to determining their contribution to turbulent fluxes. As mentioned before, the main obstacle to applying this technique is the lack of criteria to determine objectively the threshold level and the minimum period event.

In this work, the threshold level is obtained as the one for which $I_a(t)$ yields the maximum number of events. This seems to be a reasonable objective criterion for selecting the threshold level, although there is no guarantee that the maximum number of events represents the actual number of events.

The minimum period event was kept constant and equal to 10 sec. This choice was motivated by the fact that the average duration of coherent structures was 30 sec. Besides, there is evidence indicating that the intermittency factor (portion of the time series occupied by the coherent structures) is relatively insensitive to the minimum period event, and therefore could be used as a non-bias factor (Antonia et al., 1983).

3.2. Wavelet transform

The wavelet transform by itself is not a conditional sampling method, but it can be easily modified in order to detect ramplike coherent structures in turbulent flows (Hagelberg and Gamage, 1994).

The one-dimensional continuous wavelet transform of function $f(x)$ is defined as:

$$W[f(\ell, x')] = \int_{-\infty}^{+\infty} F(x)\psi^*_{\ell x'}(x)dx, \tag{2}$$

where x is the one-dimensional continuous variable. The kernel of the transform is $\psi^*_{\ell x'} = \ell^{-1/2}\ \psi((x - x')/\ell)$, where $\psi(x, \ell)$ is the mother wavelet that undergoes translation by space (or time) variable x', and dilation by scale (or frequency) ℓ.

It can be noticed that the wavelet transform acts as a harmonic analysis, expressing the function $f(x)$ as a superposition of contributions, which have the same shape as the mother wavelet.

To apply wavelet transform to detect coherent structures, the properties of the wavelet transform variance are useful. According to Collineau and Brunet (1993a), the time scale τ_0 associated with the maximum wavelet transform variance is proportional to the mean duration D of the most energetic events. The constant of proportionality is equal to the inverse of the frequency at the main peak of mother wavelet Fourier spectrum density times π. Gao and Li (1993), for instance, applied successfully this concept to evaluate the time scales of the dominant structures within and above a deciduous forest canopy.

The wavelet variance can have more than one local maximum, due to the contribution from larger scales to the total energy of the signal (Hagelberg and Gamage, 1994), but it was assumed here that the first maximum is the most representative scale for the coherent structures.

Thus, a time series can be constructed for each variable, by using the wavelet transform coefficients of scale, τ_0, containing the transformed signal related to the coherent structures. The intermittency function can then be applied using a zero threshold level. In this case the indicator function $To_a(t)$ can be written as:

$$To_a(t) = \begin{cases} 1, & \text{when } W[a(\ell_{\max}, t)] > 0 \\ 0, & \text{otherwise} \end{cases}, \tag{3}$$

where $W[a(\ell_{\max}, t)]$ represents the wavelet coefficients, for scale $\ell_{\max}$, of the original series $a(t)$. To build mean events, the expression for the conditional average:

$$\langle a(t) \rangle = (1/N) \sum_{i=1}^{N} a(t + t_i) \tag{4}$$

is evaluated, where $a(t)$ is the original series, $t \in [0, \tau_m)$, where τ_m is the period of event duration, and N is the number of events with duration τ_m (Collineau and Brunet, 1993b).

This procedure was systematically applied here and can be considered as a simplification of Hagelberg and Gamage's (1994) method. Their method involves the reconstruction of the original series by using two transformed signals, one of scale τ_0, and other containing all the other scales.

The results of any method of analysis using wavelet transform, including the one described above, will strongly depend on the choice of the wavelets (Hagelberg and Gamage, 1994), because the wavelet transform evaluates the similarity between the wavelet $\psi_{1x'}(x)$ and the function $f(x)$. Therefore, in this work, three mother wavelets were selected: (a) Haar, (b) D4, and (c) Mexican hat. The Haar function was chosen because it is one of the most used in atmospheric turbulence studies. The D4 function was preferred because it is similar to the ramplike coherent structure investigated here. The Mexican hat function was selected because, according to Collineau and Brunet (1993a), it is the most suitable for detecting ramplike coherent structures in the surface layer.

3.3. Kolmogorov–Smirnov Test

Kolmogorov introduced, in 1933, a goodness-of-fit test to evaluate whether a random sample, from an unknown distribution function, is in fact the specified function. It is considered more powerful than the chi-square test in most situations. Smirnov, in 1939, proposed a two-sample version of the Kolmogorov test, which determines whether two distribution functions, associated with two populations, are identical (Conover, 1999). This non-parametric test is sometimes called the Kolmogorov–Smirnov test.

Two mutually independent samples are considered, one that belongs to a continuous population Π_1, and the other to a continuous population Π_2. The hypothesis is that Π_1 and Π_2 are identical ever since:

$$P(x_1 \leq a) = P(x_2 \leq a), \tag{5}$$

for all a, where a is the continuous variable, and x_1 (x_2) belongs to population Π_1 (Π_2), and P represents probability (Hollander and Wolfe, 1999).

If the two samples are represented by distribution functions $F(x)$ and $G(x)$, respectively, the hypothesis assume the following form:

$$F(x) = G(x), \tag{6}$$

for all x from $-\infty$ to $+\infty$.

To test this hypothesis, empirical distribution functions are proposed for the first sample, $S_1(x)$, and for the second sample, $S_2(x)$. The greatest vertical distance between them, T, is calculated as:

$$T = \sup |S_1(x) - S_2(x)|, \tag{7}$$

where sup represents the maximum of the series (Conover, 1999).

For large samples and a level of significance of 10%, the hypothesis (7) is valid when T is smaller than

$$W_{0.9} = 1.22\sqrt{\frac{n_1 + n_2}{n_1 n_2}}, \tag{8}$$

where n_1 and n_2 are the sample sizes.

4. Results and Discussion

The wavelet transform variance was calculated for all 129 data sets, using Haar, D4, and Mexican Hat (MH) as mother wavelet. For now on, MH wavelet transform denotes the wavelet transform, which uses Mexican Hat as mother wavelet. Similar notation will be used for Haar and D4. Since there was strong evidence that the latter is the most appropriate mother wavelet for this kind of application (Collineau and Brunet, 1993a; Krusche, 1997), the mean duration obtained from MH wavelet transform variance was considered as the input parameter to evaluate the other two.

Two constraints were applied to the data set. The first one was based on the assumption that the mean duration obtained by using any mother wavelet (MH, Haar, and D4) should be similar for each individual data run, since they represent the duration of the same mean event. Therefore, individual data runs were removed from the analysis when (a) their mean duration obtained from Haar or D4 wavelet transform variances exceeded twice the mean duration obtained from MH wavelet transform variance, or (b) their mean duration, obtained from Haar or D4 wavelet transform variances, were smaller than half their mean duration obtained from MH wavelet transform variance. In the second constraint, the individual data runs were removed from the analysis when the time scale of maximum variance was the smaller possible time scale of the wavelet variance. This latter constraint is based on the fact that the time scale of maximum variance must be larger than the minimum time scale of the wavelet variance. It should be emphasized that the wavelet transform variance, using MH as mother wavelet, was calculated for scales up to 100 sec, in order to represent a mean duration as long as 222 sec. The Haar and D4 wavelet transform variances were calculated up to 150 sec, to represent mean durations as long as 101 sec.

Intermittent function and Haar, D4 and MH wavelet transforms were then applied to the resulting data set. Figure 1 exemplifies the detection ability using intermittent function and MH wavelet transform for temperature and humidity simultaneously observed at 9.4 m during the field experiment in Iperó.

4.1. Averaged Structures

The frequency distributions of the coherent-structure duration (not shown here) obtained from temperature and humidity observations at three levels (3.0, 5.0, 9.4 m) were very well characterized by an exponential frequency distribution for all four methods used here. Therefore, we decided to evaluate the average coherent structure by taking only the first six intervals of the frequency distribution of the coherent-structure duration. This assumption was based on the fact that all six intervals have an absolute frequency larger than 30, which is large enough to quantify the average for each interval and to visualize the part of the coherent structures that is really sampled by the methods used here.

As can be seen in Figure 2, both the intermittency function and MH wavelet transform sampled the signal previous to the sudden fall. The Haar and D4 wavelet transforms sampled the signal around the sudden fall, with the D4 wavelet transform sampling a little less after the sudden fall.

Since the coherent structures are, by definition, characterized by a slow rise and sudden fall in the time series of temperature and humidity fluctuations, we conclude that the average structure resulting from the application of Haar and D4 wavelet transforms did not satisfy this definition. Therefore, only the properties of the average coherent structure obtained from the intermittent function and MH wavelet transform will be considered hereafter.

The behaviour of coherent structures detected in humidity signal resembles the ones in the temperature (Figure 3). It also shows the same pattern for the vertical wind velocity component. This indicates that, on average, the detected coherent structures are characterized by a slow ascending movement followed by a quicker descending one at the end of the ramp.

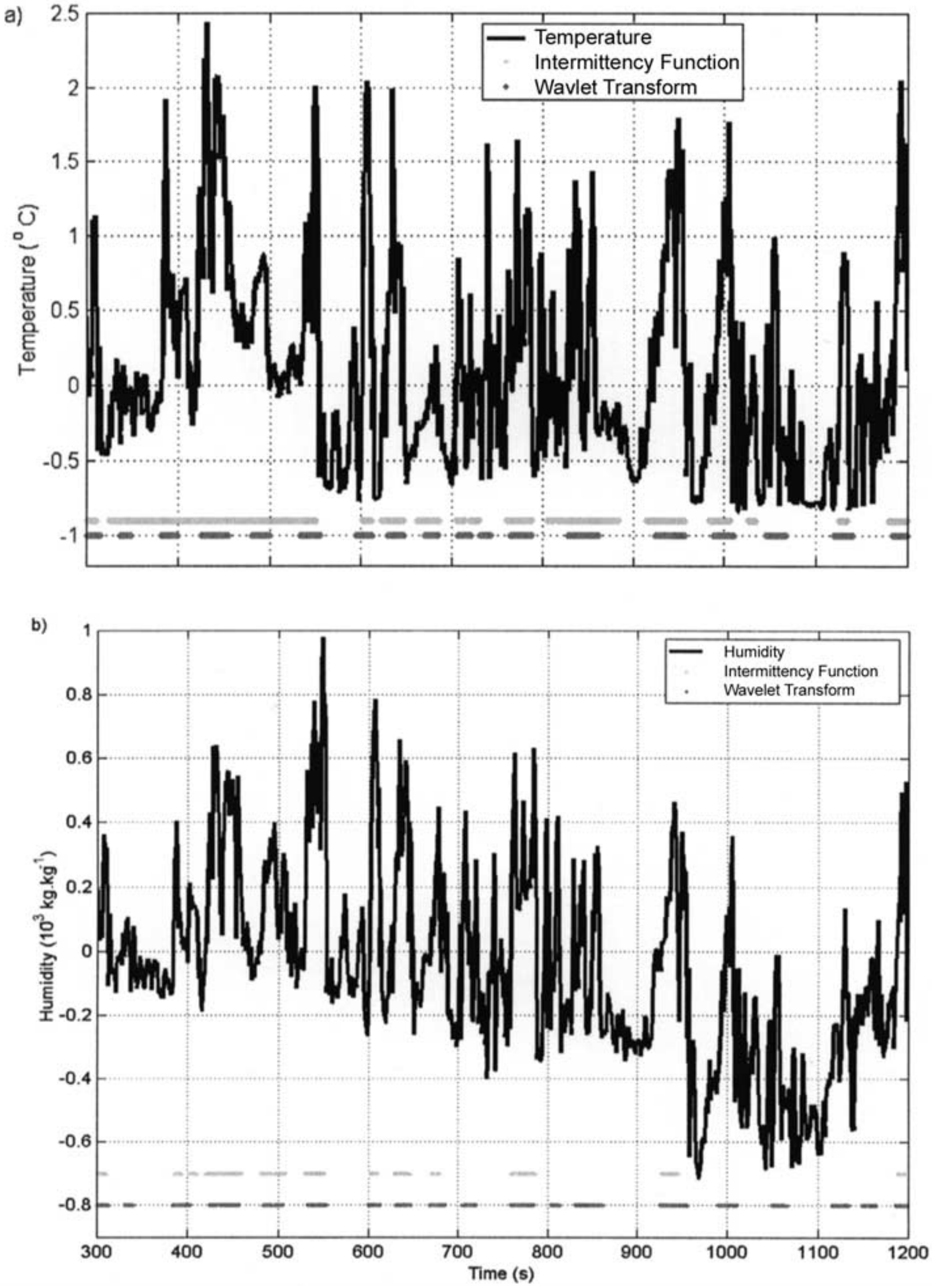

Figure 1. Example of ramplike coherent structures detected by the intermittency function and Mexican Hat wavelet transform in the (a) temperature and (b) humidity series observed at 9.4 m in Iperó.

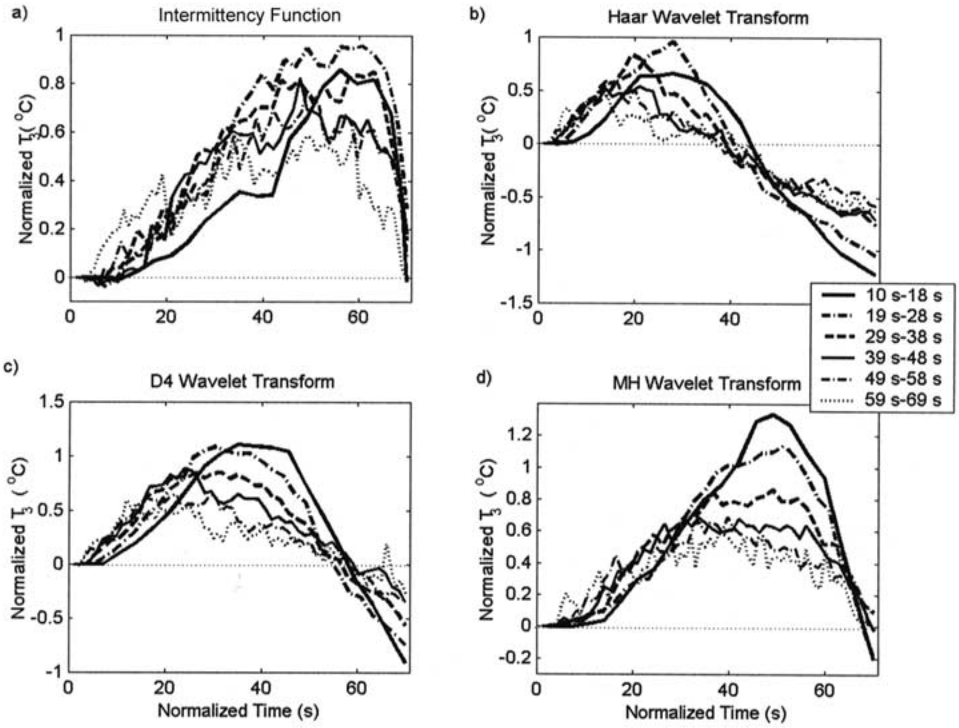

Figure 2. Conditionally averaged coherent structures detected in temperature series for (a) the intermittency function, (b) Haar, (c) D4, and (d) Mexican Hat wavelet transforms. Results obtained for six intervals of duration, which are shown in the box on the right, along with the legend to the curves in each figure. The average structure is the average over all structures detected in each interval, and normalized in intervals of 70 sec. Observations carried out at 9.4 m.

To establish the average values for longitudinal and transversal wind velocities, the horizontal wind velocity components were aligned to the mean wind (Figure 4). In these cases, the average events are not as well defined as they were in the other signals (Figure 3).

4.2. Properties of Coherent Structures

The characterization of the ramplike coherent structures is based on: (a) The number of events in a 20-min interval, (b) the duration, (c) the intensity, which is the maximum amplitude of the ramp, and (d) the intermittency factor, which is the fraction of the time series occupied by the coherent structures. The results shown in Table I indicate that the number of events decreases with height for both temperature and humidity, ranging from a maximum of 28.5 ± 1.1 events, at 3.0 m, to a minimum of 20.0 ± 1.0 events, at 9.4 m. These results agree with those available in the literature for convective conditions (Wilczak and Tillman, 1980). They indicate

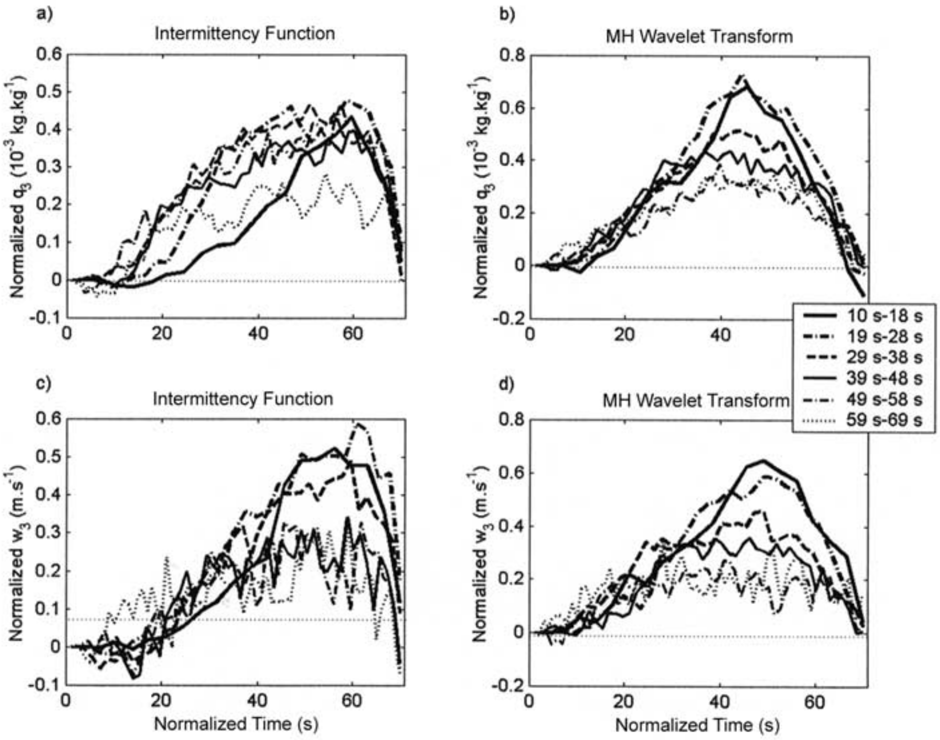

Figure 3. Conditionally averaged coherent structures detected in humidity series for (a) the intermittency function and (b) Mexican Hat wavelet transform. Conditionally averaged coherent structures detected in the vertical velocity component series using (c) the intermittency function and (d) Mexican Hat wavelet transform, are also shown. Results are obtained from six intervals of duration and normalized in intervals of 70 sec. Both variables were measured at 9.4 m.

that the shorter coherent structures tend to merge into the larger ones as the height increases in the convective surface layer.

The numbers of events detected by both methods are similar for temperature and humidity (Table I). The number of detected structures is within the range of the dispersion given by the standard deviation of both methods. This agreement was first noticed by Gao et al. (1992), and is typical of a homogeneous surface, covered by vegetation, which is not active as a source of moisture in the vertical transport of humidity carried out by the coherent structures (Hill et al., 1989). As mentioned in Section 2, the observations described here were made during a dry period, when the cornfield in the site had already reached the mature stage, and most of the evaporation came directly from the ground.

It was found that the intermittency factor also decreased with height, varying from 45.0 ± 0.4% at 5.0 m for humidity, to 59.1 ± 1.3% at 3.0 m for temperature. The range and magnitude of all intermittency factors are systematically larger for the events detected by the intermittency function (Table I). The MH wavelet

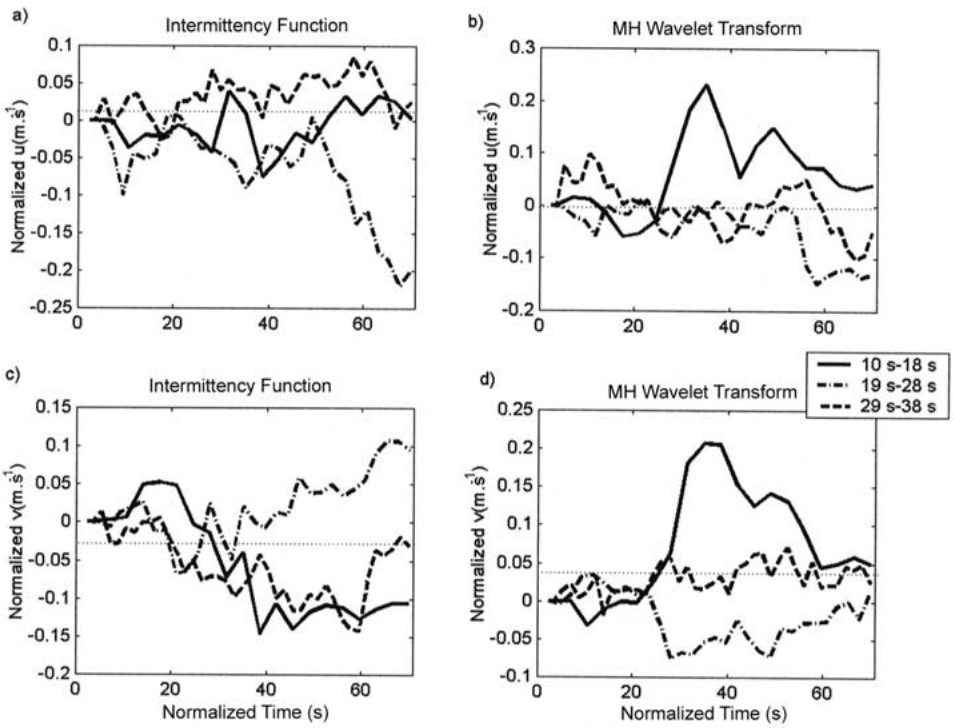

Figure 4. Conditionally averaged coherent structures of longitudinal wind velocity component in (a) and (b), while the transversal wind velocity component are presented in (c) and (d), measured at 11.5 m and associated with coherent structures detected in the temperature series measured at 9.4 m. We used the intermittency function in (a) and (c), and the Mexican Hat wavelet transform in (b) and (d). Results are obtained from three intervals of duration and normalized in intervals of 70 sec.

TABLE I

Number of events in a 20-min period and intermittency factor for the ramp-like coherent structures detected in the signals of temperature (T) and of humidity (q), measured at the lowest (1), middle (2), and uppermost (3) level on the tower, using the intermittency function and Mexican Hat (MH) wavelet transform.

	Number of events		Intermittency factor (%)	
	Intermittency function	MH wavelet transform	Intermittency function	MH wavelet transform
T_1	26.5 ± 0.8	27.8 ± 0.9	55.2 ± 1.1	45.4 ± 0.4
T_2	25.1 ± 0.9	22.6 ± 1.1	49.7 ± 1.4	45.0 ± 0.4
T_3	22.1 ± 0.8	24.4 ± 1.0	50.6 ± 1.3	45.1 ± 0.4
q_1	28.5 ± 1.1	25.7 ± 1.0	59.1 ± 1.3	47.0 ± 0.4
q_2	25.7 ± 0.9	22.8 ± 1.0	55.5 ± 1.2	46.7 ± 0.4
q_3	21.2 ± 0.8	20.0 ± 1.0	53.5 ± 1.5	46.5 ± 0.4

TABLE II

Duration of ramplike coherent structures detected in the signals of temperature (T) and humidity (q), measured at the lowest (1), middle (2), and uppermost (3) level on the tower, using the Mexican Hat (MH) wavelet transform variance, intermittency function, and Mexican Hat (MH) wavelet transform.

	Duration (s)			Intensity (°C or 10^{-3} kg m^{-3})	
	MH wavelet transform variance	Intermittency function	MH wavelet transform	Intermittency function	MH wavelet transform
T_1	25.8 ± 2.5	24.6 ± 0.4	25.0 ± 2.0	1.42 ± 0.04	1.51 ± 0.04
T_2	34.0 ± 2.6	23.7 ± 0.5	30.4 ± 1.9	1.05 ± 0.06	1.11 ± 0.07
T_3	27.2 ± 1.8	27.1 ± 0.6	26.8 ± 1.6	1.08 ± 0.03	1.11 ± 0.04
q_1	28.4 ± 2.2	25.4 ± 0.5	27.7 ± 1.8	0.70 ± 0.02	0.79 ± 0.03
q_2	32.3 ± 2.4	26.1 ± 0.5	31.8 ± 2.1	0.64 ± 0.02	0.71 ± 0.02
q_3	37.8 ± 3.0	29.4 ± 0.7	36.3 ± 2.7	0.63 ± 0.05	0.70 ± 0.05

transform yields values of intermittency factor ranging from 45.0 ± 0.4% to 47.0 ± 0.4. These values are close to the 42% proposed by Wilczak (1984) as typical of a ramplike coherent structure in the convective surface layer.

The average durations for temperature and humidity are displayed in Table II. The first column, for duration, was obtained using Collineau and Brunet's variance method, while the other two columns were obtained using an intermittency function and MH wavelet transform. It can be observed that the average duration usually increases with height, while the average intensity decreases. This indicates that coherent structures detected at higher levels are usually longer and less intense than the ones detected at lower levels in the surface layer. It should be emphasized that, although the frequency distribution of duration is highly asymmetric, its mean value still characterizes the quantity under analysis, since the duration of the coherent structures is highly variable in the surface layer.

Three parameters were selected to evaluate the relationship between the coherent structures and the characteristics of the flow: the mean wind intensity (U), which yields the strength of the mechanical source of turbulent kinetic energy; the stability parameter (z/L), which characterizes the thermal stratification; and the friction velocity (u_*), which indicates the intensity of turbulence. It should be emphasized here that the Obukhov length (L) and friction velocity used in this evaluation were estimated using vertical turbulent fluxes of sensible heat and momentum obtained from raw data without any averaging procedure (Targino and Soares, 2002). Figures 5–7 show the distribution of the coherent structures duration for eight intervals of wind intensity, stability parameter, and friction velocity, resulting from the application of the intermittency function and MH wavelet transform

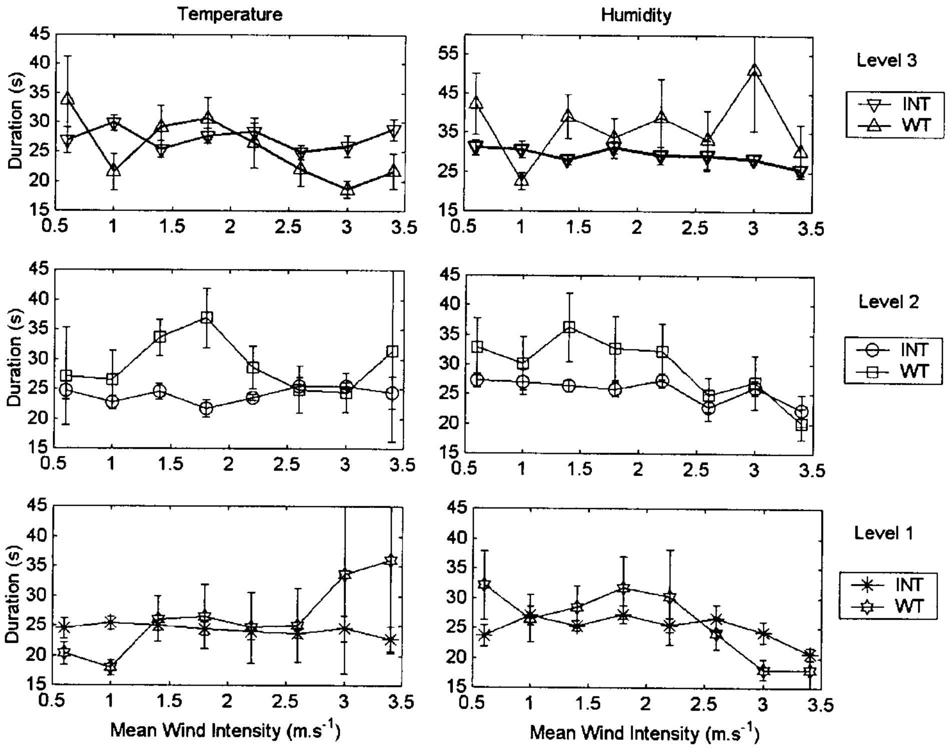

Figure 5. Distribution of the coherent-structures duration for 8 intervals of mean wind intensity (U). The average values were obtained by applying the intermittency function (INT) and MH wavelet transform (WT) for temperature (left column) and humidity (right column) observed at levels 1 (bottom line), 2 (intermediate line), and 3 (top line).

on temperature and humidity signals observed at the three different levels. In these figures, each interval is indicated by a mean value (open square) and its respective error (vertical bar). For the mean wind intensity and the friction velocity, most of the duration values occur in the middle of the total variation interval, while for the stability parameters most of the values occur for near-neutral conditions.

The analysis of coherent-structure properties may be also carried out using length scale instead of duration of the events. The coherent-structure duration can be converted to the coherent-structure length by applying Taylor hypothesis. The analysis presented here was based on time duration. This choice was made because winds are not so strong in the Ipero area and the application of Taylor's hypothesis reduced our data set to a half of the original size. Secondly, the frequency distributions of the coherent-structure length for intervals of wind intensity, stability parameter, and friction velocity (not shown here) based on the smaller set of data were very similar to the ones shown in Figures 5–7. There is also observational evidence indicanting that coherent structures travel at a speed different to the mean

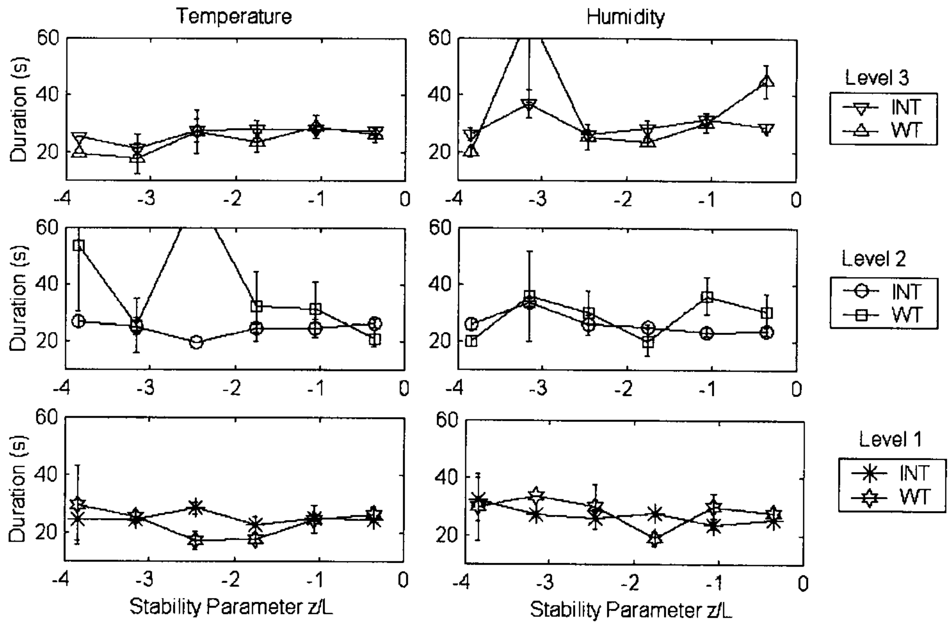

Figure 6. Distribution of the coherent-structure duration for six intervals of the stability parameter (z/L). The average values were obtained by applying the intermittency function (INT) and MH wavelet transform (WT) for temperature (left column) and humidity (right column) observed at levels 1 (bottom line), 2 (intermediate line), and 3 (top line).

wind speed (Wilczak,1984); therefore extra care should be taken in applying the Taylor's hypothesis under these conditions.

The search for a relationship between duration or length and characteristics of the flow may produce better results if it is carried out for each interval of duration established by the frequency distribution of duration. It is clear from Figure 2 that the structures that last longer are the ones that differ more from the proposed definition of ramplike coherent structures. This problem will be addressed in a future work.

Finally, the Kolmogorov–Smirnov test was applied to evaluate whether the frequency distributions of the duration of coherent structures detected in any two samples were taken from the same population. At first, the test was used to evaluate whether the coherent-structure duration obtained by intermittent function and MH wavelet transform belong to the same population for both temperature and humidity, observed at the three different levels. All test results (six) indicate that the values of coherent-structure duration obtained by intermittent function and MH wavelet transform do not belong to the same population (Table III). A visual inspection of the average temperature and humidity event detected by intermittent function (Figures 2a and 3a) and by MH wavelet transform (Figures 2d and 3b) confirms this disagreement. The results obtained with these two methods for temperature and humidity measured at the other two levels (not shown here) lead us to

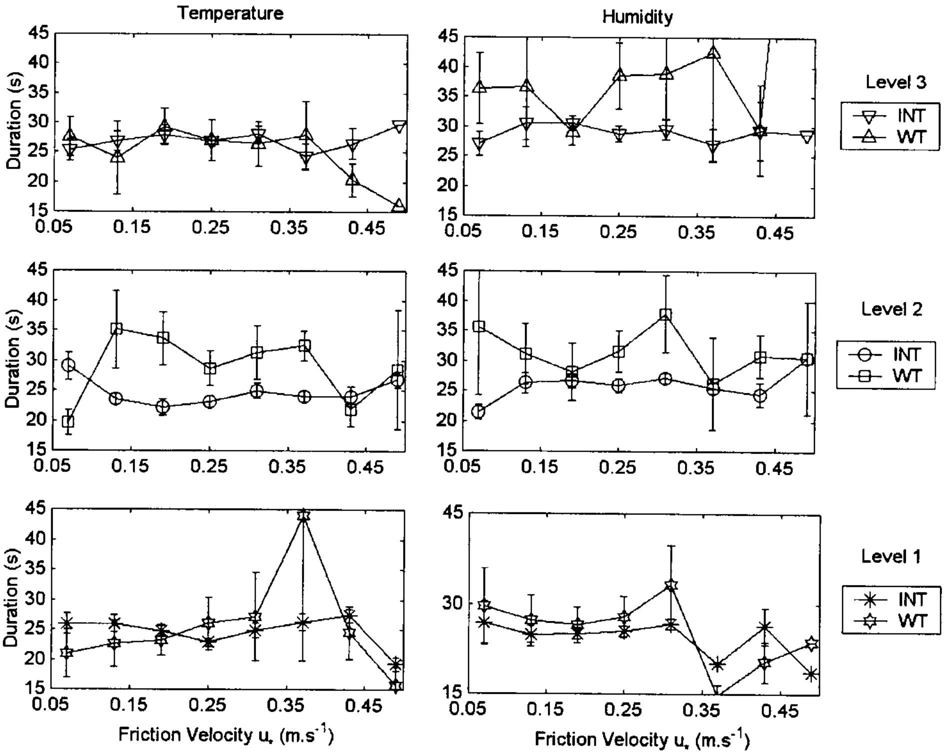

Figure 7. Distribution of the coherent-structure duration for eight intervals of friction velocity (u_*). The average values were obtained by applying the intermittency function (INT) and MH wavelet transform (WT) for temperature (left column) and humidity (right column) observed at levels 1 (bottom line), 2 (intermediate line), and 3 (top line).

a similar conclusion. An explanation for this disagreement is that the wavelet transform method is not capable of detecting features as sharp as the ones near the end of the ramplike coherent structures. Therefore, many detected events are probably in the region after the sudden fall, resulting in a less sudden fall on average.

Next, the test was applied to determine if the coherent structure duration in the temperature and humidity series, detected by intermittent function and MH wavelet transform at all three levels, belong to the same population. The results, presented in Table III, indicate that the coherent-structure duration detected in the temperature and humidity series belongs to the same population at levels 1 and 3, when detected using intermittent function and with a level of significance of 10%. The same conclusion was obtained using the MH wavelet transform at level 2 (Table III). These results should be investigated further.

TABLE III

Kolmogorov–Smirnov test results. The three columns on the left (Method) show the results for coherent structures detected in the signals of temperature (T) and humidity (q), measured at the lowest (1), middle (2), and uppermost (3) levels on the tower, using the intermittency function (INT), and MH wavelet transform (MHWT). The three columns on the right (Tracer) show the results for coherent structures detected using the intermittency function (INT), and the MH wavelet transform (MHWT), at the three levels of measurement, for temperature and humidity. $W_{0.9}$ is the maximum value for the test at a level of significance of 10%. The results that satisfy that level of significance are indicated in italic.

	Method			Tracer	
	INT and MHWT	$W_{0.9}$		T and q	$W_{0.9}$
T_1	0.119	0.034	Int_1	*0.021*	0.033
T_2	0.145	0.039	Int_2	0.058	0.036
T_3	0.092	0.040	Int_3	*0.038*	0.042
q_1	0.070	0.034	MHWT_1	0.096	0.035
q_2	0.084	0.036	MHWT_2	*0.025*	0.039
q_3	0.160	0.044	MHWT_3	0.170	0.042

5. Conclusions

In this work, the detection capabilities of the intermittent function, Haar, D4, and Mexican hat wavelet transforms are explored and tested by applying these techniques to detect coherent structures in 129 series of temperature and humidity fluctuations. This dataset corresponds to 43 hr of simultaneous measurements carried out exclusively during daytime, at three levels, 3, 5 and 9.4 m, over a flat and homogeneous area covered by cornfield and located in Iperó, São Paulo, Brazil.

Modifications were introduced in the conditional sampling methods used here to minimize their dependence on the selection criteria. An objective threshold level was applied to the intermittency function, while an adaptation of Hagelberg and Gamage's (1994) criteria was used in conjunction with the wavelet transform techniques. The results indicated that both methods have a similar capability for detecting coherent structures. However, the average ramplike coherent structures, defined by a slow rise followed by a sudden fall in the signals of temperature and humidity are best identified by the intermittency function and, secondly, by the Mexican Hat wavelet transform. The analysis of the average structures presented here confirmed that the efficiency of wavelet transform techniques depends strongly on the mother wavelet. For instance, the Haar wavelet transform samples the region around the sudden fall, while the D4 wavelet transform samples a little less than the Haar wavelet transform after the sudden fall. Therefore, there is still a need to define more precisely the ramplike coherent structures to compare results obtained by different researchers.

The resulting conditionally averaged structures, detected by intermittency function and Mexican hat wavelet transform, were similar for temperature, humidity, and vertical velocity, observed at heights of 3, 5 and 9.4 m. However, large discrepancies were found for zonal and meridional components of the wind at 11.5 m.

The intermittency function and Mexican Hat wavelet transform were applied to characterize the ramplike coherent structures based on a number of events normalized by 20-min interval, duration, intensity, and intermittency factor. The results indicate that the duration of coherent structures have an exponential frequency distribution characteristic of homogenous terrain. Their average duration increases with height, while their intensity, number, and intermittency factor decrease with height. The average duration ranged from 23.7 ± 0.5 s to 37.8 ± 3.0 s. The number, in a 20-min period, and the intensity of the events ranged from 20.0 ± 1.0 to 28.5 ± 1.1 and from $45.0 \pm 0.4\%$ and $59.1 \pm 1.3\%$, respectively.

No significant relationship was identified between the coherent-structure properties (number of events, duration, intensity) and characteristic of the surface-layer flow, such as the mean wind velocity, friction velocity, and stability parameter. Even though this result requires further investigation, it casts some doubts on the possibility of developing a parameterization of the coherent-structure contribution to the turbulent fluxes in terms of the mean properties of the flow.

Finally, despite the good matching obtained by the intermittent function and MH wavelet transform, the Kolmogorov–Smirnov test indicated that the results of these two methods do not belong to the same populations. This unexpected result indicates that the conclusion of Yuan and Mokhtarzadeh-Dehghan (1994) is also valid in this case. It is important to note that the results presented here are not final. Further investigations must be made in order to define which parameters are the most relevant in the depiction of the ramplike structures. Since Boppe et al. (1999) identify several kinds of structures in the surface layer the conditional sampling methods must be improved to be able to distinguish ramplike coherent structures unmistakably among them. That should improve the identification of a relationship between their properties and the characteristics of surface-layer flow.

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