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VARIATION OF SENSIBLE HEAT TURBULENT FLUXES DURING MAY, 1995, IN CANDIOTA, RS, BRAZIL

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Abstract. Sensible heat turbulent fluxes transport to the atmosphere part of the energy stored by the surface. Numerical models must parameterize suitably the response of those fluxes to the influence of local conditions. This research evaluated the turbulent fluxes and the contribution of ejection and sweep regions to them, along with their variations under local conditions. Data was measured in south of Brazil, in May 30th, 1995. The estimated roughness length corroborates previous results about the homogeneity of the region. The most significant variations of the sensible heat flux were due to stability conditions, with values from 106.2 Wm^{-2}, in convective period, to -25.4 Wm^{-2}, in stable one. Quadrant analysis clearly reveals the transition from the stable to the convective period. In the convective period, the ejections contributed more to the turbulent fluxes, while the duration, which is the period spent in each quadrant, of the sweeps is smaller than the ejections. In the night, the reverse occurs, but the interactions are as intense as the ejections and sweeps. The interactions are small in the convective period. Further investigation of the heat fluxes, especially during the stable period, might provide information that may lead to a parameterization of ejections and sweeps.

Keywords: sensible heat flux, quadrant analysis, ejections and sweeps.

1. Introduction

The lower region of the atmosphere is directly influenced by the surface. The part of the troposphere that respond to the surface forcings with timescale of up to one hour define the Planetary Boundary Layer (PBL) (Stull, 1988). This region is dominated by turbulence. During the day, the turbulence is mainly due to the diurnal heating cycle, generating the Mixing Layer. The topography and the wind shear generate the mechanical turbulence that is present in the Stable Nocturnal Layer (Stull, 1988).

Random fluctuations of wind velocity, temperature, and other scalar quantities reveal the occurrence of a turbulent flow. The turbulence is usually much more efficient to transport properties than molecular diffusion (Tennekes e Lumley,1990). Therefore, turbulence regulates the momentum, sensible, and latent heat fluxes. It also have a relevant role in the dispersion of atmospheric pollutants (Lamesa, 2001). The computation of these turbulent transports is important to evaluate their parameterizations in numerical models design for pollutant dispersion, or for weather forecasting, where their contribution is in the subgrid energy. In the latter, the determination of the PBL height and of the atmospheric stability is essential to parameterize the dispersion, since the diurnal convection enhance the atmospheric diffusive properties, while the nocturnal stability inhibit vertical movements.

Quadrant analysis is useful to divide, in wall-bounded turbulent shear flows, events associated to downdrafts (sweeps) or updrafts (ejections) which are the constitutive motions of several kinds of quasi-coherent motions in the Surface Layer, such as buoyancy generated thermals and shear-related transverse vortices (Boppe et al., 1999). Katul et al. (1998) have demonstrated that the mean momentum ejection and sweep frequencies, evaluated at sites with different roughness lengths, are constant and independent of the longitudinal velocity skewness. Nevertheless, the mean scalar sweep time fraction depends on the temperature skewness, while the mean scalar ejection time fraction was constant. That might indicate a relationship between sweep time fraction and the skewness for heat.

Heckler et al. (2003) have applied a procedure, similar to the one that will be presented in this article, to the turbulent data obtained on March, 2002, during the I Meteorological Experiment in Rio Grande, RS. They evaluate that the sensible heat fluxes did not vary perceptible with the mean wind direction or the roughness length, but they had a tendency to be susceptible to the mean wind intensity and the friction velocity. The quadrant analysis indicated the inversion of quadrants with the change of stability and the strong variability associated to this transition. The duration of the ejections were larger in the stable period, while the duration of the sweeps dominated the convective period.

The turbulent data was obtained in the experiment in Rio Grande during just three convective periods and a stable one. Therefore, analysis of a larger database is necessary to validate those conclusions. The measurements performed during an experiment in Candiota, RS, in May 1995, were used. Moraes (2000) provides a complete description of that experiment. Since the terrain is quite homogenous in this region, the data is adequate to study variations in the sensible heat fluxes associated to local conditions, as the roughness length and the atmospheric stability. Sensible heat turbulent fluxes were also evaluated for their stress fraction and duration.

We will present the first results of that investigation, performed for just one day, which includes the stable and the convective periods. This analysis have already shown some interesting information that is quite different from the one obtained for Rio Grande's dataset. In the next section, the data, along with the stability and roughness parameters and the quadrant analysis technique, will be briefly described. The results and discussions will be presented at the following section. The last section contains our conclusions.

2. Methodology

The data is compose by measurements of vertical velocity, specific humidity, and temperature, collected with high respond sensors at a 10 m level, with a sampling frequency of 1 Hz, along with measurements of longitudinal and transverse velocity, collected with Gill anemometers. They were measured in May, 1995, during one of the field experiment that took place in Candiota, RS. A selection was performed, using a quality control procedure developed by Vickers and Mahrt (1996), resulting in about 14 hours of data for day 150 (May, 30th 1995), 5 hours in the stable period and 9 in the convective one.

2.1 Stability and Roughness Parameters:

The stability parameter ζ is a relation between the height of measurement z and the Obukhov length L, which is proportional to the height above the surface where the buoyant generation of turbulence first dominates over the mechanical production. In convective conditions, $\zeta \approx -0.5$, which means that $z \approx -0.5L$ (Stull, 1988).

The Obukhov length is inversely proportional to the sensible flux at the surface, and follows the expression:

$$L = -\frac{T_v u_*^3}{\kappa g (\overline{w'T'})_s} \tag{1}$$

where T_v is the virtual temperature, u_* is the friction velocity, κ=0.4 is the Von Karman constant, g=9.8 m.s^{-1} is the gravity acceleration, $(\overline{w'T'})_s$ is the turbulent sensible heat vertical flux at the surface. That is supposed to be the same as the one measured at 10 m, applying the definition of Surface Layer, which states that the turbulent fluxes vary by less than 10% in magnitude in this region (Stull, 1988).

Turbulent vertical fluxes are mainly positive during the day, when the buoyant processes dominate. Therefore, the Obukhov length and, as a consequence, the stability parameter are negative in convective periods. Conversely, they are positive in stable situations, and null when the conditions are neutral.

The roughness length is define as the average height of the roughness elements that compose a surface (Stull, 1988). The logarithmic wind profile, along with the Businger-Dyer relationships to adjust it to different stability conditions, might be applied to estimate the roughness length (Stull, 1988). The wind profile is inverted and the following expression is obtained:

$$z_o = z.\exp\left(\Psi(\zeta) - \frac{\kappa \overline{M}}{u_*}\right) \tag{2}$$

with

$$\Psi(\zeta) = \begin{cases} 4.7\zeta & \text{if} \quad \zeta > 0 \\ 0 & \text{if} \quad \zeta = 0 \\ -2\ln\left[\frac{(1+x)}{2}\right] - \ln\left(\frac{(1+x^2)}{2}\right) + 2\tan^{-1}(x) - \frac{\pi}{2} & \text{if} \quad \zeta < 0 \end{cases} \tag{3}$$

and

$$\zeta = \frac{z}{L} \qquad\qquad x = [1 - 15\,\zeta\,]^{1/4} . \tag{4}$$

where z is the height of measurement, L is the Obukhov length, κ=0.4 is the Von Karman constant, $\overline{M}$ is the mean wind velocity, u_* is the friction velocity, and ζ is the stability parameter.

2.2 Quadrant Analysis

This technique is quite useful to identify and quantify the contributions to vertical turbulent fluxes to an event, or during a period of time. It consists in dividing the vertical flux in four sectors, according to the vertical movement and the sign of the other turbulent variable, which may be the horizontal velocity or a scalar such as temperature, humidity, or gas concentration (Gao et al., 1989). For the sensible flux, in the convective period, the first sector is associated to ejections, when a updraft carries warm air; the third sector is related to sweeps, when a downdraft transports cold air, and the other two sectors are called interactions. During the stable period, an ejection will be associated to an updraft carrying cold air, and a sweep, to a downdraft transporting warmer air. Figure (1) presents those definitions. It is important to notice that, although the scheme is the same for other scalar quantities, it has to be adapted to study momentum flux, when ejections are associated to negative horizontal movement.

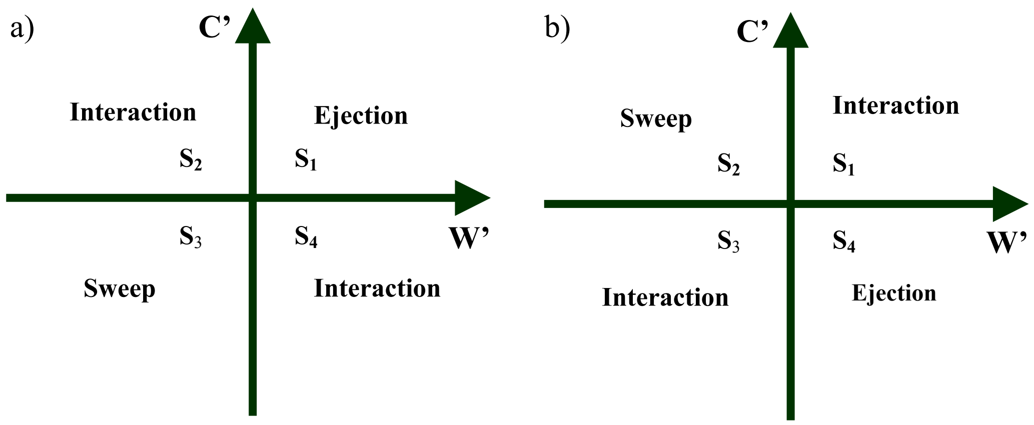

Figure 1 Quadrant analysis scheme is presented for a) convective period; b) stable period, showing ejection, sweep, and interaction sectors, along with S_i, i=1,2,3,4, which represents the stress fractions.

There are several ways to discuss the results provided by this technique. The one proposed by Katul et al. (1997) will be applied to the selected dataset. Those authors define the stress fraction S_i for quadrant *i* as the flux contribution from that quadrant to the total flux. That can be expressed as:

$$S_i = \frac{\langle\langle wc \rangle\rangle_i}{wc} \tag{5}$$

where

$$\langle\langle wc \rangle\rangle_i = \frac{1}{T_p} \int_0^{T_p} w(t)c(t)I_i dt \tag{6}$$

and where w(t) is the vertical velocity turbulent component, c(t) is the scalar turbulent component, wc is the vertical turbulent flux due to scalar c, T_p is the sampling period, $\langle\langle \ \rangle\rangle$ are conditional averages and I_i is the indicator function defined by:

$$I_i = \begin{cases} 1, & \text{if coordinates (w,c) are within quadrant i, i=1,2,3,4} \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

with $S_1+S_2+S_3+S_4=1$.

The total duration of events in quadrant i or time fraction of measurement events in quadrant i is also defined by Katul et al. (1997) as:

$$D_i = \frac{1}{T_p} \int_0^{T_p} I_i(t)\, dt \tag{8}$$

where D_1 and D_4 are total ejection duration and D_3 and D_2 are total sweep duration, in sampling period T_P, for convective and stable situations, respectively.

Katul et al. (1997) also evaluated an expression for the difference between stress fractions due to sweeps and ejections (ΔS), obtained through third order cumulant expansion method. ΔS is a measure of the relative importance of the two types of mechanisms (sweeps and ejections). The expression might be written as:

$$\Delta S_o = \frac{R_{wc} + 1}{R_{wc}\sqrt{2\pi}} \left(\frac{2C_1}{(1 + R_{wc})^2} + \frac{C_2}{1 + R_{WC}} \right) \tag{9}$$

where

$$C_1 = (1 + R_{wc}) \left(\frac{1}{6}(M_{03} - M_{30}) + \frac{1}{2}(M_{21} - M_{12}) \right) \tag{10}$$

$$C_2 = -\left(\frac{1}{6}(2 - R_{wc})(M_{03} - M_{30}) + \frac{1}{2}(M_{21} - M_{12}) \right) \tag{11}$$

with the correlation coefficient R_{wc} define as:

$$R_{wc} = \frac{\langle wc \rangle}{\sigma_w \sigma_c} \tag{12}$$

and M_{ij} are the dimensionless joint moments given by:

$$M_{ij} = \frac{\langle w^i c^j \rangle}{(\sigma_w)^i (\sigma_c)^j} \tag{13}$$

where σ_w and σ_c are the standard deviations of w and c, respectively, and $M_{11}=R_{wc}$.

3. Results and Discussions

The average wind direction during the day 150 of 1995 (May 30th) range from 0° to 55° and from 325° to 360°, that is, the wind blew from the northeast to the northwest. Therefore, the wind direction range was small, and it was not possible to establish if any relationship between the wind direction and the sensible heat flux exists due to that limited variation. The wind speed also varied in a limited range, from 0.64 ms^{-1} to 4.37 ms^{-1}, which correspond to scale forces of 1 to 3 in the Beaufort Scale, that is, from light to mild winds. There is no significant relationship of wind speed to the fluxes, but there is a tendency that larger fluxes happen along with larger speeds, specially in the convective periods, as can be observe in Figs. (2a) and (2b).

The friction velocity ranges from 0.05 ms^{-1} to 0.42 ms^{-1}. Those values agree to the ones found by Moraes (2000) for the autumn period, in Candiota. The author found values from 0.1 ms^{-1} to 0.5 ms^{-1}. There is no significant relationship between the friction velocity and the sensible heat fluxes, but, similar to the wind speed, there is a tendency of larger fluxes to be associated to larger friction velocities, as shown in Figs. (2c) and (2 d).

The sensible heat vertical turbulent fluxes were determined by eddy correlation method. Their temporal evolution, shown in Fig. (3), has some variation during the day, with a maximum of 106.2 Wm^{-2}, but they are much less energetic and in the inverse direction in the stable period, with a maximum of 25.3 Wm^{-2}. Moraes (2000) found values between -25 and 150 Wm^{-2}, for the same region and time of the year. The flux variations during convective conditions might be due to the presence of clouds, which attenuate the solar energy that reaches the surface.

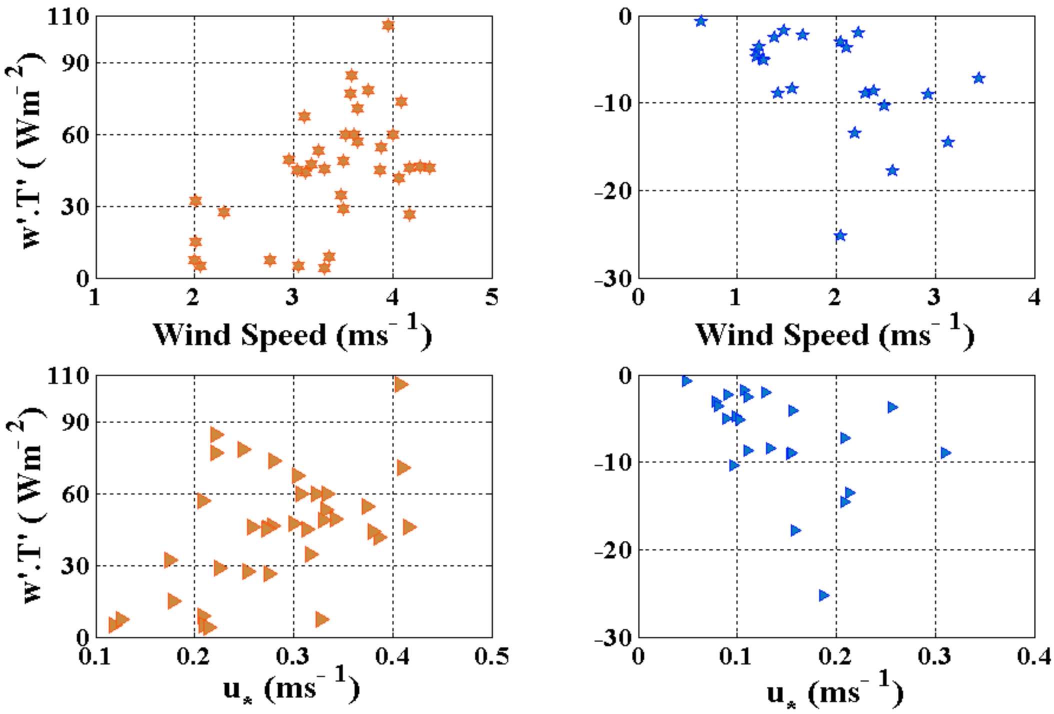

Figure 2 Variation of the sensible heat flux to a) the wind speed in the convective period; b) the wind speed in the stable period; c) the friction velocity in the convective period; d) friction velocity in the stable, period.

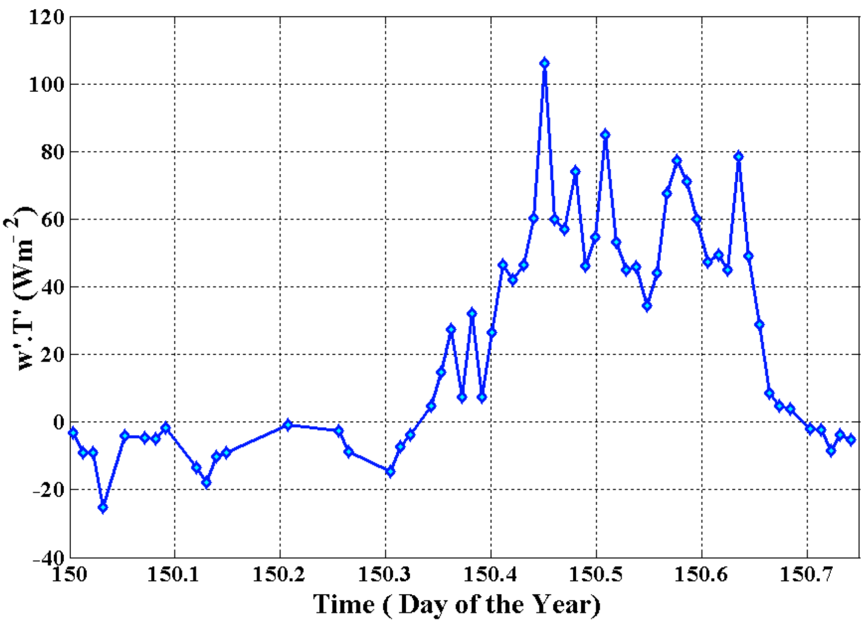

Figure 3 Evolution of the sensible heat flux, for day 150 of year 1995, May 30th. The stable period corresponds to 150.0 to 150.3, that is, from 0:00 to 7:30 AM local time. The convective period comprises from 150.3 to 150.7, that is, from 7:30 AM to 5:30 PM local time.

The temporal evolution of the stress functions are depicted in Fig. (4). During the day the stress function of quadrant 1, S_1, and that of quadrant 2, S_2, which are associated to ejections and sweeps, respectively, are positive. Moreover, the net heat flux is upwards, from the surface to the atmosphere, since the ejections are always larger than the sweeps.

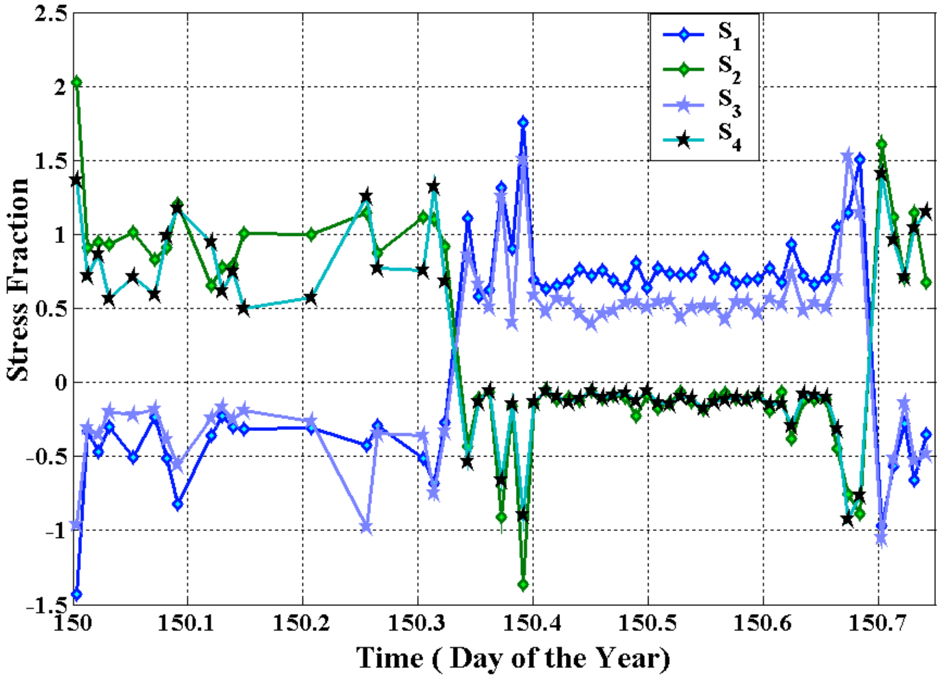

Figure 4 Evolution of the stress fractions, S_i, where i=1, 2, 3, 4 is the quadrant. In the stable period , quadrants 1 (blue diamond) and 3 (blue star) represent interactions, 2, sweeps (green diamond), and 4 (green star), ejections. In the convective period, quadrants 2 and 4 denote interactions, 1 , ejections and 3, sweeps.

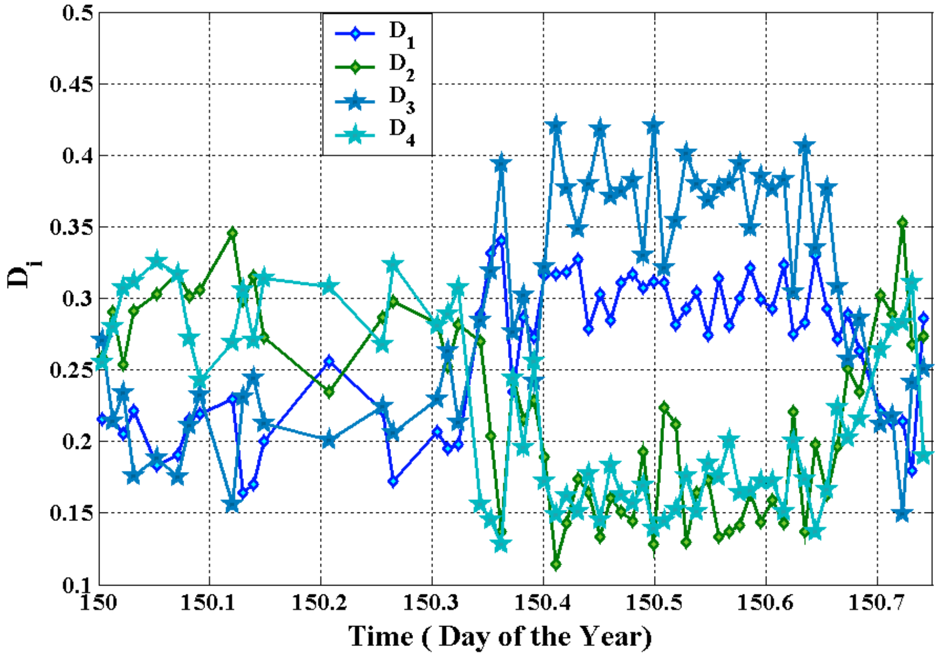

Figure 5 Evolution of the event duration, D_i, the time fraction of measurement events in quadrant i=1, 2, 3, 4. In the stable (convective) period, quadrants 1 (2) and 3 (4) represent interactions, 2(3) denotes sweeps, and 4 (1) ejections.

During stable conditions, the ejections are related to the stress function of quadrant 4, S_4, and the sweeps, to that of quadrant 2, S_2. Since S_2 is larger than S_4, the net heat flux is downwards, from the atmosphere to the surface. In Fig. (4), at 150.32, which corresponds to 7:30 AM local time, and at 150.70, 5:30 PM local time, the quadrant inversion which characterizes the change of stability from stable to unstable and from unstable to stable, respectively, can be observed, along with the great variability in the fluxes that occurs during the transition period. During the stable period, the interactions, S_2 and S_4, have low magnitudes, while in the stable period the interactions, S_1 and S_3, have magnitudes similar to the ejections and sweeps. The results obtained by Heckler et al. (2003), applying the same technique to another dataset, are quite dissimilar to the ones obtained here. They found larger ejections/sweeps and interactions, which are of the same order of magnitude of the ejections and sweeps, during convective conditions, and conditions very similar to the ones presented here for the convective period, during the stable one. That behavior might be due to the larger energy available during day 150, in Candiota, or to differences in the topography.

During the convective period, the sweeps have larger duration than the ejections, as can be observed in Fig.(5). The sweeps have a stress fraction that is smaller than the one for the ejections, shown in Fig. (4). Therefore, the sweeps are slower than the ejections. For stable conditions, the duration of ejections is usually slightly larger than that of the sweeps, but that difference is not significant. The time fraction of the ejections, which is represented by D_4 in the stable period and for D_1 in the convective one, has little variation with stability, while the duration of the sweeps change, in the convective period, to about twice the value it had in stable conditions.

To verify the relationship between temperature skewness and the occurrence of ejections and sweeps associated to sensible heat flux, graphs were built for the convective and for the stable periods, as can be observed in Fig. (6). There is a dependence between the sweep events and the temperature skewness which is more noticeable during unstable conditions, which was also noticed by Katul et al. (1997).

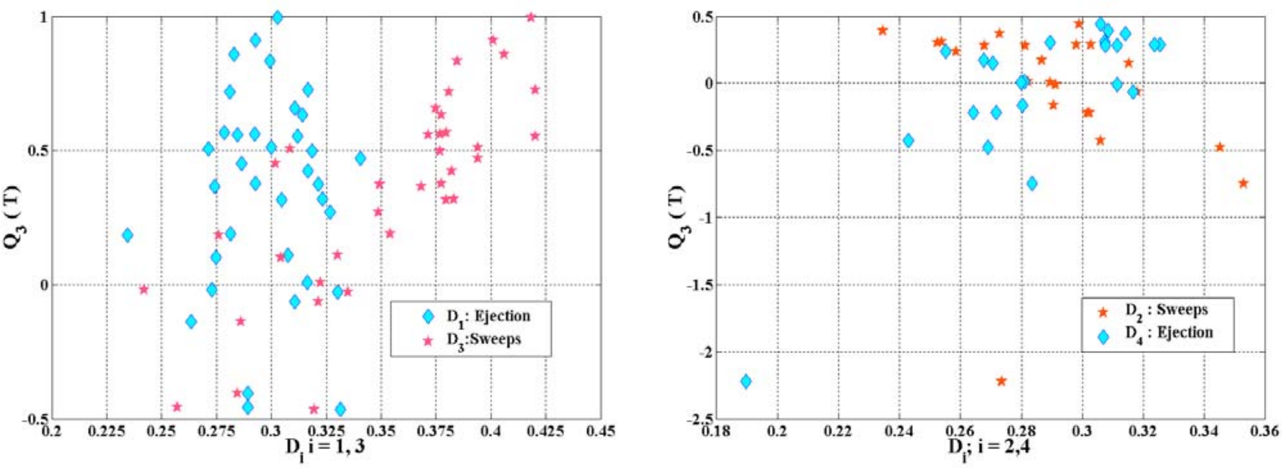

Figure 6 Variation of temperature skewness $Q_3(T)$ along with the duration of ejections (blue diamond) and sweep (red star), during a) unstable conditions, b) stable conditions.

Table (1) compares the duration calculated for Candiota and those presented by Katul et al. (1997) for a surface covered by grass. The value for ejections are similar while there is a difference for the sweeps. The standard deviations for Candiota's values are larger than for those ones of Katul as a consequence of the smaller dataset, measured with a smaller sampling frequency, which produces a larger dispersion of the results. Therefore, the relation obtain is probably a stable one.

Table 1 Comparison of the duration of ejection and sweep, for convective and stable periods, for Candiota results and those presented by Katul et. al. (1997). The values in parentheses denote the standard deviation of the average.

SENSIBLE HEAT FLUX	SWEEP/EJECTION	CANDIOTA	KATUL
		Grass (z_o= 0 - 52 cm)	**Grass (z_o= 4 -10 cm)**
Unstable	D_{sweep}	0.35 (0.047)	0.34 (0.024)
	$D_{ejection}$	0.30 (0.022)	0.30 (0.015)
Stable	D_{sweep}	0.29 (0.027)	***
	$D_{ejection}$	0.29 (0.031)	***

4.Conclusions

The atmospheric stability of day 150 was close to neutral, the mean wind direction was from northwest to northeast, and the mean wind speed was from 0.64 ms^{-1} to 4.37 ms^{-1}. The roughness length also has little variation, as a consequence of the small deviation of the wind direction. Since the wind amplitude was small, both in magnitude and direction, no attempt was made to establish a relationship between the fluxes and the mean wind or the roughness length. Moreover, the fluxes did not have any significant variability with the friction velocity.

The largest sensible heat flux observed on that day was of 106.2 Wm^{-2}, during the convective period, and of 25.3 Wm^{-2}, in the opposite sense, during the stable one. There were several sudden variations during the convective period that, along with not very intense fluxes, might be a consequence of a cloudy day.

The stress fractions presented the quadrant inversion characteristical of the stability change, from the stable condition, to the convective one, with a strong variability in the transition period. During the stable period, the ejections and sweeps have intensity similar to the interactions, while, in the unstable period, the latter present intensity near zero in comparison with the intensity of ejections and sweeps.

The duration showed that the sweeps are slower than the ejections in the unstable period, but the duration of ejections is usually slightly larger than the duration of the sweeps during stable conditions. The duration of the ejections did not vary with the stability, while the duration of the sweeps did. Comparison of the event duration to the temperature skewness denoted a relationship of the latter with the duration of the sweeps especially during the unstable period.

In summary, the quadrant analysis method depict the physical processes that dominate the turbulent transport, for all stability conditions. The stress fractions, during the stable period, have a larger variability than the stress fractions obtained for another site, Rio Grande, and, conversely, the stress fractions from Rio Grande, during the convective period, change more often and are larger than the ones estimated for Candiota. Therefore, a analysis of a larger dataset is indispensable, especially to establish the assumed conditions for the stress fraction and duration in the stable period.

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6. References

Boppe, R. S., Neu, W. L., Shuai, H., 1999, "Large-Scale Motions in the Marine Atmospheric Surface Layer", Boundary-Layer Meteorology, 92, pp. 165-183.

Gao, W., Shaw R. H., Paw U, K. W., 1989, "Observation of organized structure in turbulent flow within and above a forest canopy". Boundary-Layer Meteorology, **59**, pp. 35-57.

Heckler, M., Krusche, N., Saraiva, L. B., 2003, "I Experimento Meteorológico de Rio Grande: Efeitos das Condições Locais nos Fluxos de Calor Sensível", Ciência e Natura, Santa Maria, RS, v. Espec., pp. 265-268.

Katul, G., Kuhn, G., Schieldge, J., Hsieh, C.I., 1997, “The Ejection-Sweep Character Of Scalar Fluxes In The Unstable Surface Layer”, Boundary-Layer Meteorology, 83, pp. 1-26.

Lamesa, J.E., 2001, “Estudo Espectral da Camada Limite Superficial de Iperó – São Paulo”, Masters Thesis, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, SP, Brazil (in portuguese).

Moraes, O. L. L., 2000, "Turbulence Characteristics in the Surface Boundary Layer over the South America Pampa ", Boundary-Layer Meteorology, 96, pp. 317-335.

Stull, R.B., 1988, "An Introduction to Boundary Layer Meteorology", Kluwer Academic Publishers, Dordrecht, The Netherlands , 666 p.

Tennekes, H., Lumley, J. L., 1990, 13th printing, "A First Course in Turbulence", The MIT Press, Cambridge, Massachusetts, United States of America, 300 p.

Vickers, D., Mahrt, L., 1996, "Quality control and flux sampling problems for tower and aircraft data", J. Atmos. Ocean. Tech., 14, pp. 512-526.

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