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Micrometeorological database for air pollution modelling in the Mexico City metropolitan area

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Abstract

To overcome the lack of the surface micrometeorological data needed for air quality modelling in the Mexico City Metropolitan Area (MCMA), a long-term micrometeorological campaign was carried out during the year 2001. Three surface stations were installed at sites found at NNW, NE, and S of the MCMA, each one equipped with a 3D ultrasonic anemometer and conventional meteorological sensors for temperature, relative humidity, pressure, global radiation, net radiation, and rainfall. One-hour averages were calculated for all measurements and for the estimates of the turbulence parameters such as friction velocity, scale temperature, Monin-Obukhov length, sensible heat flux and turbulent kinetic energy, among others. A simple micrometeorological database is available at an Internet site. In addition, some preliminary analyses of the turbulence data of one of the stations was done to estimate the surface roughness length and some similarity relations.

1 Introduction

Air pollution is one of the more worrying problems in the Mexico City metropolitan area (MCMA). For some years, the local Environmental Authorities have been doing working hard in promoting and planning emission abatement actions and more recently, in applying complex photochemical models, such as the Multiscale Climate Chemistry Model (MCCM), to evaluate the efficiency of their clean air initiatives. However, one of the main drawbacks of air pollution modelling in MCMA is the lack of the proper micrometeorological data the advanced dispersion models require. The MCMA meteorological stations, including those of the Mexico City atmospheric monitoring network (RAMA), provide only conventional meteorological data, which is not enough for using the more recent air quality models. In particular, none of the atmospheric turbulence parameters are available.

To overcome this lack of micrometeorological data, the M^{4}CA group of the Mexican Electrical Research Institute (Instituto de Investigaciones Eléctricas, IIE) carried out, during the 2001-year, a long-term surface micrometeorological campaign in three sites of MCMA, supported by the Mexican Consejo Nacional de Ciencia y Tecnología (CONACyT, grant No. 218470-5-R32457-T). The main objective of this project was to prepare a one-year micrometeorological database for the MCMA air pollution modelling purposes.

The first part of this paper presents a brief description of the MCMA experimental campaign and micrometeorological database. The second one presents a preliminary analysis of the turbulence data of one of the stations. In particular, it reports some estimates of the surface roughness length and of the similarity relations.

2 The 2001 MCMA micrometeorological campaign

Three surface meteorological stations (Texcoco [TEX], Azcapotzalco [AZC], and Xochimilco [XOC]) were installed at the sites described in Table 1.

Table 1: Geographic location of the monitoring sites.

Station	Latitude	Longitude	Altitude (masl)
Texcoco	N 19° 27' 53.1''	W 98° 59' 54.4''	2250
Azcapotzalco	N 19° 30' 9.4''	W 99° 11' 12.2''	2190
Xochimilco	N 19° 18' 18.3''	W 99° 6' 6.2''	2250

Texcoco station was installed in the NE-sector of MCMA, nearby the old Texcoco Lake. It is a rural terrain site close to the Mexico City international airport. The other two were installed in urban sites located in the NNW and S sectors of MCMA, in the Azcapotzalco and Xochimilco campus of the Metropolitan University. Sensors were mounted on a 10m tower, which was installed direct on ground in the Texcoco station, and on the roof of a 20m-height building in the other two. There were no relevant obstacles above the measuring height. Each station was equipped with a 3D ultrasonic anemometer (wind velocity components and temperature) and with conventional sensors for temperature, relative humidity, pressure, rainfall and net and global solar radiation. Table 2 includes a description of all sensors.

Table 2: Meteorological sensors installed in each station.

Qty	Sensor	Trademark	Model
1	Ultrasonic Turbulence Sensor	METEK	USAT-3
1	Pressure Gauge	Campbell Scientific	PTA427
1	Temperature and Relative Humidity Probe	Campbell Scientific	HMP35C
1	Net Radiometer	REBS	Q-7
1	Pyranometer	LI-COR	LI200X
1	Rain Gauge	Texas Electronics	TE525MM

Two data acquisition systems were employed in each station, one for the ultrasonic anemometer, and other one for the rest of meteorological sensors. The sampling rates were 10 Hz in the first case and 1 Hz in the second one. We described the procedures of calibration, maintenance, and data quality control in [1, 2].

A simple evaluation of the data recovery performance was done, and a monthly qualification was assigned to each station. To do this, we divided the measurement equipment of a station in two sets: one of them was the ultrasonic sensor, and the other one all the conventional sensors. Table 3 provides a description of the performance results we found. Qualifications (in %) reflect the combined performance of the sensors and their respective data-acquisition. To calculate them, we compared the number of valid data against the number of expected data in a month. The Xochimilco station got the better performance qualification, with an average of 92.9% for the ultrasonic sensor and 95.4% for the conventional sensors. Azcapotzalco station, with 72.2% for the ultrasonic sensor and 78.9% for the conventional sensors, got the worst qualification. The average qualification of the experimental campaign was 85.0%.

Table 3: Combined performance of sensors and data-acquisition.

2001	Ultrasonic Sensor Measuring Set			Conventional Sensors Measuring Set		
Month	TEX	AZC	XOC	TEX	AZC	XOC
JANUARY	79.4	63.9	83.2	62.3	65.2	95.0
FEBRUARY	91.4	67.9	98.3	87.2	85.7	99.9
MARCH	95.6	68.6	98.3	85.8	85.9	100
APRIL	71.2	75.6	90.6	79.8	80.8	92.4
MAY	92.2	72.7	98.2	85.1	79.8	100
JUNE	95.0	72.3	98.2	85.2	87.2	100
JULY	66.1	70.1	98.3	61.2	83.5	100
AUGUST	98.3	48.2	64.8	82.7	60.8	65.9
SEPTEMBER	98.2	68.4	90.1	86.4	77.2	91.6
OCTOBER	98.2	63.4	97.8	87.0	80.8	99.9
NOVEMBER	95.3	96.7	98.3	83.8	82.1	100
DECEMBER	93.2	98.3	98.3	84.1	78.0	100
AVERAGE	**89.5**	**72.175**	**92.9**	**80.9**	**78.9**	**95.4**

3 The 2001 MCMA micrometeorological database

We prepared a simple micrometeorological database for MCMA using the data recovered from January to December 2001. It is available for the scientific community concerned with MCMA air pollution through an Internet page (temporally hosted at http://www.geocities.com/mexicombd). This database contains the 1-hour averages of wind speed (WSP, m/s), wind direction (WDR, °N), temperature (TEM, K), wind direction standard deviation (SWD, °), Pasquill-Gifford stabilities (STB, 1=A...6=F), relative humidity (HRL, %), global radiation (RGL, W/m^2), net radiation (RNT, W/m^2), pressure (PAT, mmHg), and rainfall (PPL, mm). It includes also the variances and covariances of the U, V, W

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and T turbulent fluctuations (<UU>, <UV>, <UW>, <UT>, <VV>, <VW>, <VT>, <WW>, <WT> and <TT>), friction velocity (UST, m/s), scale temperature (TST, K), sensible heat flux (FCS, W/m^2), Monin-Obukhov length (LMO, m), and turbulent kinetic energy (TKE, m^2/s^2). We calculated the turbulent parameters with the eddy covariance method as described by Sozzi & Favaron [3]. In Table 4, we reported the annual minimum, maximum, mean, standard deviation, and most frequent values of some micrometeorological variables for each station. Here, third column includes the number of valid hourly values found in the year.

4 Preliminary analysis of the Texcoco Station turbulence data

In this section, we consider only the measurements performed by the ultrasonic anemometer at Texcoco station from November 2000 to January 2001. This data set contains the values of the wind velocity components and temperature measured with a 10 Hz sampling rate. Because of this sampling rate, so as the dynamic and geometric features of the ultrasonic anemometer, we could apply the eddy-covariance method to estimate the main turbulence parameters. In particular, friction velocity (u_*), sensible heat flux (H_0), scale temperature (T_*), and Monin-Obukhov length (L) were estimated. The calculations followed the guidelines given by Sozzi & Favaron [3], McMillen [4], Vickers & Mahrt [5], and Aubinet *et al* [6]. The data processing, in practice, was performed with two software packages: ECOMET, developed at the CNR-ISAO (Bologna - Italia), and SADAUS/MCT, developed by Atmospheric Systems (Cuernavaca, Mexico). Both software products produced similar results.

From the considered data, we found 4106 data periods of 30 minutes, which represent the 93% of the expected data for this period. In what follows, we present the results we found from a preliminary analysis of the wind speed, wind direction, virtual temperature, friction velocity, sensible heat flux, and the standard deviations of temperature and wind velocity.

4.1 Wind speed and wind direction

Although the maximum mean wind speed was 9.2 m/s in the period, the low intensity winds prevailed. In fact, the wind speed frequency distribution (Figure 1, left) was essentially monovariate and lognormal, the most frequent interval was from 1 to 1.5 m/s, and the 61% of wind speed values were between 0.5 and 2.5 m/s. The wind-rose graph shows that at Texcoco station the most probable wind directions belonged to the E and NW sectors.

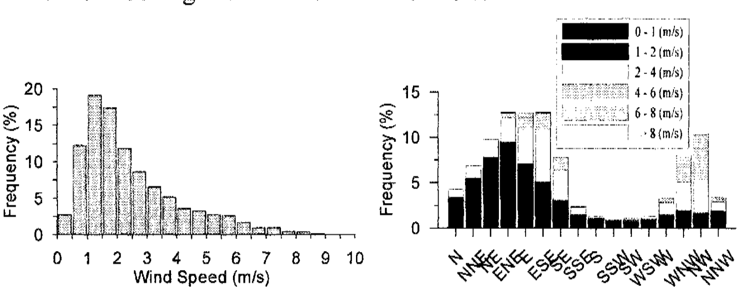

Figure 1: Wind speed frequency distribution (left) and wind rose (right).

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Table 4: Preliminary statistics of the experimental campaign data

Variable	Hours	Valid Data	Minimum	Maximum	Mean	Standard Deviation	Most Frequent Value	%
TEXCOCO								
WSP	8760	8133	0.41	11.80	3.08	1.74	1.89	7.63
WDR	8760	8133			20.56	77.04	334.77	4.97
TEM	8760	8133	274.50	301.29	288.90	4.67	289.24	4.61
HRL	8760	7128	5.69	100.00	62.83	24.02	87.11	3.04
RGL	8760	7128	0.00	1050.92	224.13	311.81	10.51	42.32
RNT	8760	7128	-87.28	766.65	112.52	214.00	-44.59	16.08
PPL	8760	7128	0	12.70	0.04	0.41	0.13	79.40
UST	8760	8133	0.03	1.65	0.27	0.14	0.17	8.29
FCS	8760	8133	-336.80	376.97	25.77	52.91	-1.32	34.55
TST	8760	8133	-1.17	1.04	-0.09	0.18	0.04	22.91
AZCAPOTZALCO								
Variable	Hours	Valid Data	Minimum	Maximum	Mean	Standard Deviation	Most Frequent Value	%
WSP	8760	8465	0.30	8.65	2.08	1.08	1.22	7.26
WDR	8760	8465			327.89	78.43	349.20	6.62
TEM	8760	8465	276.00	302.00	290.00	4.22	288.80	5.51
HRL	8760	6954	3.80	89.90	48.77	21.90	73.58	3.50
RGL	8760	6954	0.00	992.30	195.50	275.60	9.92	41.30
RNT	8760	6954	-116.60	646.52	97.45	205.88	-63.18	11.97
PPL	8760	6954	0	15.30	0.06	0.61	0.15	77.40
UST	8760	8465	0.04	0.94	0.28	0.14	0.12	5.70
FCS	8760	8465	-157.24	187.41	25.99	32.40	4.75	23.70
TST	8760	8465	-0.46	0.11	-0.09	0.10	-0.03	8.90
XOCHIMILCO								
Variable	Hours	Valid Data	Minimum	Maximum	Mean	Standard Deviation	Most Frequent Value.	%
WSP	8760	8365	0.18	8.91	2.19	1.32	1.32	8.40
WDR	8760	8365			111.75	120.94	147.60	4.40
TEM	8760	8365	275.83	301.95	289.13	4.22	288.11	5.39
HRL	8760	8357	6.19	98.08	57.70	21.19	73.27	3.30
RGL	8760	8357	0.00	1050.00	190.90	276.19	10.50	51.99
RNT	8760	8357	-112.05	672.95	90.08	196.94	-25.70	12.66
PPL (*)	8760	8357	0.00	6.20	0.01	0.09	0.06	95.10
UST	8760	8365	0.01	0.89	0.22	0.13	0.08	5.87
FCS	8760	8365	-223.18	198.13	13.21	25.52	0.11	36.53
TST	8760	8365	-0.39	0.25	-0.05	0.09	0.01	11.14

(*) Rainfall data of the Xochimilco station are not good. The rain sensor was failing from April on, and it could not be repaired.

4.2 Virtual temperature

Because of the influence of air specific humidity, the temperature measurements of the ultrasonic anemometer are more representative of virtual temperature than normal temperature [7]. In the period, virtual temperatures were between 0.95 and 24.45 °C, with a mean value of 13.6. In the frequency distribution (Figure 2), however, the most frequent value was close to 3 °C.

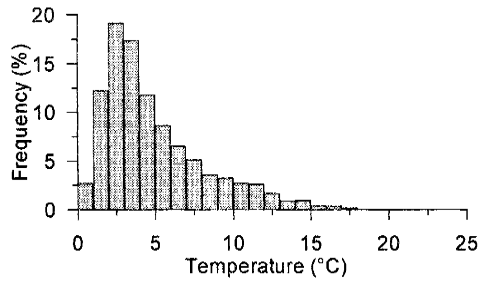

Figure 2: Virtual temperature frequency distribution.

4.3 Friction velocity

As ordinary, friction velocity u* was calculated with the turbulent fluctuations of the vertical and horizontal wind components [8]. Figure 3 shows the u* frequency distribution. The shape of this distribution is similar to that one of wind speed, and the most frequent value was around 0.1 m/s.

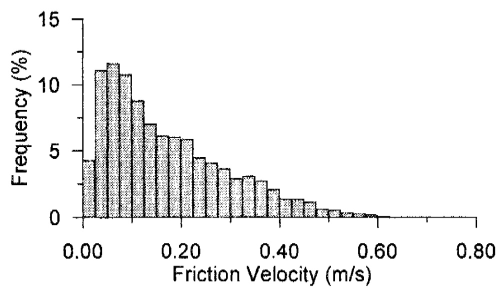

Figure 3: Friction velocity frequency distribution.

4.4 Sensible heat flux

Sensible heat flux H_0 represents the thermal contribution to the atmospheric turbulence in the PBL. It was calculated with the covariance between the turbulent fluctuations of the vertical wind component and virtual temperature. In the period, the minimum value of H_0 was close to –95 W/m^2, and its maximum was close to 235 W/m^2. The frequency distribution of H_0 is shown in Figure 4. This figure shows the characteristic peak around zero, pointing out the presence of the quasi-adiabatic conditions that are typical of the first hours of the day and of all those meteorological conditions with moderate winds.

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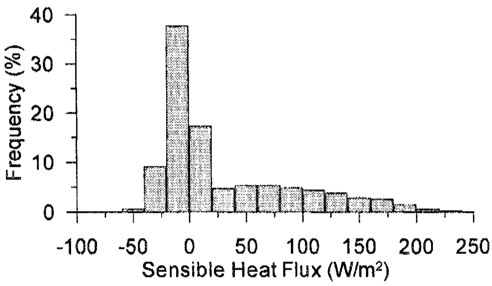

Figure 4: Sensible heat flux frequency distribution.

4.5 Standard deviations of wind velocity components and temperature

Standard deviations of the wind velocity components are important parameters in air pollution modelling. Figures 5 and 6 show the frequency distributions of these variables. As noted in Figure 5, high σ_u and σ_v values (of the same order of magnitude as wind speed) came out often.

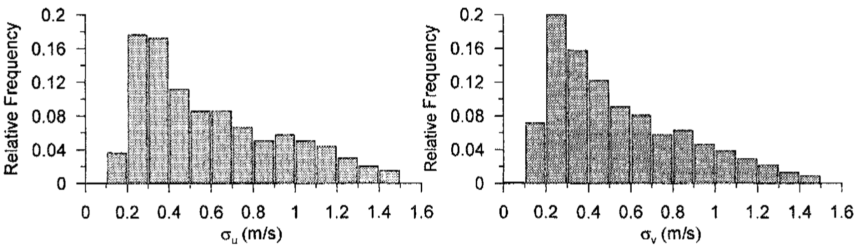

Figure 5: Frequency distributions of horizontal wind standard deviations.

The standard deviation of the vertical wind (Figure 6, left) had also relatively high values in the period, but not higher than those ones of the horizontal wind components. These high values of σ_w suggest an important vertical dispersion ability of PBL in MCMA under convective conditions.

Another interesting parameter of PBL turbulence is the standard deviation of virtual temperature σ_θ. Figure 6 (right) shows its frequency distribution. Here, one can see that σ_θ values of 0.5K came out often, suggesting meteorological conditions with rather high convectivity.

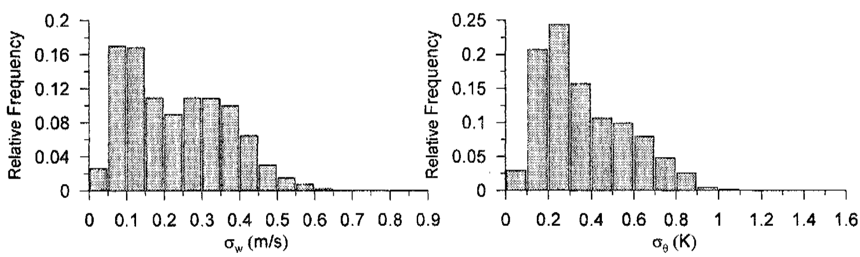

Figure 6: Frequency distributions of σ_w (left) and σ_θ (right).

4.6 Estimation of surface roughness length

In this section, we present the estimates of those parameters that characterize surface roughness around the Texcoco station. These estimations can be done starting with the similarity relations that define the vertical profiles of wind speed u and potential temperature θ within the atmospheric surface layer:

$$u(z) = \frac{u_*}{k}\left\{ \ln\left(\frac{z-d}{z_{0m}}\right) - \Psi_m\left(\frac{z-d}{L}\right)\right\} \tag{1}$$

$$\theta(z) = \theta(z_{0h}) + \frac{T_*}{k}\left\{ \ln\left(\frac{z-d}{z_{0m}}\right) - \Psi_h\left(\frac{z-d}{L}\right)\right\} \tag{2}$$

Here, z_{0m} y z_{0h} are the roughness lengths associated with the momentum and heat exchanges, respectively, d is the zero-plane displacement height, and Ψ_m and Ψ_h are the mechanical and thermal similarity functions.

In what follows, however, we will estimate only the roughness length z_{0m}. Estimating z_{0h} needs more information than that provided by the ultrasonic anemometer. We underline also the rural, plane and regular terrain characteristics around the Texcoco station, which allow to neglect the displacement height parameter d.

To estimate the roughness length z_{0m}, we used the method proposed by Sozzi et al [9] and Martano [10] based on eqn (1). Neglecting displacement height, eqn (1) leads to

$$z_{0m} = \frac{z}{\exp\left[\frac{ku}{u_*} + \Psi_m\left(\frac{z}{L}\right)\right]} \tag{3}$$

The ultrasonic anemometer data allows to calculate wind speed u (at a measuring height $z = 10\ m$), friction velocity u_*, and the stability parameter z/L (being L the Monin-Obukhov length), and so eqn (3) allows to estimate z_{0m}. The expressions of Ψ_m we considered in this analysis are the Businger-Dyer relation for convective conditions [11] and the Van Ulden & Holtslag relation for stable conditions [12].

In practice, for each averaging interval (30-minutes, in this case) we can calculate a value of z_{0m}, which will be dependent of wind direction. However, because of turbulence in PBL is not, in general, in a steady state, and because of the unavoidable measuring errors, for a number N of measurements in the same wind direction, eqn (3) will produce N similar but different z_{0m} values. Then, once one has a statistically valid number of measurements for certain wind direction, the characteristic z_{0m} value associated to that wind direction can be the average or the most frequent value of the single estimates. Obviously, not all the possible wind directions can be considered, and, as usual, it is necessary to divide the complete wind direction range in several sectors. Due to the terrain characteristics around the Texcoco station, we considered appropriate to divide the full wind direction range in 16 sectors; each one centered in a cardinal direction.

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In principle, this method could be applied under any atmospheric stability conditions, but in practice, it is convenient to exclude some of them that could produce an estimate influenced strongly by non-steady turbulence conditions. In this case, we excluded the following: when wind speed was smaller than 1 m/s; when friction velocity was smaller than 0.05 m/s; conditions close to free convection with $|z/L| > 2$; and strongly stable conditions with $z/L > 2$. In Table 5 and Figure 7, we reported the estimates found for the Texcoco measuring site surroundings.

Table 5: Roughness length around the Texcoco measuring site.

Wind direction sector	Number of elementary estimates of z_{0m}	Most frequent value of z_{0m} (m)
N	51	0.043
NNE	55	0.022
NE	93	0.011
ENE	165	0.016
E	227	0.019
ESE	286	0.058
SE	165	0.068
SSE	22	0.031
S	11	0.025
SSW	10	0.064
SW	18	0.229
WSW	12	0.091
W	52	0.020
WNW	217	0.026
NW	329	0.031
NNW	72	0.025
Total	**1785**	**0.038**

As noted, the total number of elementary estimates is large, and each sector of wind direction, excepting S and SSW, contains enough data for a statistically valid estimation of the most frequent value z_{0m}, which represents the effective roughness-length there. In addition, from Table 5 and Figure 7, one can observe that, at the Texcoco measuring site, the effective z_{0m} ranges from 1 to 23 cm, which points out that this site is homogeneous and obstacles free. The relatively high value found for the SW-sector (0.23 m) could be a result of the small number of available data for it. However, it is worth of mention that just in sectors SW and WSW, 150m far from the meteorological tower position, there exist some buildings of the Mexican Comisión Nacional del Agua (CNA) with some trees inside (10m height, approx.). On the other hand, we note, in addition, that the smaller z_{0m} values (≈0.015m) concord with the NE and ENE sectors, where the new Texcoco Lake is located, 100m far from the tower position, nearly.

Because of the terrain homogeneity around the Texcoco station, a weighted average of the effective z_{0m} values could be calculated and used to characterize roughness at the Texcoco measuring site. This value is 0.038 m.

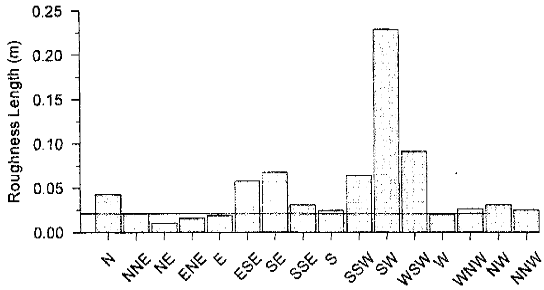

Figure 7: Roughness length distribution around the Texcoco station.

4.7 Monin-Obukhov similarity relations

An important task in the analysis of atmospheric surface layer turbulence is to evaluate how experimental data fit the Monin-Obukhov similarity relations already reported. As an example, we considered the vertical profile of the standard deviation of the vertical wind, as measured at the Texcoco station.

In according to the Monin-Obukhov similarity theory, the following relation must hold in the atmospheric surface layer

$$\frac{\sigma_w}{u_*} = \Phi_w(z/L) \tag{4}$$

where Φ_w is the universal similarity function for σ_w. This function has been extensively studied in literature (see Businger *et al* [13], Dyer [14] and Hogstrom [15]), but the Kaimal & Finnigan [16] relation is more often used:

$$\Phi_w = \begin{cases} 1.25\left(1+3|z/L|\right)^{1/3} & -2 \le z/L \le 0 \\ 1.25\left(1+0.2\,z/L\right) & 0 \le z/L \le 1 \end{cases} \tag{5a}$$

Eqn (5a) came out (almost exclusively) of data obtained during the well-known Kansas campaigns. However, if we consider campaigns carried out more recently, it is observed that some relations that did not agree completely with eqn (5a) exist. In particular, if one considers the experimental campaign reported by Andreas *et al* [17], eqn (5a) results replaced by:

$$\Phi_w = \begin{cases} 1.2\left(0.7+3|z/L|\right)^{1/3} & -4 \le z/L \le 0 \\ 1.2\left(1+0.2\,z/L\right) & 0 \le z/L \le 1 \end{cases} \tag{5b}$$

Eqns (5a) and (5b) are very similar, but it must be observed that eqn (5b) was obtained from a limited number of data (69) concentrated within a very small time-period, just as it occurred when eqn (5a) was derived. Moraes [18] reported results of a similar campaign. The number of measurements, however, was larger (192), and spread along a year. In this case, despite dispersion of data (see Fig. 3a in Moraes [18]), it could be obtained

$$\Phi_w = \begin{cases} 1.08\left(1+4.4|z/L|\right)^{1/3} & -2 \le z/L \le 0 \\ 1.08\left(1+z/L\right) & 0 \le z/L \le 1 \end{cases} \tag{5c}$$

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The differences between eqn (5c) and eqn (5a) are more relevant: in part, they come out from a different data processing method, but also because of different instrumentation.

In our case, from the available data, we selected only those ones with a friction velocity larger than 0.05 m/s and a negative covariance $\overline{u'w'}$. This way, the meteorological situations we considered were close to stable conditions. Figure 8 (left) shows the values we got for σ_w/u_*. The data dispersion is similar to that found in literature (for example, in Moraes [18]). However, the comparison with the correlations already reported for this universal similarity function, and, in particular, with eqn (5a), is easier if the available data are reorganized in z/L intervals 0.1 wide, and then averaged. In Figure 8 (right), the average values and the correlation given by eqn (5a) are shown. Here we remark that eqn (5a) overestimate the Texcoco measurements.

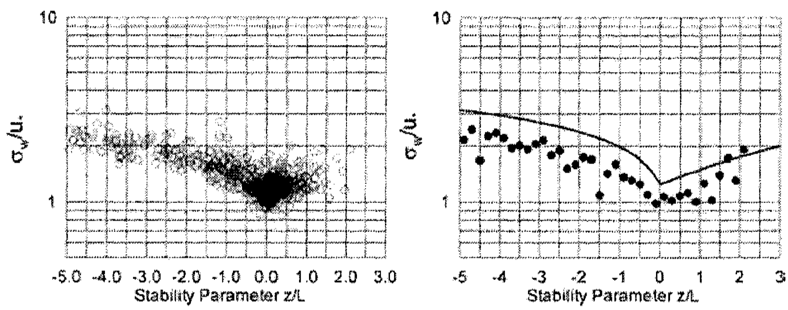

Figure 8: σ_w/u_* as a function of the stability parameter z/L.

5 Conclusions

A micrometeorological long-term experimental campaign was carried out in the Mexico City Metropolitan Area along the 2001-year. Data recovered was used to prepare a one-year micrometeorological database, which may contribute to overcome the lack of micrometeorological data in this region. A preliminary analysis of the Texcoco turbulence data registered from November 2000 to January 2001 was also reported. This analysis shows how experimental data can be used to estimate some other turbulence parameters, such as the surface roughness length and the Monin-Obukhov similarity relations, that some of the most recent dispersion models need as data. In particular, it was found that the Kaimal & Finnigan [16] universal similarity function overestimates the results here reported for the Texcoco measuring site.

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