Spectral characteristics of the wind components in the surface Atmospheric Boundary Layer

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Abstract: - The objective of this work is the study of the spectral characteristics of the wind components in the surface Atmospheric Boundary Layer (ABL). The analyzed data are based on an experimental campaign measurements which has been conducted in the framework of the European project ECATS, at the Athens International Airport (AIA), Greece, from 13th to 25th of September 2007, with the use of remote sensing and in situ instrumentation. Among other instrumentation, a 10 m high meteorological mast was installed, equipped with a sonic anemometer and a fast hygrometer at 10 m height, with high frequency (20 Hz) sampling, for the three-dimensional wind components (u, v and w) and virtual temperature (T) measurements, as well as for water vapor (q) measurements. These high frequency measurements yield estimates of the vertical transport of the momentum (u'w' and v'w'), the heat (w'T') and the humidity (w'q') fluxes through the eddy correlation method, for 10-min time intervals. In order to quantify the background air flow, additional information related to the synoptic conditions as well as radiosonde data from a nearby station was also used. Spectra of the wind components (u, v and w) were also calculated and analyzed. Results showed that the slope values of the spectra at the inertial sub-range reveal certain deviations from the expected theoretical ones, but the mean values eliminate these deviations between theory and observations. Also, the atmospheric stability and the mean wind speed influence the slope values of the spectra. According to the analysis an increase of the wind speed or the friction velocity lead to a decrease of the spectra slope values while the evolution of the atmospheric stability from unstable to stable conditions increase the spectra slope values which generally become steeper, meaning that the turbulence in the surface ABL dissipates faster than expected.

Key-Words: - Atmospheric Boundary Layer, ECATS, turbulence, wind components spectra, spectral slope.

1 Introduction

In the framework of the European project "A European Network of Excellence for an Environmentally Compatible Air Transport System (ECATS)" a detailed experimental study was conducted related with the influence of the Athens International Airport (AIA), operating at Messogia Plain of Attika, Greece, over the surrounding greater area [1]. Also since it is well known that the wind turbulence has a substantial influence on the dispersion of air pollutants, an analytical study of the spectral characteristics of the three wind components in the surface Atmospheric Boundary Layer (ABL) over the AIA area, was conducted.

Spectra of the wind components in the surface Atmospheric Boundary Layer are widely used in various turbulence studies and according to the Monin - Obukhov (MO) similarity theory as well as various experimental studies, the spectra of the atmospheric parameters exhibit a -5/3 slope in the inertial sub-range and they are related with the atmospheric stability and the surface roughness [2]. These spectral characteristics were also found according to published results over complex terrain [3] or close to the shoreline [4], with some deviations from theory, depending on the atmospheric stability. Deviations from the MO similarity theory were also found by other researchers and these are probably related with the large persistent eddies that modify the shape of the spectra [5], [6] and [7].

This work aims to study the surface ABL's spectral characteristics of the wind components and the vertical momentum transport, using data from the Athens AIA ECATS experimental campaign conducted from 13th to 25th of September 2007. Also an effort was made to reveal possible deviations from the MO theoretical expected values and to examine the possible relation and correlation between the estimated by the measurements spectral slope values in the inertial sub-range and ABL parameters such as, the atmospheric stability (z/L), the friction velocity (u_*) and the mean wind speed (U).

2 Instrumentation - Methodology

The Messogia Plain (Fig. 1) is the northeastern part of the Greater Athens Area (GAA) where the AIA is located (blue area). At the north-eastern part of the airport, at a distance of 4 km from the shoreline,

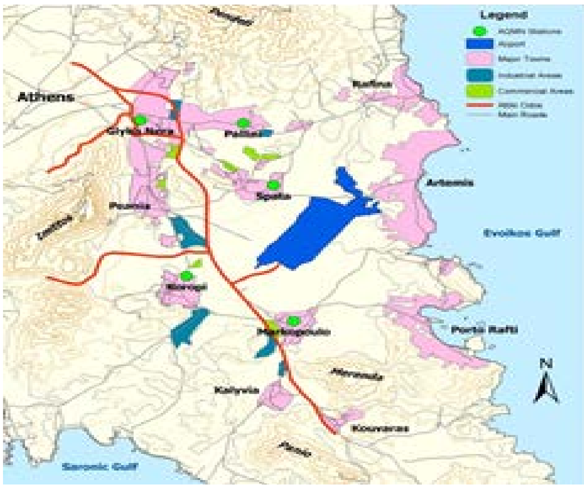

Fig.1. The Messogia Plain with the location of the Athens International Airport (blue area).

a 10 m high meteorological mast equipped with a sonic anemometer (Campbell Scientific CSAT-3) and a fast hydrometer (Campbell Scientific Licor 7500) at 10 m height was installed, with a sampling frequency of 20 Hz (Fig. 2). Thus, the three-dimensional wind components (u, v and w), the

Fig.2. Topography of the area within the AIA where the 10 m high mast was installed (cross)

virtual temperature (T) and the water vapor (q) were estimated as well as the vertical transport of the momentum (u'w' and v'w'), the heat (w'T') and the humidity (w'q') fluxes through the eddy correlation method, for 10-min time intervals. In order to quantify the background air flow, additional information related to the synoptic conditions (synoptic maps) as well as radiosonde data from a nearby station was also used.

The raw ABL data (u, v, w, T and q) were separated in 10 minute successive sections, an adequate time period for turbulence measurements and they were quality controlled, where any spikes due to instrumental noise were detected and eliminated. Then, the 3-D wind data was tilt corrected using the planar fit method [8] and the final time series of all parameters at the sampling frequency of 20 Hz were generated. The u, v, w tilt corrected 10 minute records were adjusted to the mean wind natural coordinate system and by using the Reynolds averaging, each parameter was separated in a mean and a fluctuating part. The fluctuating part was used for the spectral analysis and for the estimation of the friction velocity u_* and the stability parameter z/L (where z is the height of 10 m and L is the MO length scale). It is worth mentioning that positive values of the parameter z/L correspond to stable conditions, negative ones correspond to unstable conditions and values in the range -0.01 to +0.01 correspond to neutral conditions. Only statistically stationary records were used for analysis according to Mahrt et al. study [9].

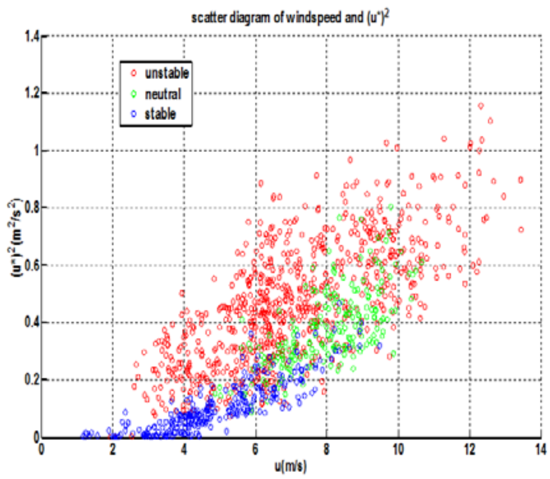

Fig.3. Scatter diagram of the surface vertical momentum flux (u_*^2) in relation with the wind speed at 10 m height, under stable (blue), neutral (green) and unstable (red) atmospheric conditions.

The spectra (power spectral density) of every 10 min record were estimated using a 1024 Fast Fourier Transform (FFT). The frequency range 0.5-5 Hz was selected as the range where the inertial sub-range theoretically is expected to be [2]. The slope of the estimated spectra was calculated by linearly fitting a line on the curve of each spectrum in the range of frequencies 0.5-5 Hz.

3 Results and Discussion

Fig. 3 gives the scatter diagram of the surface vertical momentum flux values in relation with the wind speed at 10 m height, under stable, neutral and unstable atmospheric conditions. According to the figure the surface vertical momentum flux values are increased by increasing the wind speed, while the higher and the lower values for the same wind speed, correspond to the unstable and stable conditions respectively.

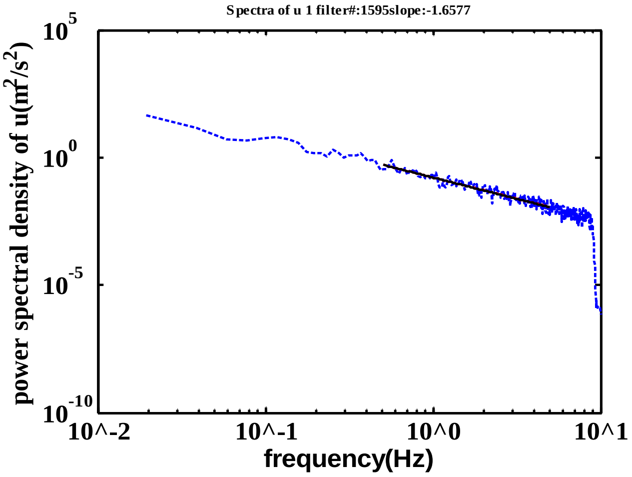

Fig. 4: Power spectrum of the u (longitudinal) component of the wind for a 10 min segment at the 11th of September 2007, time 19:30 LST.

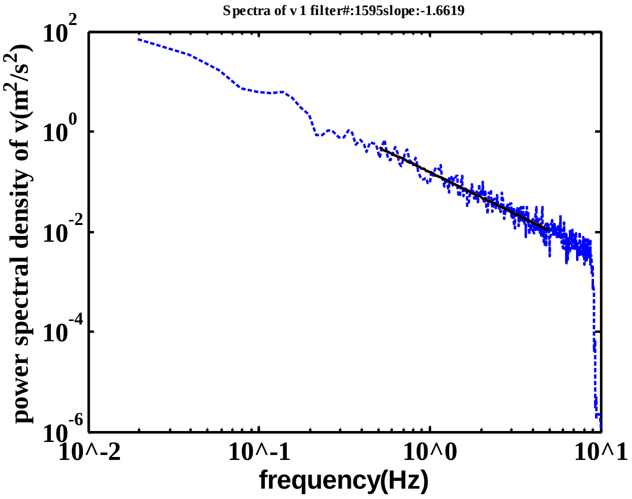

Fig. 5: Power spectrum of the v (lateral) component of the wind for a 10 min segment at the 11th of September 2007, time 19:30 LST

Figures 4, 5 and 6 are the power spectra of the three components of the wind (u, v and w), for a 10 min segment at 11th of September 2007, time 19:30 LST (local standard time). All spectra are characterized by the expected theoretically value of the slope -5/3 (1.66). It is of interest to note that all spectra from

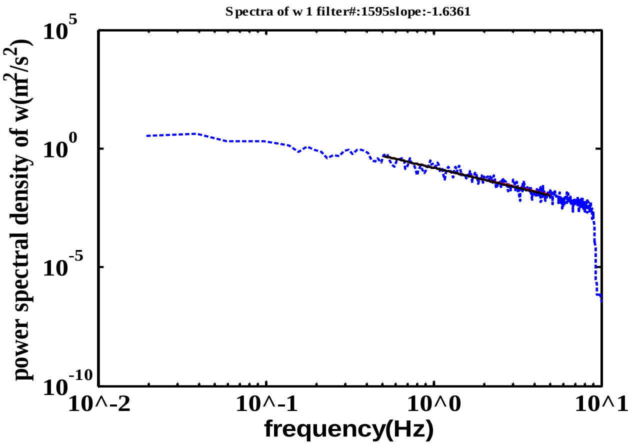

Fig. 6: Power spectrum of the w (vertical) component of the wind for a 10 min segment at the 11th of September 2007, time 19:30 LST

the available 10 min records, do not follow the theoretically expected slope of -5/3. Table 1 gives the estimated mean values of the calculated slope

Table 1: Mean spectral slope values of the three components of the wind (u, v and w), under different atmospheric conditions

Parameter /conditions	neutral	stable	unstable
U’	-1.66±0.01	-1.70±0.02	-1.63±0.01
V’	-1.65±0.01	-1.69±0.02	-1.64±0.01
W’	-1.61±0.01	-1.65±0.01	-1.59±0.01

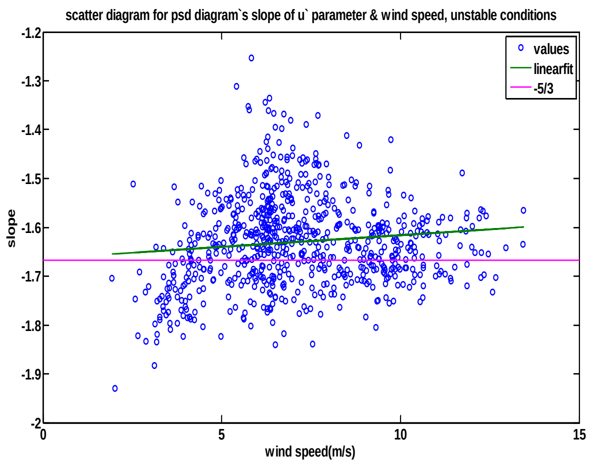

Fig. 7: Scatter plot of the u (longitudinal) wind component spectral slope and the wind velocity, under unstable conditions.

of the power spectra from all 10 min segments, by linearly fitting a line on the curve of each spectrum, in the range of frequencies 0.5-5 Hz, under different atmospheric conditions. It seems that the slope mean values are very close to the theoretically expected slope value (-5/3 or -1.66).

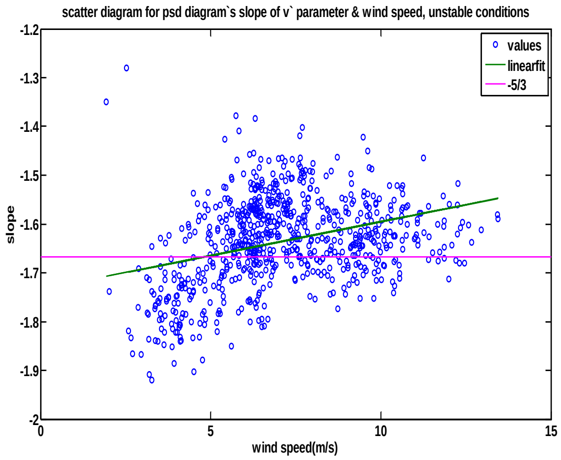

Fig. 8: Scatter plot of the v (lateral) wind component spectral slope and the wind velocity, under unstable conditions.

It is of interest to study the possible relation and influence between the estimated spectral slope values in the inertial sub-range and the ABL parameters such as, the atmospheric stability z/L, the drag coefficient C_D and the mean wind speed.

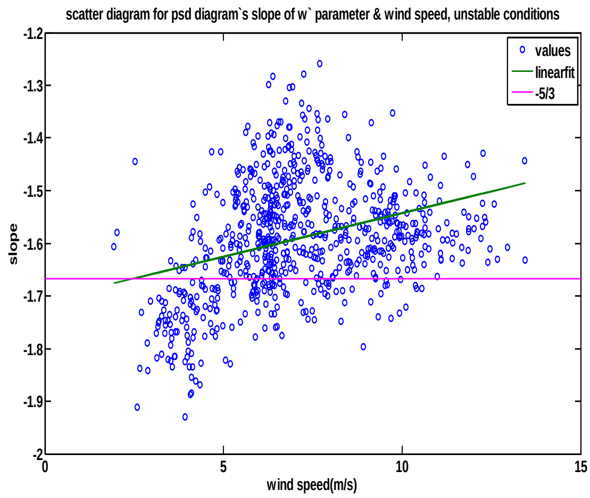

Fig. 9: Scatter plot of the w (vertical) wind component spectral slope and the wind velocity, under unstable conditions

Figure 7 gives the scatter plot of the u (longitudinal) wind component spectral slope and the wind velocity, under unstable conditions. It seems that as the wind speed decreases the slope become steeper, meaning that the turbulence dissipates faster than according to the similarity theory. The green line is the linear regression estimation from the data under unstable conditions, while the red line is the theoretically expected slope value (-1.66). The same

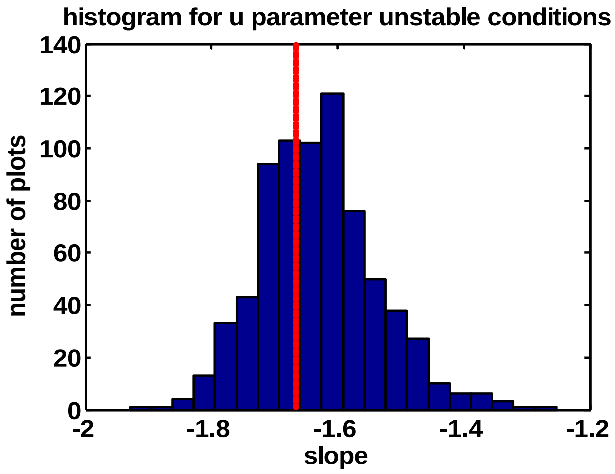

Fig. 10: Histogram of the u wind component spectral slope values, under unstable conditions. The red line is the theoretically slope value (-1.66).

characteristics are given for the u wind component under neutral or stable conditions (not shown). Figures 8 and 9 give the corresponding scatter plots of the spectral slope values of the v (lateral) and w (vertical) wind components and the wind velocity, under unstable conditions. It seems that as the wind

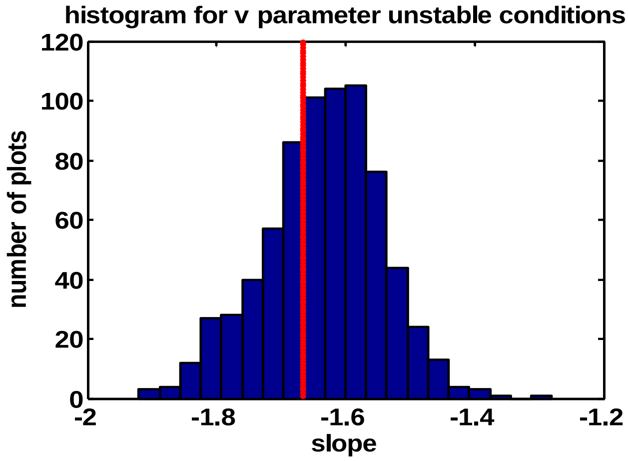

Fig. 11: Histogram of the v wind component spectral slope values, under unstable conditions. The red line is the theoretically slope value (-1.66).

speed decreases the slope become steeper than in Figure 7, meaning that the turbulence dissipates faster than previously. The green lines again are the linear regression estimations from the data under unstable conditions, while the red lines are the theoretically expected slope value (-1.66). On the other hand as the wind increases the slope become flatter in the inertial sub-range, meaning that the turbulence dissipates slower than according to the similarity theory, which was also observed by other studies [10], [11] and [12]. The same characteristics are given for the two wind component v and w under neutral or stable conditions (not shown).

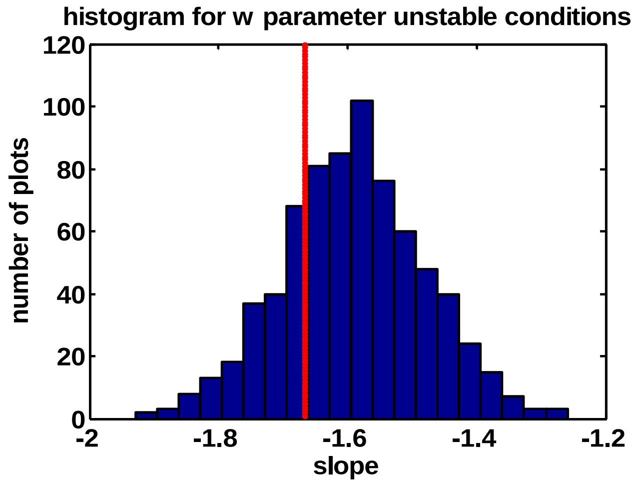

Fig. 12: Histogram of the w wind component spectral slope values, under unstable conditions. The red line is the theoretically slope value (-1.66).

Figures 10, 11 and 12 are the histograms of the three wind components (u, v and w) spectral slope values estimated under unstable conditions. The red line is the theoretically slope value (-1.66). It seems that

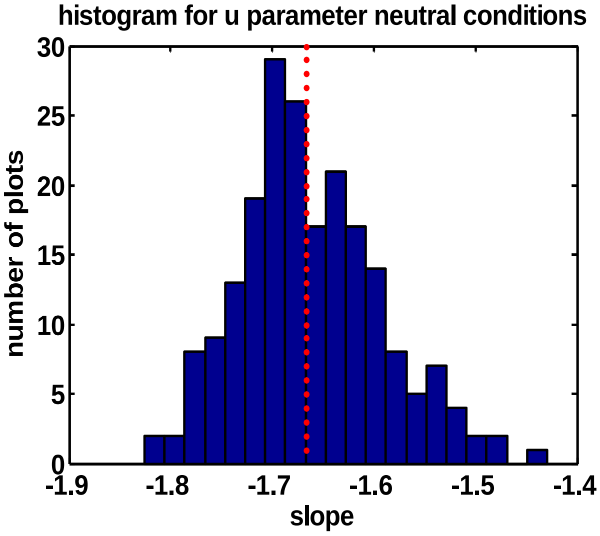

Fig. 13: Histogram of the u wind component spectral slope values, under neutral conditions. The red line is the theoretically slope value (-1.66).

for all three cases the majority of the estimated slope values are in a range of values which are lower than the theoretically expected ones, meaning that the turbulence dissipates slower than according to the similarity theory. Also it is worth mentioning that the estimated spectral slope values lie in a rather wide range from -1.3 to -1.9.

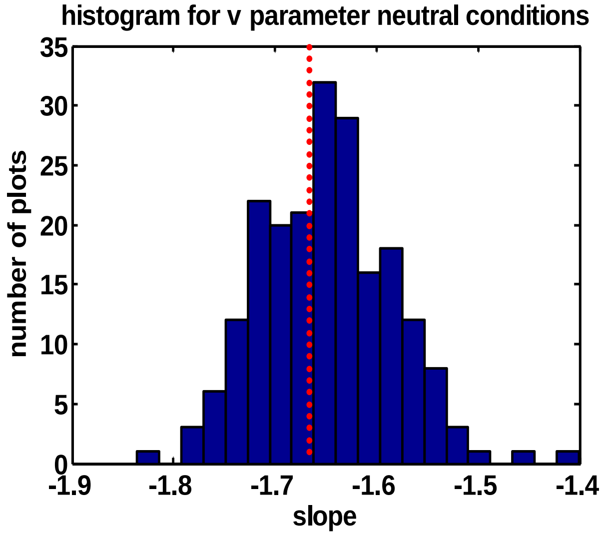

Fig. 14: Histogram of the v wind component spectral slope values, under neutral conditions. The red line is the theoretically slope value (-1.66).

Figures 13, 14 and 15 are the histograms of the three wind components (u, v and w) spectral slope values estimated under neutral conditions. The red line is the theoretically slope value (-1.66). It seems that for all three cases the majority of the estimated

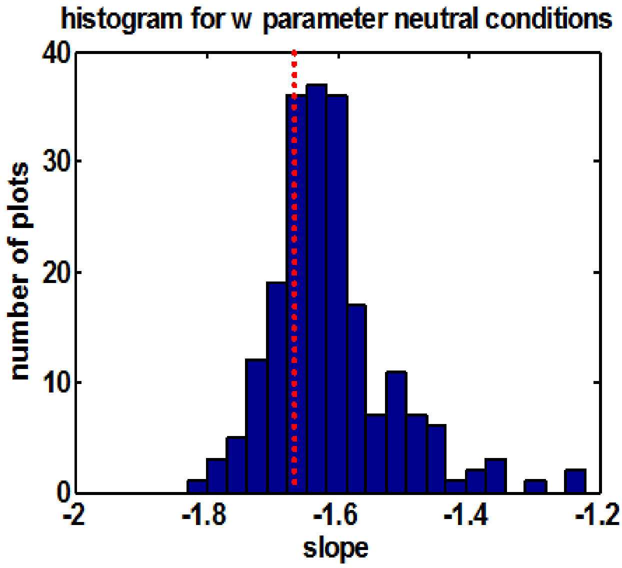

Fig. 15: Histogram of the w wind component spectral slope values, under neutral conditions. The red line is the theoretically slope value (-1.66).

slope values are in the center of the histogram very close to the theoretically expected value, meaning that the turbulence dissipates, in most cases, according to the similarity theory. Also it is worth mentioning that the estimated spectral slope values lie in a range which is narrower than the previous one (values from -1.5 to -1.8). Regarding the histograms of the three wind components (u, v and

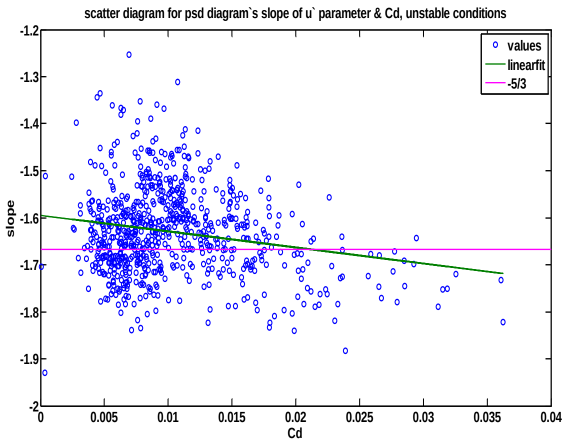

Fig. 16: Scatter plot of the u (longitudinal) wind component spectral slope values and the drag coefficient C_D, under unstable conditions

w) spectral slope values, estimated under stable conditions, it seems that again the majority of the estimated slope values are in the center of the histogram, very close to the theoretically expected

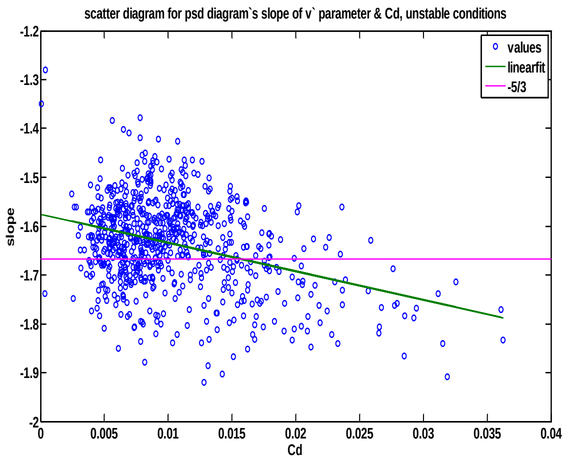

Fig. 17: Scatter plot of the v (lateral) wind component spectral slope values and the drag coefficient C_D, under unstable conditions

value and the estimated slope values lie in a range which is very close to the one of the neutral cases (not shown here). Thus under neutral or stable conditions the turbulence dissipates in most cases according to the similarity theory.

Figure 16 gives the scatter plot of the u (longitudinal) wind component spectral slope and the drag coefficient C_D, which is related with the friction velocity u_* according to the equation $C_D=u_*^2/U^2$. This plot was estimated under unstable conditions. It seems that as the drag coefficient decreases (lower values of vertical momentum transport), the slope become flatter (lower absolute values), meaning that the turbulence dissipates slower than according to the similarity theory. The green line is the linear regression estimation from the data under unstable conditions, while the red line is the theoretically expected slope value (-1.66).

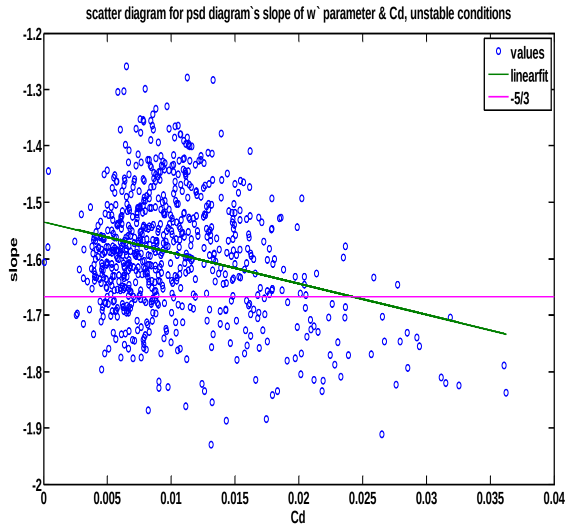

Fig. 18: Scatter plot of the w (vertical) wind component spectral slope values and the drag coefficient C_D, under unstable conditions

Figures 17 and 18 give the scatter plots of the v (lateral) and the w (vertical) wind components spectral slope values and the drag coefficient C_D respectively, under the same unstable conditions. These figures show a more intense decrease than the one in Figure 16 of the spectral slope values for low values of the drag coefficient, meaning again turbulence dissipation slower than according to the similarity theory. These results are very close to previously found results by relative studies over the sea surface [13].

4 Conclusions

An experimental campaign was conducted in the framework of the European project ECATS, in the area of the Athens International Airport (AIA), operating at Messogia Plain of Attika, Greece. The aim of this work was to study the surface ABL's spectral characteristics of the three wind components and the vertical momentum transport, as well as to reveal possible deviations of the estimated spectral slope values from the MO theoretical expected values and to examine the possible relation between the estimated by the measurements spectral slope values in the inertial sub-range and the ABL parameters such as, the atmospheric stability z/L, the friction velocity u_* and the mean wind speed.

From the analysis it was revealed that the surface vertical momentum flux values are increased by increasing the wind speed, while the higher and the lower values for the same wind speed value, correspond to the unstable and stable conditions respectively. The calculated power spectra of the three components of the wind (u, v and w) are characterized by spectral slopes which have mean values very close to the expected theoretically slope of -5/3 (1.66), under different atmospheric conditions.

Regarding the possible relation and the influence between the estimated by the measurements spectral slope values in the inertial sub-range and the ABL parameters such as, the atmospheric stability z/L, the drag coefficient C_D and the mean wind speed, it is clear that:

- As the atmospheric stability and/or the wind speed decreases the slope generally become steeper, meaning that the turbulence dissipates faster than according to the MO similarity theory.
- Also for lower values of the drag coefficient or of the friction velocity (lower values of vertical momentum transport), the spectrum slope becomes flatter (lower absolute values), meaning that the turbulence dissipates slower than it does according to the similarity theory.

ACKNOWLEDGMENTS

This work was supported by the EC-funded Network of Excellence in the framework of ECATS project (ANE-CT-2005-012284). The authors would like to acknowledge Mr. Ilias Karampatsos' work regarding spectral analysis of the data.

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