On the temporal evolution of the vertical momentum fluxes within the Marine Atmospheric Boundary Layer

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Abstract: - In the frame of the CBLAST-Low project, the vertical structure of the Marine Atmospheric Boundary Layer (MABL) was studied using remote and in situ sensing instrumentation at the southern coast of the Nantucket Island, MA, USA, during 2003. Since a Low-Level Jet (LLJ) was frequently observed at low heights, it is of interest to examine the modification of the vertical transport of momentum fluxes and the possible influence on the vertical structure of the Turbulent Kinetic Energy (TKE). Thus two cases of a LLJ development (the 3rd and the 7th of August 2003) were examined, regarding the momentum transport and the standard deviation of the vertical component of the wind profiles which is related with the TKE. According to this study an intense modification of the vertical profiles of momentum fluxes and TKE was evident mainly above the LLJ core, following the temporal evolution of the developed LLJ. This fact modifies the vertical turbulent structure of the marine Atmospheric Boundary Layer as well as the expected levels of TKE values.

Key-Words: Momentum flux, Marine Atmospheric Boundary Layer, Turbulent Kinetic Energy, SODAR, LLJ

1 Introduction

The air flow characteristics, the mean and turbulent vertical structure and the stability of the Marine Atmospheric Boundary Layer (MABL) as well as the parameterization of the mass, heat and moisture exchange between the air and sea are issues of major interest for atmospheric physics [1], [2], [3]. Also, the influence of the MABL over the land close to the shoreline has received considerable attention mainly in terms of the growth of the thermal internal boundary layer near the coast [4] or the development of the recirculation flow of the sea-breeze [5] due to the practical concern on the coastal pollution or for wind energy applications [6]. The turbulence structure (spectra, variances and length scales) of the stable MABL as well as the transport of the momentum within the MABL are influenced under the development of a Low-Level Jet (LLJ) [7], [8]. Since the observations within the stable MABL are limited, this experimental work aims to the understanding of the air-sea interaction and the modification of the turbulent structure of the stable MABL dominated by a LLJ. The vertical profiles of momentum fluxes were estimated with the use of a SODAR system operating very close to the shoreline. The ability of the SODAR system to measure the mean and turbulent structure of the Atmospheric Boundary Layer (ABL) is well known [9], [10], [11], [12] as well as to estimate the Turbulent Kinetic Energy (TKE), using the semi empirical theory of turbulence together with a simple parameterization under near neutral conditions [13], [14]. In this work two experimental cases characterized by stable MABL, dominated by a LLJ are studied and the modification of the vertical transport of momentum and the vertical profiles of the standard deviation of the vertical component of the wind profiles which is related with the TKE are given and discussed.

2 Experimental site and Instrumentation

An extensive experimental campaign was conducted at Nantucket Island (Figure 1), MA, USA, between July 22 and August 27, 2003, in order to study the turbulent vertical structure of the MABL. The measurement site was on the west side of the island, at a distance of 90m from the shoreline, the land surface of the island was relatively flat and the certain site was chosen since the wind in this area was predominantly south or south westerly, so we had better chance to measure the marine ABL [15], [16].

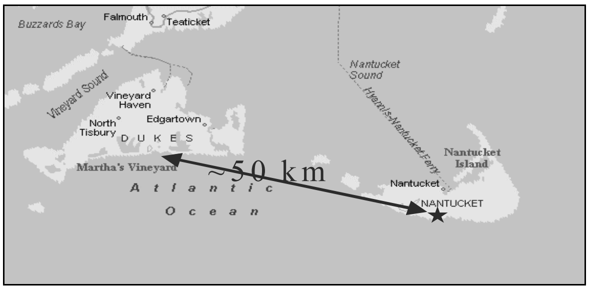

Fig. 1: The island of Nantucket

Combined in situ and remote sensing instrumentation was in operation in the Nantucket site (Figure 2). A Remtech (PA2) SODAR system was operated to measure the vertical profiles of the horizontal wind speed and direction, the standard deviations of the three wind components, the momentum fluxes $\overline{u'w'}$ and $\overline{v'w'}$ of the wind components, the acoustic echo strength and the atmospheric static stability. The three wind fluctuation components u', v' and w', used for the calculation of the momentum fluxes, are related with the SODAR antenna frame, being in our case u' (the horizontal north-eastward component at 35^O), v' (the horizontal north-westward component at 305^O) and w' (the vertical). The calculation of Reynold's stresses is performed with the application of the "spatial time lag approach", provided by the manufacturer, in order to avoid spatial and temporal de-correlation effects due to the fact that SODARS sample sequentially from one axis to another. This procedure includes high pass filtering and time lag cross correlation calculations applied to the three radial wind component (u'_1, u'_2 and u'_3) time series, in order to correct both spatial and time separation, between the individual measurements made in the three scattering volumes at a given altitude. The calculation of the Reynold's stresses is conducted from the corresponding estimated w', u' and v' wind speed fluctuation components which are related to the SODAR antenna frame, using the measured radial fluctuation components. The calculation of the atmospheric static stability is based on the "detection technique", employed by the manufacturer, which is consisted of simultaneous use of echo pattern recognition technique plus the information provided by the SODAR regarding the standard deviation of the echo strength, the vertical gradient of horizontal wind speed and the turbulence indicators σ_θ and σ_w. More details of the methods can be found in previous studies [17], [18], as well as in the manufacturer manuals. The SODAR estimations were given at 30 minutes average interval with a vertical resolution of 40 m and a range up to the height of 700m. In order to protect the SODAR antenna from the acoustic noise (mainly from the breaking sea waves) as well as to protect the nearby area from the emitted acoustic pulses, the SODAR antenna was placed into a square hole with 2m side length and 1m depth, shielded with bales of hay and wooden boards. Close to the SODAR antenna there were two meteorological masts (20m and 2m high) equipped with high and low response sensors at different levels for the estimation of momentum, sensible heat and latent heat fluxes and also measurements of the mean wind, temperature, and relative humidity (RH), air pressure, precipitation, and downward solar radiation. In addition, radiosondes were launched four or six times daily, at the experimental site. Since the in-situ measurements are not used in this work, they are not described in details but more information can be found elsewhere [15].

Fig. 2: Center: The experimental site. Left: the 20m meteorological mast. Right: the SODAR antenna.

3 The MABL case during the 3rd of August 2003

3.1 The Synoptic Conditions and the vertical mean structure of the MABL

The synoptic conditions and the mean vertical structure of the chosen experimental day, the 3rd of August 2003, were presented and discussed at the proceedings of the WSEAS Remote'05 Conference, in Venice, Italy, 2005 [19], [20]. According to the mean sea level pressure fields, weather observations and the 500 hPa geopotential distribution, the area of Nantucket was inside the warm sector of a frontal depression, while a large scale anticyclone prevailed over the greater Atlantic area. Thus, a strong surface SSW flow of 12 to 13 m/sec was established over the island, (marine sector), which was persisting the whole day. The wind field, between 00:30 to 08:00 UTC, is characterized by a low to moderate south-westerly flow which was changed later to an intense south-westerly flow. Conversion from UTC to LST requires a subtraction of 4 hours (LST = UTC - 4hr). Between 04:30 UTC to 12:00 UTC a LLJ was developed at heights between 200-250m while after 17:00 UTC two LLJs were developed at 150 and 400m height which gradually descended to the height of 100 and 250m respectively and their strength was increased. Also very stable atmospheric conditions were characterized the first 150m with slight stable to neutral conditions at higher levels. It is worth to mention that there are many ways to define the presence of LLJ's; different investigators have used different criteria for identifying LLJs [21]. In this work, the presence of LLJ is identified following Banta et al. criteria [22] using the wind measurements from SODAR wind profiles. The chosen LLJs were the ones that exhibited a decrease of at least a minimum threshold (1.5 m s^{-1}) both above and below the altitude of a single prominent local wind maximum (LLJ core)

3.2 The momentum Transport - Results and discussion

In order to study the temporal evolution of the vertical structure of the momentum fluxes within the MABL, the relevant estimations using data from the SODAR (up to 600m height) for the 3rd of August, 2003 are presented. Since this day was dominated by the developed LLJ it is worth mentioning that according to the literature, a large scale horizontal temperature difference causing baroclinicity in the ABL [23] or an inertial oscillation due to frictional decoupling over the sea [7], are possible causes of the LLJ. According to our analysis, with very stable stratification at the lower part of the ABL, the main mechanism is likely to be the frictional decoupling and the subsequent inertial oscillation [24], [25], although horizontal temperature gradients are also present.

Figure 3 gives the time-height cross sections of the standard deviation σ_w of the vertical wind component (m/sec) during the 3rd of August 2003, 00:00 – 24:00 UTC. It is evident from the figure that high values of the σ_w parameter, which is a measure of the TKE [13], exist at heights above the LLJ core due to the shear forcing near the developed wind maximum, while secondary maxima are observed below the LLJ core. Close to the surface, the increased stability of the surface layer restrains the turbulence. After 17:00 UTC the development of the two intense LLJs at 150 and 400m height and their gradually descending to the height of 100 and 250m respectively increased the values of σ_w even close to the surface.

Figure 4 presents the time-height cross section of the momentum flux $\overline{u'w'}$ wind component during the same day. High values of positive (upwards) momentum transport is observed above the LLJ core while close to the surface lower negative values (downwards) are estimated. This is expected since the *u* wind component is alongside the dominant wind flow. After 17:00 UTC the development and descend of the two intense LLJs increase the momentum flux values even close to the surface. On the other hand $\overline{v'w'}$ momentum flux exhibits lower values due to the fact that the *v* component is vertical to the prevailing flow (see Fig. 5). At Figure 6 the time-height cross section of the Total Vertical Momentum Flux, the sum of the momentum fluxes $\left(\left(\overline{u'w'}\right)^2+\left(\overline{v'w'}\right)^2\right)^{1/2}$ for the whole day is presented. It is evident that the developed LLJ modifies the profiles of the total vertical momentum fluxes, with high values of momentum fluxes above the wind maximum height and much lower ones close to the surface. After 17:00 UTC the development of the two LLJs, increase the total momentum flux values close to the surface. The variation in time of the estimated values of the total momentum fluxes is associated with the evolution and the intensity of the LLJs during the day.

4 The MABL case during the 7th of August 2003

4.1 The Synoptic Conditions and the vertical mean structure of the MABL

The synoptic conditions over Nantucket area during the 7th of August 2003 were characterized by a large scale trough located over the Northeastern States and a large scale anticyclone over the greater Northwestern Atlantic Ocean. The trough moved slowly to the east producing a strong

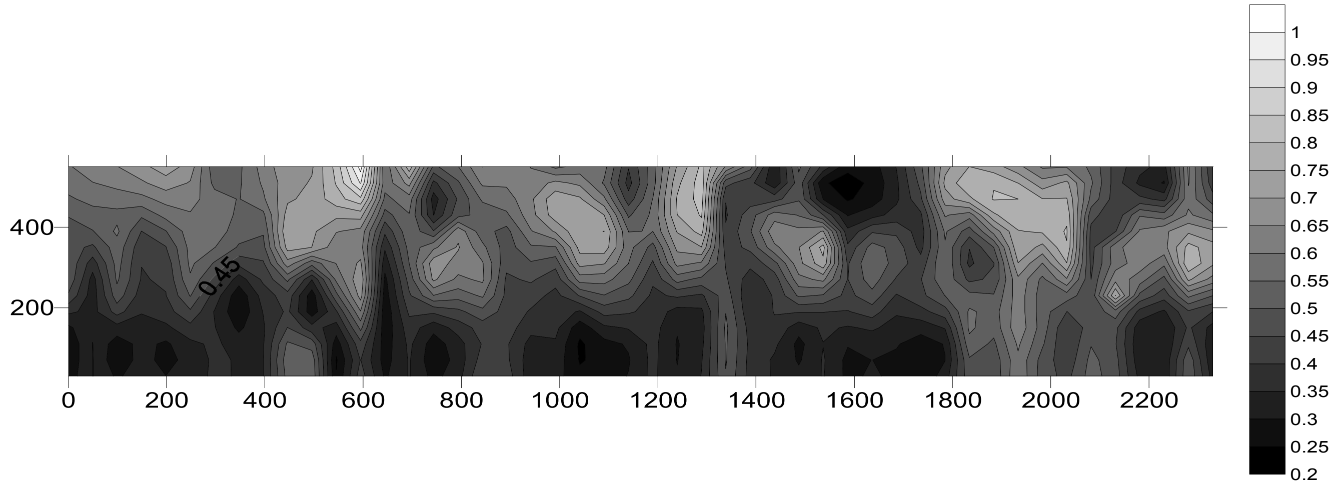

Fig. 3: Time-height cross section of the standard deviation σ_w of the vertical wind component (m/sec) during the 3rd of August 2003, 00:00 – 24:00 UTC

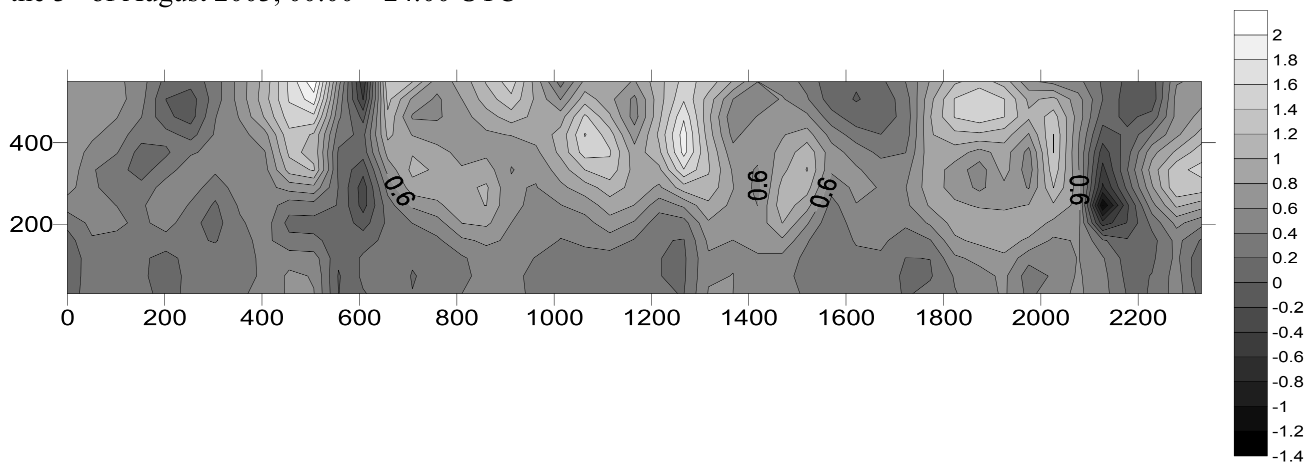

Fig. 4: Time-height cross section of the momentum flux $\overline{u'w'}$ wind component (m^2/sec^2) during the 3rd of August 2003, 00:00 – 24:00 UTC

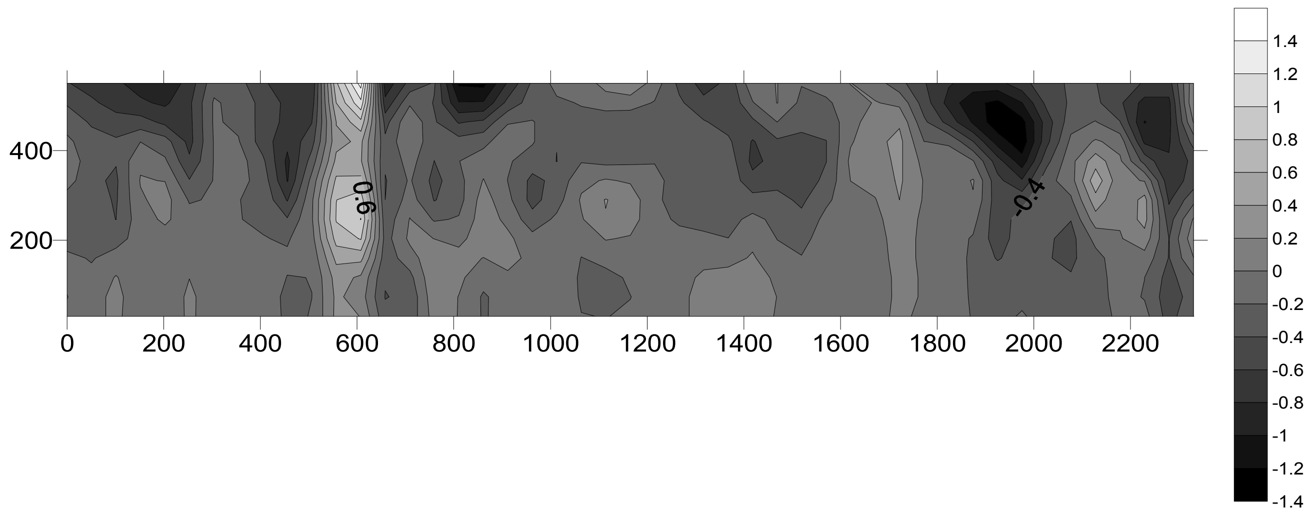

Fig. 5: Time-height cross section of the momentum flux $\overline{v'w'}$ wind component (m^2/sec^2) during the 3rd of August 2003, 00:00 – 24:00 UTC

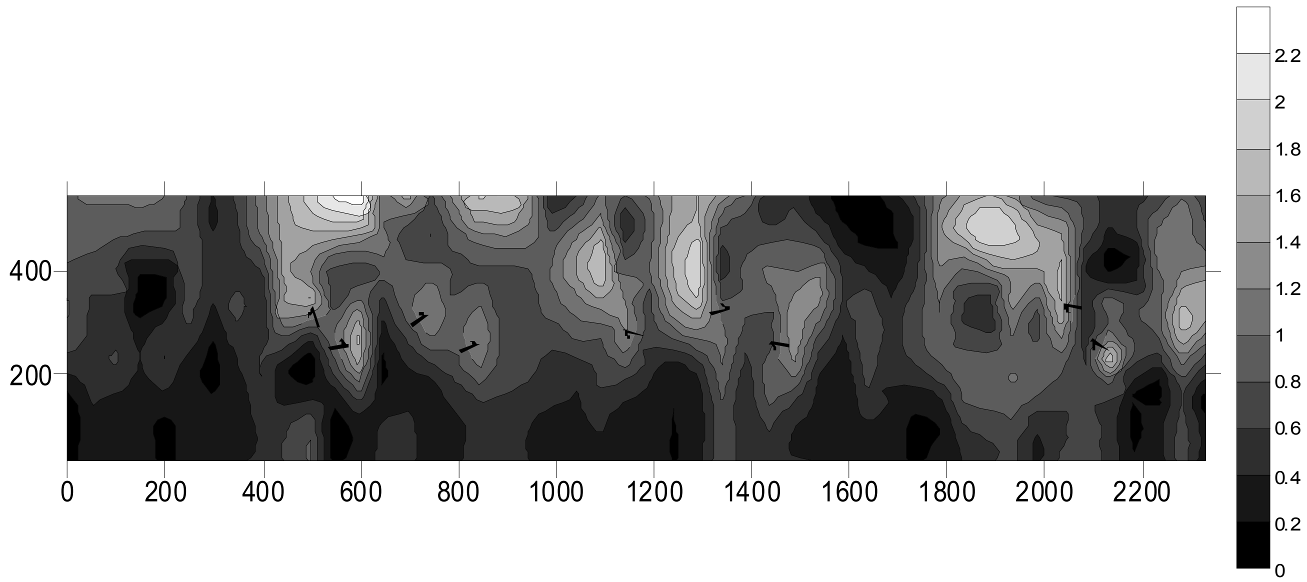

Fig. 6: Time-height cross section of the momentum total fluxes of the two wind components (m^2/sec^2) during the 3rd of August 2003, 00:00 – 24:00 UTC

SSW flow while the satellite images and the surface map analyses showed no presence of a front over a large area near Nantucket. Clouds existed for most of the 7th of August with a low cloud base height that decreased from 250 to 150 m by 0800 UTC and then it was remained constant with scattered weak rainfall during the morning and early evening hours. According to the SODAR measurements during this day the wind was blowing from the SSW direction until the end of the day and a LLJ established after 1300 UTC at 200 to 250 m (11-12 m s^{-1}) which gradually decreased in strength and descended to 180 m during night time. The wind direction profiles depict mainly the wind vector veering (oscillation) at lower levels from SSW to SW and back again due to the frictional decoupling and the subsequent inertial oscillation [20], [23]. It is worth mentioning that the wind speed and direction values from the SODAR are in good agreement with the respective rawinsonde measurements when available. Figure 7 gives the atmospheric stability class derived from the Sodar for the whole day. Stability classes 1, 2, 3, and 4 correspond to stable, slightly stable, neutral, and slightly unstable thermal stratification respectively. Very stable atmospheric conditions characterize the first 100 to 200 m followed by slight stable to neutral conditions at higher levels. It is of interest to mention the very stable conditions around 1300 UTC up to 400 m height which signals the onset of the frictional decoupling and the subsequent development of the LLJ.

4.2 The momentum Transport - Results and discussion

The temporal evolution of the vertical structure of the transport of momentum and turbulent energy within the MABL (up to 600m height) are presented, using data from the SODAR for the 7th of August, 2003. Figure 8 gives the time height plot of the vertical wind component (w) calculated by the SODAR for this day. Before the development of the LLJ a succession of positive and negative air mass motions is evident while after the LLJ development, upward motion is observed below and close to the LLJ core layer. Low downward motion characterizes the surface layer while above the LLJ layer mainly negative (downward) motions are predominant. Figure 9 presents the time-height cross sections of the standard deviation σ_w of the vertical wind component (m/sec) during the 7th of August 2003, 00:00 – 24:00 UTC. It is evident from the figure that high values of the σ_w parameter exist after the LLJ development (around 1300 UTC) at heights above the LLJ core, due to the shear forcing near the developed wind maximum. Close to the surface, the increased stability of the surface layer restrains the turbulence. After 20:00 UTC the gradually descending of the LLJ increased the values of σ_w even close to the surface.

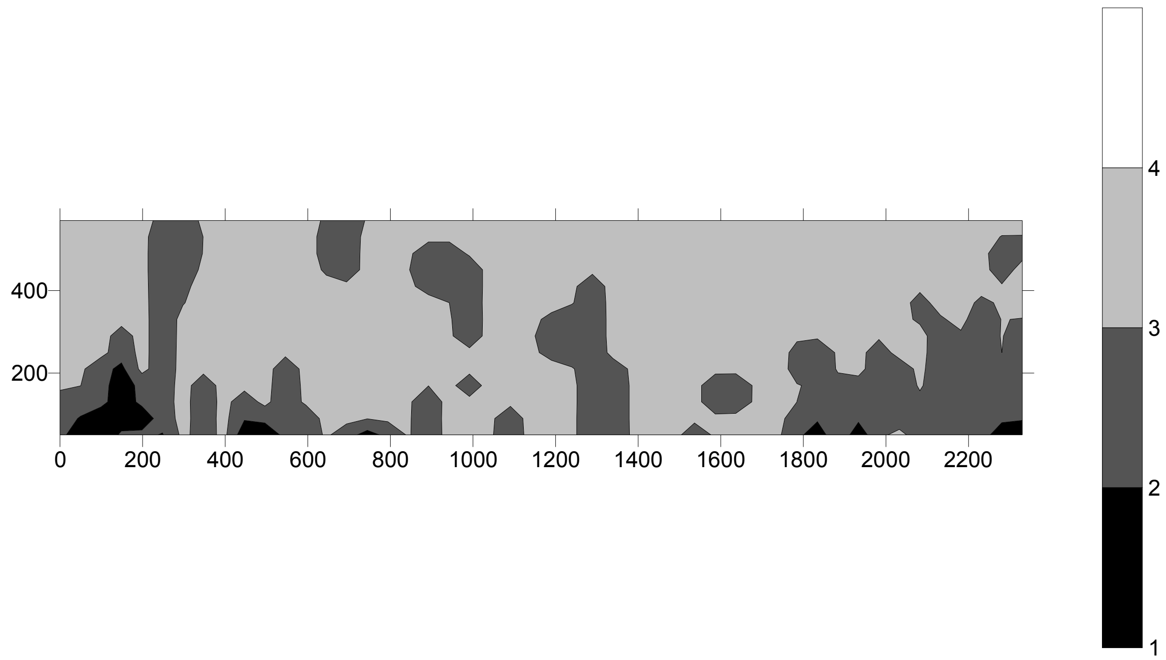

Fig. 7: Time-height cross section of the atmospheric stability class during the 7th of August 2003, 00:00 – 24:00 UTC. Stability classes are given in the text

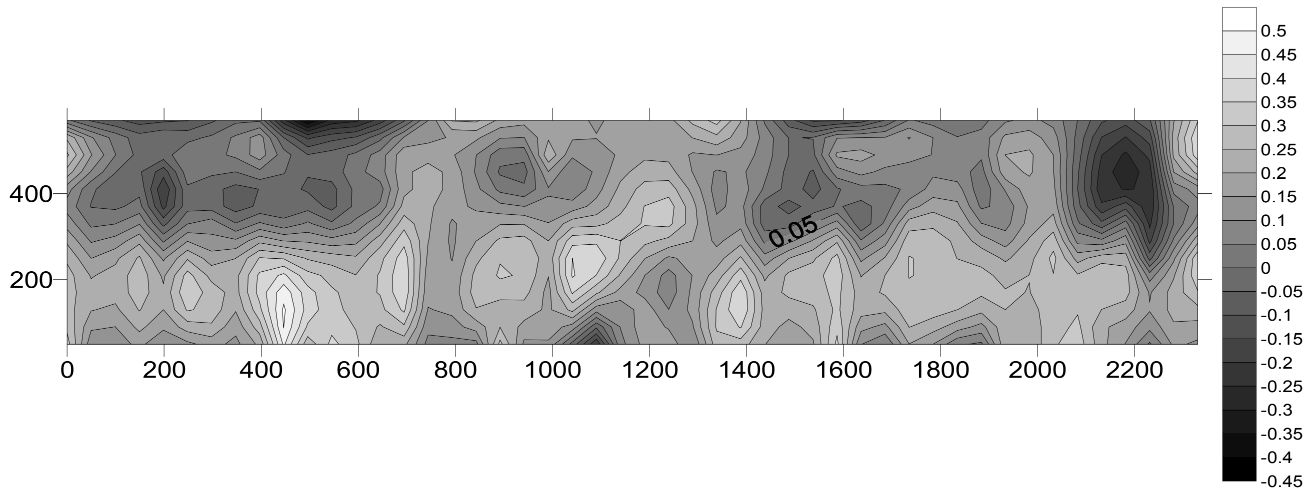

Fig. 8: Time-height cross section of the vertical wind component (m/sec) during the 7th of August 2003, 00:00 – 24:00 UTC.

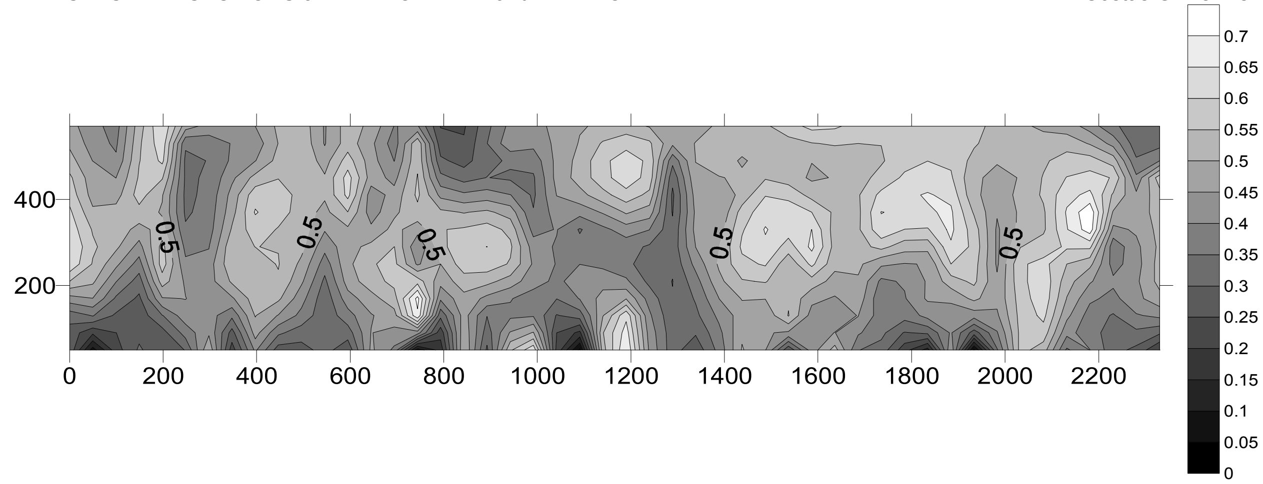

Fig. 9: Time-height cross section of the standard deviation σ_w of the vertical wind component (m/sec) during the 7th of August 2003, 00:00 – 24:00 UTC

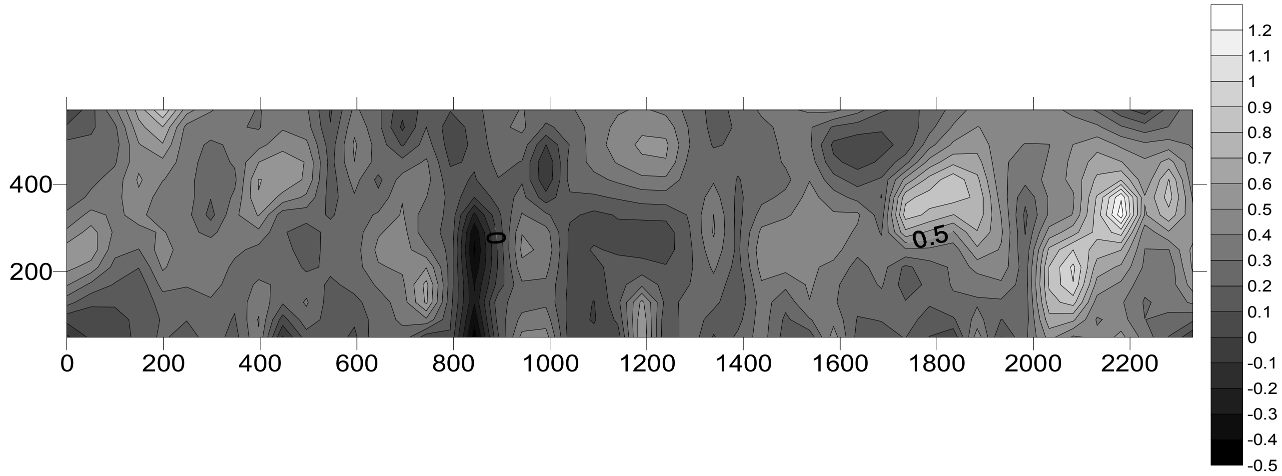

Fig. 10: Time-height cross section of the momentum flux $\overline{u'w'}$ wind component (m^2/sec^2) during the 7th of August 2003, 00:00 – 24:00 UTC

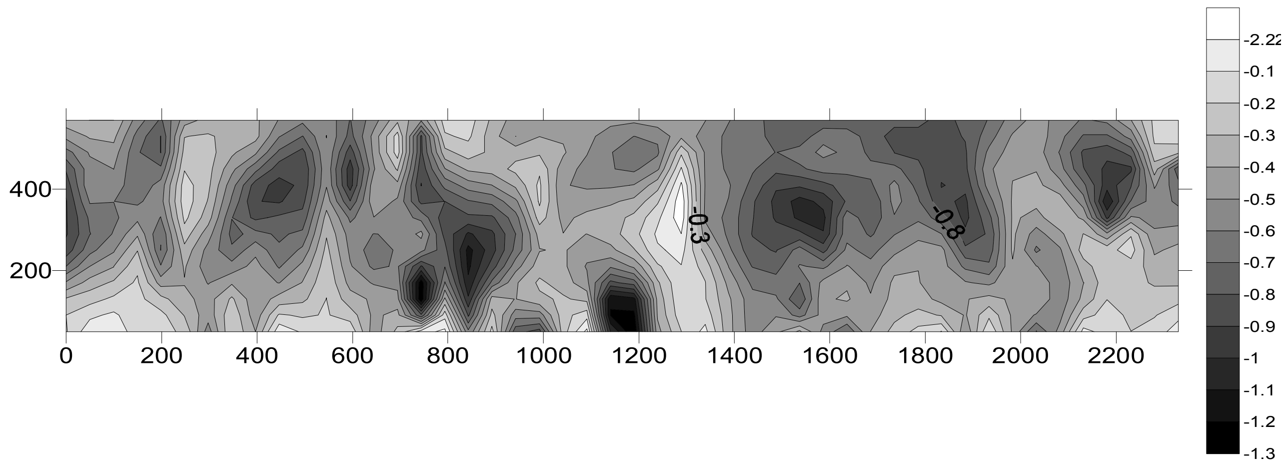

Fig. 11: Time-height cross section of the momentum flux $\overline{v'w'}$ wind component (m^2/sec^2) during the 7th of August 2003, 00:00 – 24:00 UTC

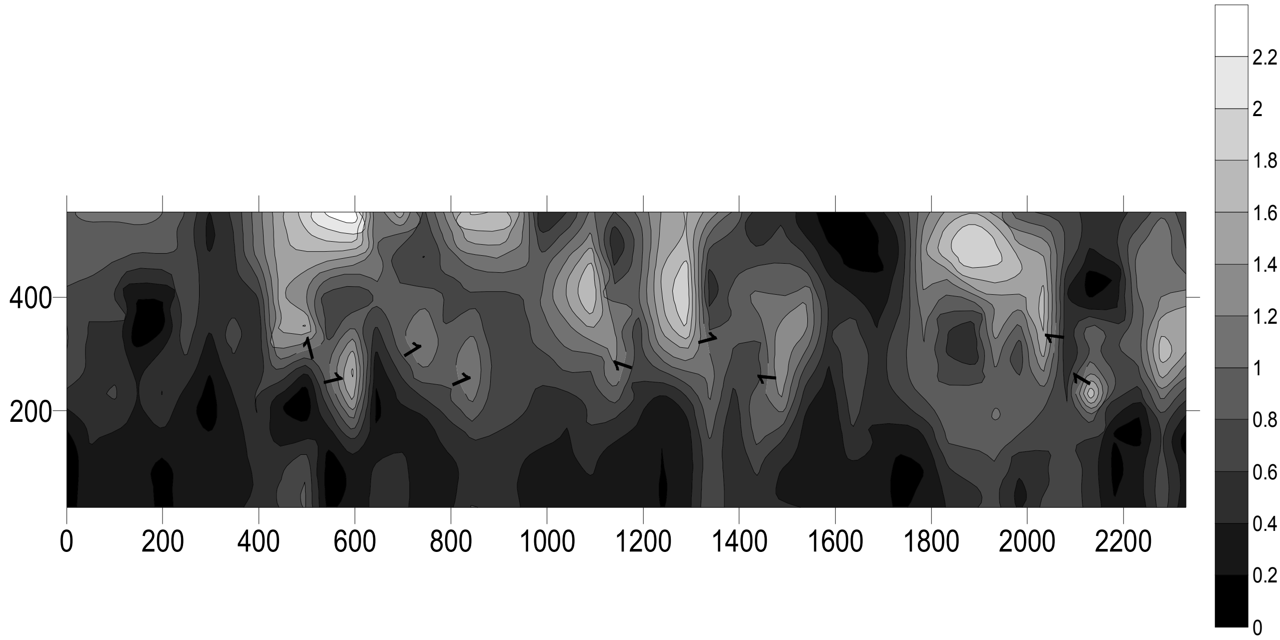

Fig. 12: Time-height cross section of the momentum total fluxes of the two wind components (m^2/sec^2) during the 7th of August 2003, 00:00 – 24:00 UTC

According to Kouznetsov et al. [13] the vertical wind component fluctuations give a method to derive TKE under neutral stratification from σ^2_w using the relation $TKE \cong 3.4\,\sigma_w^2$ in the SODAR-covered part of the ABL, while under non-neutral conditions the coefficient of the relation should be a function of M-O stability parameter z/L. Thus the modification of σ^2_w profiles, modify as well the TKE transport. Figure 10 presents the time-height cross section of the momentum flux $\overline{u'w'}$ wind component during this day. High values of positive (upwards) momentum transport is observed above the LLJ core while below it negative values (downwards) are estimated which was expected since the *u* wind component is alongside the dominant wind flow. After 18:00 UTC the descend of the LLJ increase the momentum flux values close to the surface. On the other hand the time-height cross section of the $\overline{v'w'}$ momentum fluxes exhibits lower values and mainly downward transport after the development of the LLJ (see Fig. 11). At Figure 12 the time-height cross section of the Total Vertical Momentum Flux, the sum of the momentum fluxes $\left((\overline{u'w'})^2 + (\overline{v'w'})^2\right)^{1/2}$ for the whole day is presented. It is evident that the developed LLJ, modifies the profiles of the total vertical momentum fluxes, with high values of momentum fluxes above the wind maximum height and much lower ones close to the surface. After 16:00 UTC the development of the LLJ, increase the total momentum flux values close to the surface. The variation in time of the estimated values of the total momentum fluxes is associated with the evolution and the intensity of the LLJs during the day.

5 Concluding Remarks

The analysis of the estimated momentum flux values by the SODAR data for two typical experimental days characterized by the development of a LLJ, revealed the following characteristics of the turbulence structure and the momemtum transport within the MABL:

- The vertical turbulent structure of the stable MABL as well as the transport of the momentum within the MABL is influenced from the development of a LLJ.
- High values of the σ_w parameter, which is a measure of the TKE, exist at heights above the LLJ core due to the shear forcing near the developed wind maximum, while secondary maxima

are observed below the LLJ core. Close to the surface, the increased stability of the surface layer restrains the turbulence.

- High values of positive (upwards) momentum transport of the *u* wind component which is alongside the dominant wind flow is observed above the LLJ core while close to the surface lower negative values (downwards) are estimated. The descend of the intense LLJs during the afternoon and evening hours, increase the momentum flux values even close to the surface.
- The $\overline{v^{'}w^{'}}$ momentum flux exhibits lower values due to the fact that the *v* component is vertical to the prevailing flow.
- The Total Vertical Momentum Flux profiles reveal the modification of the momentum fluxes, with high values above the wind maximum height and much lower ones below the LLJ core and close to the surface, while the descend of the LLJs, increases the total momentum flux values close to the surface. The variation in time of the estimated total momentum flux profiles is associated with the evolution and the intensity of the LLJs during the day.

6 Acknowledgements

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