P12.5 FRICTIONAL DECOUPLING AND THE INERTIAL OSCILLATION IN STABLE MARINE ATMOSPHERIC BOUNDARY LAYER

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1. INTRODUCTION

The study of coastal ABL has been received recently considerable attention with respect to the upwind Marine Atmospheric Boundary Layer (MABL), since uncertainties related to the parameterization of the mass, heat and moisture exchange between the air and sea are existed, as well as modification of the wind flow field related to terrain and surface thermal effects (Smedman et al., 2004). Moreover, according to previous studies, Low Level Jets (LLJ) associated with intensified thermal stratifications are characterized the coastal ABL (Smedman et al, 1993, 1995). It is worth mentioning that according to previous work, local topography and/or a large scale horizontal temperature contrast causing baroclinicity in the ABL (Gerber et al., 1989 and Li et al. 1983) or an inertial oscillation due to frictional decoupling (Smedman 1995, Stensrud 1996), are possible causes of the LLJ development. The latter mechanism was first studied by Blackadar (1957) who suggested that after sunset, the layer close to the ground becomes statically stable due to the radiation cooling, the mixing decreases, the wind is not affected by the surface (frictional decoupling) and the boundary layer winds are enhanced, resulting in the generation of intense wind shear due to the subsequent developed inertial oscillation. The period of the oscillation is $2\pi/f_c$ where f_c is the Coriolis parameter ($f_c = 2\,\omega\,\sin\varphi$, where ω is the angular velocity of the earth and φ the latitude) and at mid-latitudes the estimated theoretically inertial period is about 17h (Stull 1988). The magnitude of the oscillation depends on the amount of the geostrophic departure of the wind at the start of the frictional cease and typical geostrophic departures are of the order of 2 to 5 m/sec, leading to jet maxima that can reach speeds 2 to 5 m/sec higher than geostrophic wind (Garratt 1985 and Kraus 1985). In this experimental study, the characteristics of the vertical structure of the upwind MABL, the frictional decoupling over a maritime area and the development of the LLJ are examined, combining both in situ and remote sensing data. This work was conducted in the frame of the CBLAST-Low project which was aimed at the understanding of the air-sea interaction and the coupled atmospheric and oceanic boundary layer dynamics at low wind speeds, where the dynamic processes are driven and/or strongly modulated by thermal forcing (Edson et al, 2004).

The development and the evolution of the LLJ were studied with the use of an Acoustic Radar (SODAR) which was in operation at the shoreline of Nantucket Island. It should be mentioned that the ability of SODARS to measure the mean and the turbulent characteristics of the wind flow as well as the thermal structure of the ABL is well known (Coulter and Kallistratova, 2004, Helmis et al, 2000) and the experience of using these systems have demonstrated the feasibility of SODARS operating over the ocean (Fairall et al, 1997, Petenko et al, 1996), over small island (Helmis et al. 2002) or on the shoreline (Helmis et al. 1987). The aim of this study is the understanding of the possible cause for the development of the LLJ, which is associated with the strong stability of the MABL lower layer and the confirmation of this mechanism from experimental measurements and theoretical considerations.

1. EXPERIMENTAL AREA AND INSTRUMENTATION

The experimental campaign was carried out during summer 2003 (31st of July to 27th of August) at the Nantucket Island, MA, USA. Our measurement site was at the southerly-westerly coast of the island, at a distance of 90m from the waterfront where the land surface was relatively flat. A suite of in situ and remote sensing instruments designed to characterize the changing structure of the MABL was deployed. A SODAR system was measuring the

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vertical profiles of the horizontal wind speed and direction, the echo strength, the vertical (w) and the two horizontal wind components u (north-westward) and v (north-eastward), the standard deviations of the three wind components, the momentum fluxes ($u'w'$ and $v'w'$) and the atmospheric static stability class at 30 minutes intervals, with a vertical resolution of 40m and a range up to the height of 600m. More details regarding SODAR system and its parameters can be found at Helmis et al. (2004). The Nantucket instrument suite also includes a 20m meteorological mast equipped with fast response sensors at two levels (10 and 20m) and slow response sensors at three levels (5, 10, and 20m) as well as a laser ceilometer that detects the cloud base height continuously (Wang et al. 2004). The high-rate measurements (20Hz) yield to the estimation of momentum, sensible heat and latent heat fluxes through the eddy correlation method. In addition, rawinsondes were launched at the experimental site every four to six hours per day.

2. METHODOLOGY AND DATA ANALYSIS

During the experimental campaign, the study of the vertical structure of the MABL (by the SODAR and radiosonde measurements) indicated the development, very frequently, of a LLJ at low heights associated with very stable atmospheric conditions, characterized the first 200 to 300m, followed by slight stable to neutral conditions at higher levels. In order to study the occurrence and characteristics of the LLJ and the possible subsequent inertial oscillation in the MABL, a time period of 7 successive days was selected which was characterized by steady south-westerly flow (marine flow) with moderate to high wind.

Since the evolution of the LLJs showed significant variation regarding its intensity and the magnitude of the wind shift, Hilbert – Huang transform (HHT) was selected in order to reveal the temporal characteristics of the intermittent and non-stationary wave events such as the inertial oscillations (Huang et al. 1998, 1999, 2000). The recently developed HHT is a thorough method for analysing non-stationary and nonlinear data and is an adaptive empirically based data -analysis method which has been applied also in ABL time series data (Lundquist, 2003). The HHT method is consisted of two steps of analysis. The first step called Empirical Mode Decomposition breaks the original time series into a finite number of intrinsic mode function (IMF) components, based on the intrinsic timescales of the dataset, which heighten the different local character of the original data. Each intrinsic mode represents a simple oscillation, which will also be symmetric with respect to the "local mean." At any given time, the data may have many different coexisting modes of oscillation, one superimposing on the others. The second step is the application of Hilbert transform to each component in order to obtain the instantaneous frequency and amplitude as function of time. This frequency-time distribution of the amplitude is designated as the Hilbert amplitude spectrum, which could well response the distribution law of energy in time scales from the physical process. Compared with traditional spectrum method, the HHT method eliminates the need for spurious harmonics of redundant physics sense to represent non-stationary signals (Li et al. 2005). The HHT method was applied to the SODAR time series data, at heights close to the LLJ core and the corresponding frequency-time distribution of the amplitude of different oscillations was produced. The instantaneous frequency it must be taken into account as the frequency of a sine wave that locally fits the signal, rather than the frequency of a sine wave that is present throughout the entire signal. In this way, an energy–frequency–time distribution (known as the Hilbert spectrum) is calculated. As the stable atmospheric boundary layer is subject to nonstationary phenomena and is marked by intermittence, this method is well-suited to studies of the stable boundary layer (Lundquist, 2003). Also for each experimental day the vertical profiles of the horizontal wind speed and the wind direction, the potential temperature and the relative humidity estimated by the successive radiosonde launches as well as the time-height cross section of the wind speed and the atmospheric stability class derived from the SODAR were produced and compared.

3. RESULTS AND DISCUSSION

The experimental period between the 1st to the 8th of August 2003 was characterized by a large scale trough (500 hPa level) which was located over the Northwestern States, while a large scale anticyclone prevailed over the greater

Northwestern Atlantic area. This trough moved slowly to the east producing a relatively strong and moist south – southwesterly flow over the greater area of Nantucket Island during the whole time period. The horizontal surface pressure gradient remained considerably weak, producing a persistent south–southwesterly flow with high relative humidity values. Nantucket Island, during the first 3 days, was affected by a rather persistent stationary front, accompanied with high relative humidity values, cloudiness and some scattered rainfall. A slight increase of the maximum surface temperature was observed, varying form 22.7^{o}C at the 1^{st} to 25^{o}C at the 4^{th} of August, while the minimum surface temperature remained steady (20 to 20.5^{o}C). After the 3^{rd} of August stationary fronts were observed north of Nantucket and the 4^{th} of August was characterized by a considerable decrease of the relative humidity values (74%) without rainfall. During the period 5^{th} to 8^{th} of August, the maximum surface temperature showed little variation while scattered rainfall was continued with moderate wind and high relative humidity values.

During this period a LLJ was developed frequently at low heights, on the top of the ground based strong temperature inversion, characterized the first 200 to 300m of the MABL. The following figures, corresponding to the experimental day of the 2^{nd} of August, give an example of the vertical structure of the upwind MABL and the characteristics of the developed LLJ. Figure 1 gives the vertical profiles of the horizontal wind speed and the wind direction, estimated by three successive radiosonde launches at 00:00, 05:00 and 14:00 UTC respectively during the experimental day. Conversion from UTC to LST requires a subtraction of 4 hours (LST = UTC - 4hr). The wind direction is almost constant up to 1000m height from the south–south-westerly sector (210-230 degrees).

At the corresponding wind speed profiles the development of a shallow LLJ (13.4m/s) at 250m height during the second launching as well as the development of an intense LLJ at 14:00 UTC, into a relatively shallow layer (about 100m) between 300m and 400m height with high wind speed (15.5m/s) are evident.

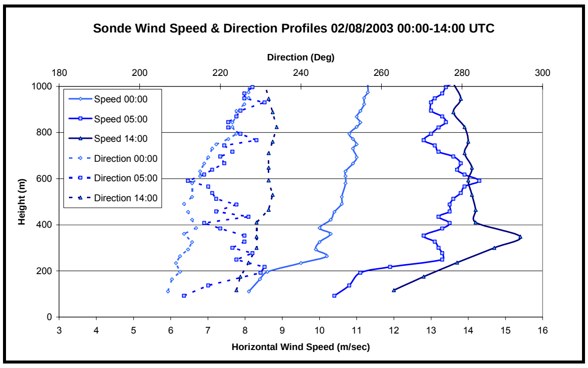

Fig. 1: Horizontal Wind Speed and Direction measured by the radiosonde for 02/08/2003.

Figure 2 gives the vertical profiles of the potential temperature and the relative humidity for the same time periods. The potential temperature profiles show a very stable surface layer (with mean potential temperature gradient $\Delta\theta/\Delta z = 2^{o}K/100m$) extending up to 150m height and a slightly stable layer (with gradient $\Delta\theta/\Delta z$ = 0.3 to 0.6^{o}K/100m) at higher levels. It should be mentioned that the first launching is characterized by an inversion layer at 700m height while during the third launching the ground based inversion was enhanced and covered the first 300m on the top of which the LLJ was developed. The relative humidity profiles give a surface layer with high values (more than 97% due to cloudiness) at the first 170m followed by lower values, in the range of 87-95%, at higher levels. Intense relative humidity values (94-96%) were observed during the third launching at heights above 250m.

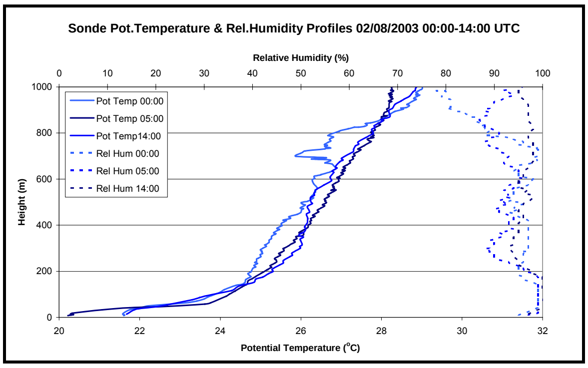

Fig. 2: Potential Temperature and Relative Humidity measured by the radiosonde for 02/08/2003.

Figure 3 gives the time-height cross sections of the wind speed estimated by the SODAR during the whole period of this day. During the period from 04:30 to 15:00 UTC the evolution of wind maxima at the height of 200-300m is evident, while the development of a strong LLJ is observed between 13:00 to 15:00 UTC. It should be mentioned that the time on the horizontal axis correspond to averaged values of the wind incorporating the previous half an hour time period. The ABL up to the first 80m is characterized by intense wind speed shear, which is more intense when the LLJ is present. Figure 4 gives the atmospheric stability class derived from the SODAR for the same period. Stability classes 1, 2 and 3 correspond to stable, slightly stable and neutral stratification respectively. Very stable conditions characterize the first 200m of the MABL which are extending to 300m after 12:00 UTC while slightly stable and neutral stratification of the MABL is observed above. For a time period of about 3 hours (12:00 – 15:00 UTC) and under the presence of the strong LLJ, neutral conditions exist for the layer above its core. The break up of wind maxima (after 17:00 UTC) is accompanied with an increased stability at higher levels.

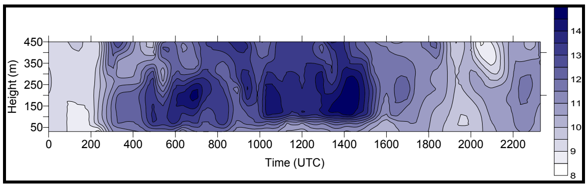

Fig. 3: Time-height cross section of the Wind Speed (m/sec) measured by the SODAR for 02/08/2003.

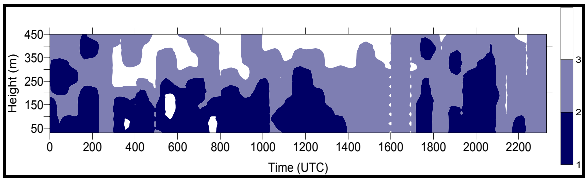

Fig. 4: Time-height cross section of the atmospheric stability estimated by the SODAR. Stability classes are given in the text.

In Figure 5 the horizontal wind speed hodograph derived from the SODAR data for the time period between 01:00 to 21:00 UTC of the 2nd of August at the level of 230m height with a step of two hours is given. In the same Fig. the corresponding horizontal wind speed hodograph derived from the radiosonde data for four successive launches during this day is also given. It is interesting to note that the two hodographs are very close and a wind vector oscillation and a directional shift to more westerly wind directions are evident. This fact is strengthening the suggestion that the inertial oscillation due to frictional decoupling is the main possible mechanism for the generation of the LLJ.

Figure 6 gives the results of the Empirical Mode Decomposition analysis which breaks the original time series of SODAR data of the wind speed at 230m, for the whole period of seven days into a finite number of intrinsic mode function (IMF) components, based on the intrinsic time scales of the dataset. Each intrinsic mode represents a simple oscillation and at any given time, the data may have many different coexisting modes of oscillation, one superimposing on the others. In our case the IMF identification process produces six IMFs where the higher-frequency and lower-amplitude motions are contained in IMF1 and IMF2. Low-frequency motions are found in IMF4 and IMF5 and they are strong but since they are rather stationary, they are not relevant to our interest. The last IMF represents the linear trend of the wind speed time series. IMF3 which is characterized with medium frequency (close to our interest) and high amplitude motions relevant to our inertial oscillation study. It should be mentioned that for latitudes like the one corresponding to Nantucket area (41° 14'), the expected theoretically inertial oscillation period is 18,36h (0.054 cycles/hour).

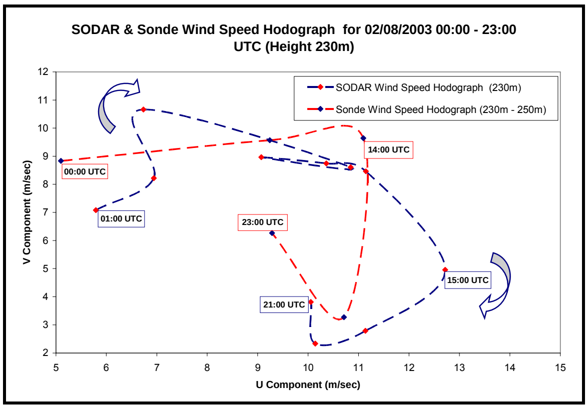

Fig. 5: Horizontal Wind Speed Hodograph derived by a) SODAR (blue dashed line) and b) Radiosonde (red dashed line) data.

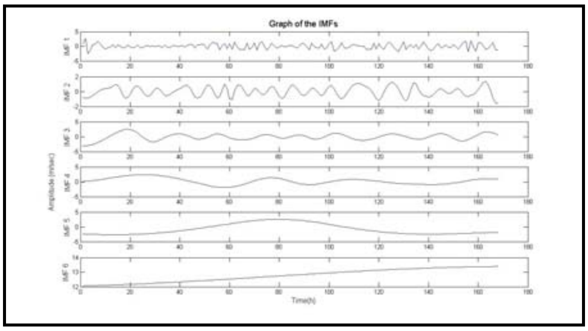

Fig. 6: Graph of the six successive IMF components of the SODAR horizontal wind speed time series for the period 01/08/2003 17:00 – 08/08/2003 16:00 UTC.

Finally Figure 7 gives the complete Hilbert spectrum (frequencies and energy as a function of time) for the IMF3 of the time series of SODAR data, after the Hilbert transform was applied to determine the local frequencies and amplitudes.

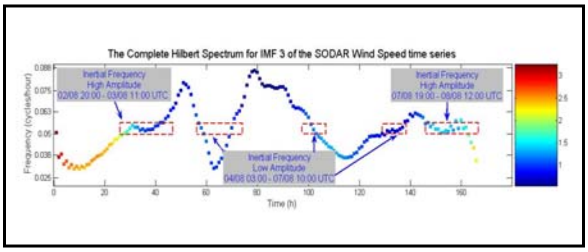

Fig. 7: The complete Hilbert Spectrum for IMF3 of the SODAR horizontal wind speed time series for the period 01/08/2003 17:00 – 08/08/2003 16:00 UTC.

In this three-dimensional representation of the time series analysis frequencies are plotted as a function of time and coloured to indicate amplitude (weak amplitudes less than 0.5m/s are not shown). The strongest amplitudes correspond to frequencies lower than 0.04 cycles/hour (a period of 25h) during the first day of our time period. However there are certain time periods with strong amplitude and frequencies close to the inertial period (inertial frequency: 0,054 cycles/hour) shown at the figure. These periods correspond to days and time periods where the development and the persistence of the LLJ was observed from both SODAR and radiosonde measurements. More precisely during the periods 02-03/08/2003 and 07-08/082003 strong amplitudes of the LLJ inertial oscillation were observed while during the rest of the LLJ episodes weaker amplitudes were found. Thus it could be concluded that the observed LLJ episodes are characterized by frequencies close to the expected inertial period and the above mentioned mechanism of the inertial oscillation due to frictional decoupling is confirmed.

4. CONCLUDING REMARKS

The analysis of the measurements using both in-situ and remote instrumentation, revealed the characteristics of the frequently observed LLJ, under medium to high wind speeds, which is developed on the top of the surface based stable layer of the MABL. A possible mechanism for the development of the LLJ is the frictional decoupling over the sea due to the strong stability and the subsequent developed inertial oscillation. This plausible explanation is in agreement with the calculated hodographs of the wind vector, estimated from SODAR and radiosonde data at the LLJ core layer, where the relative increase of the wind speed and the wind direction turning were evident. The application of the Hilbert – Huang transform (HHT) analysis on a seven days time series SODAR data set confirmed the above mentioned mechanism for all the observed LLJ episodes during this period.

5. ACKNOWLEDGEMENTS

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