Low-level Jets, Turbulence and Waves in the Tyrrhenian Coastal Zone as Shown by Sodar

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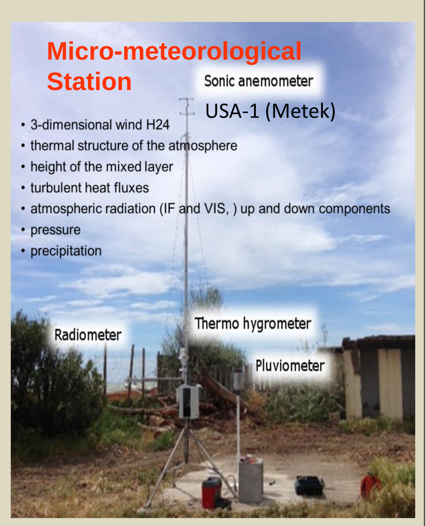
INTRODUCTION

•The Low-Level Jet (LLJ) in the atmospheric boundary layer is a fast increase of the wind speed with height up to a certain maximum magnitude (5-20 m s^{-1}) at some altitude (50-1000 m), and a further decrease above this level. Different remote sensing devices as radars, lidars and sodars allowed not only to measure the vertical profiles of wind velocity, but also to visualize the spatial and temporal structure of turbulence within the LLJ. However, till now, some aspects of this phenomenon (especially, the behaviour of the turbulence structure within it) need to be deepened.

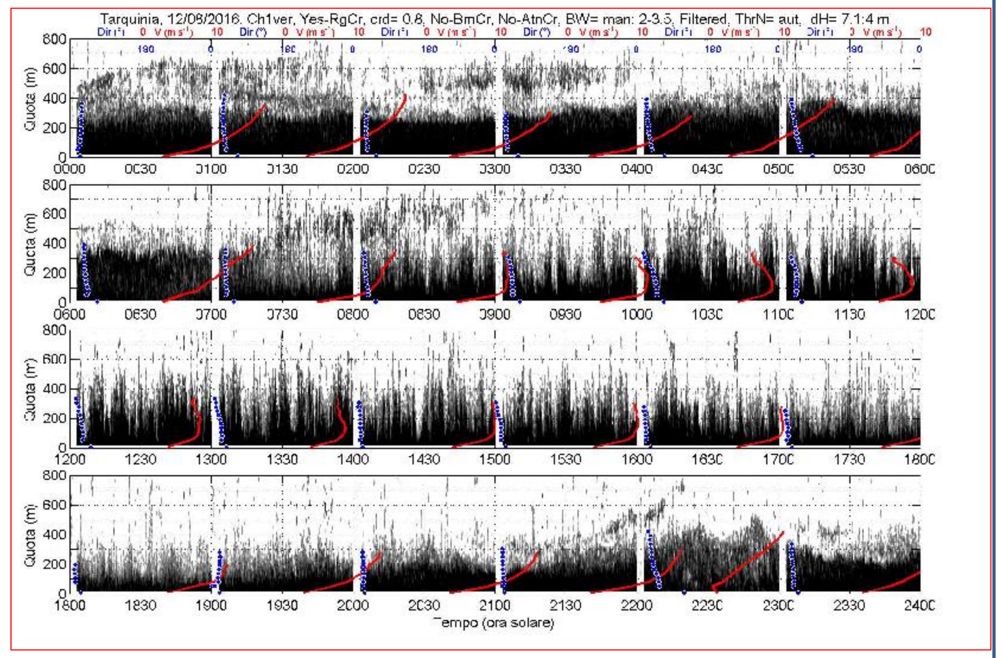
•A long-term monitoring of the planetary boundary layer using a sodar and micrometeorlogical sensors was carried out in proximity to the coast of the Tyrrhenian Sea (Tarquinia, Italy). Some results concerning the behaviour of the coastal boundary layer are presented. This zone is under the strong influence of local circulation producing rather regular daily variations in the wind field and different atmospheric boundary-layer turbulence regimes. The seasonal statistics of the diurnal cycle of meteorological and turbulence parameters for a two-year period has been done. Sodar observations showed some interesting features of the structure of lower troposphere not observed earlier. During the nighttime and early morning hours, LLJs are often observed together with two separated turbulent layers below and above the wind-speed maximum. The LLJ peak magnitude reaches 8-15 m s^{-1} at heights between 200-300 m. The upper layer extends up to 400-500 m. The wind shears below and above the maximum are respectively 0.035-0.040 s^{-1} and 0.025-0.030 s^{-1}. A high-resolution visual inspection of sodar echograms allowed us to reveal and expose the presence of the Kelvin-Helmholtz billows (KHBs) exhibiting the braid (or, herringbone) structure with different tilts within these layers. Such a wave pattern is in line with some earlier hypothesized assumptions on the possible structure of LLJ flows. The angle of braid tilts seems to be connected with the height dependence of the mean flow speed within a wavy layer. As shown in some recent papers, the vorticity of the wind disturbance within KHBs may be either clockwise or counterclockwise, depending on the wind gradient profile. If the wind speed increases with height, then the upper part of the braid structure appears over a sodar first, and, on the echogram, the tilt will be shown directed from the point on top left side to the right bottom. If the wind speed decreases with height, then the lower part of a braid appears first, and the tilt direction will be from the point on the left bottom side to the up right point on the sodar echogram. Previous observations showed mostly the first case or the second one, but never the two patterns simultaneously. Undulation within the elevating turbulent layer was observed for the significant part of the time. Mainly, the form of wavelike fine-scale turbulent layers is classified as "braid" (or "herringbones") pattern. They can be associated with internal gravity-shear waves attributed to the Kelvin-Helmholtz instability. Some characteristics (spatial and temporal scales, occurrence) of the wavelike structures are determined and presented.

SITE and INSTRUMENTATION

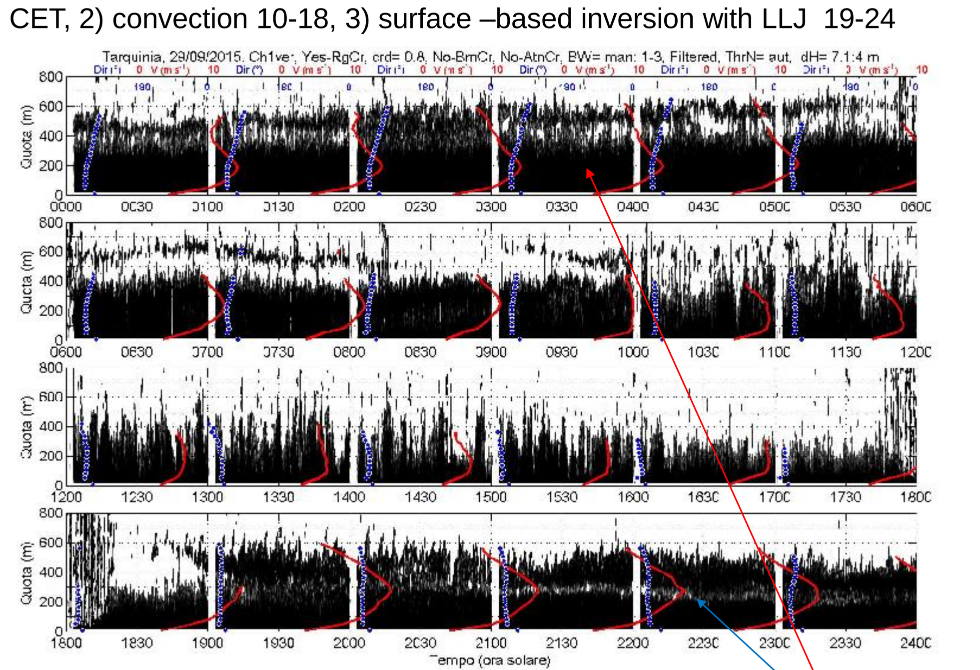


Examples of the Diurnal Behaviour of the ABL Turbulence Structure (shown with a sodar)

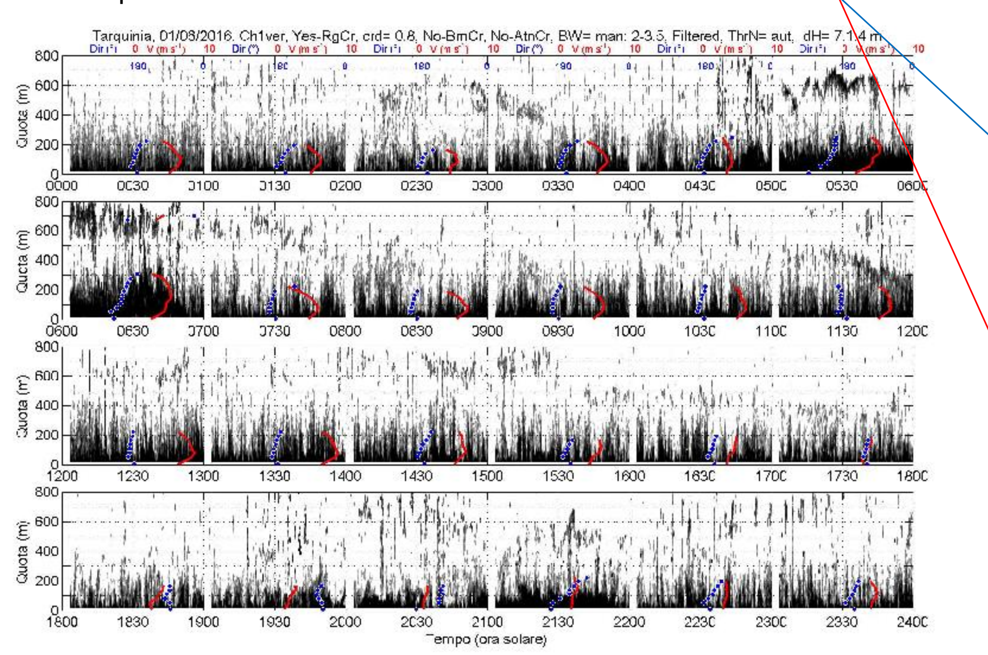
1. Classical (land-reference) 24h pattern: 1) surface –based inversion 00-07 CET, 2) convection 07-19, 3) surface –based inversion 19-24



2. 24h pattern with nocturnal LLJ: 1) surface –based inversion with LLJ 00-10 CET, 2) convection 10-18, 3) surface –based inversion with LLJ 19-24



3. 24h pattern : convection 00-24



4. 24h pattern with the surface–based and elevated inversion layers 00-24 CET

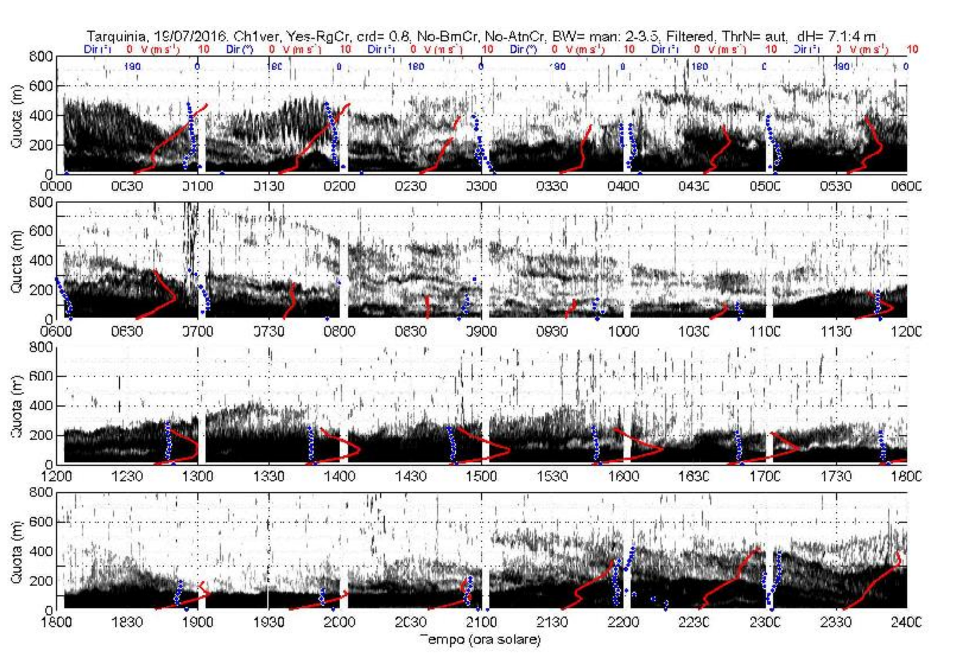
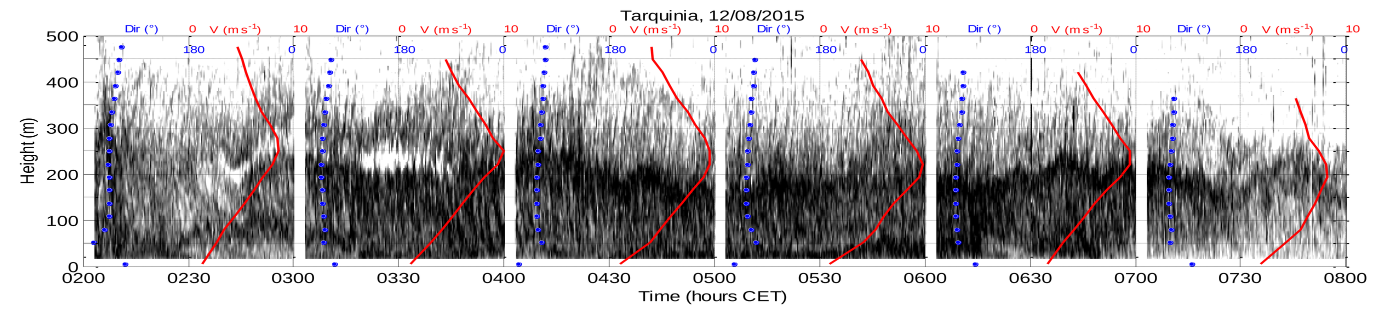


Fig. 1 An example of the typical sodar echogram in summer).

Typical Types of Turbulence-Structure Pattern within LLJs shown by SODAR

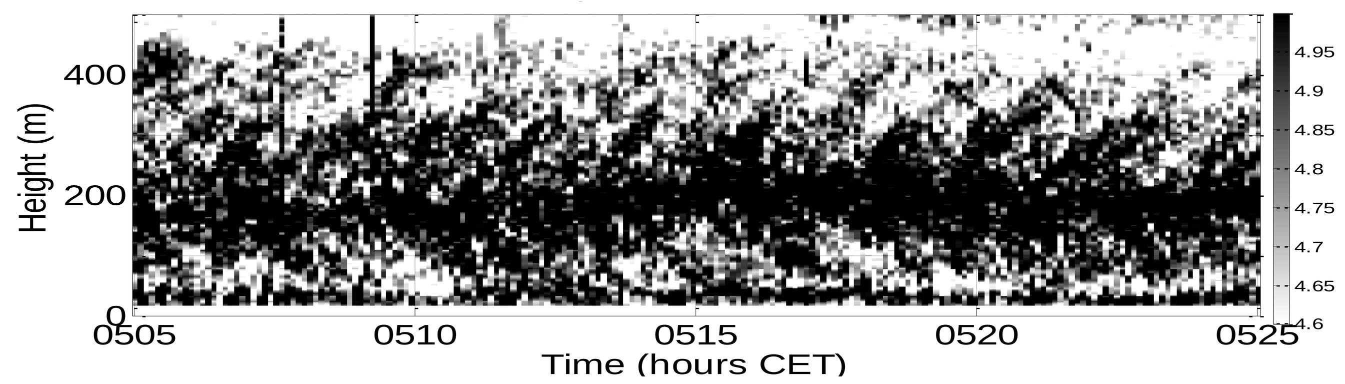
Low-Level Jets with Kelvin-Helmholtz billows

SODAR echogram: superimposed the wind speed profiles (red lines) and direction (blue circles) in presence of Kelvin-Helmholtz billows (KHBs) at 2 layers



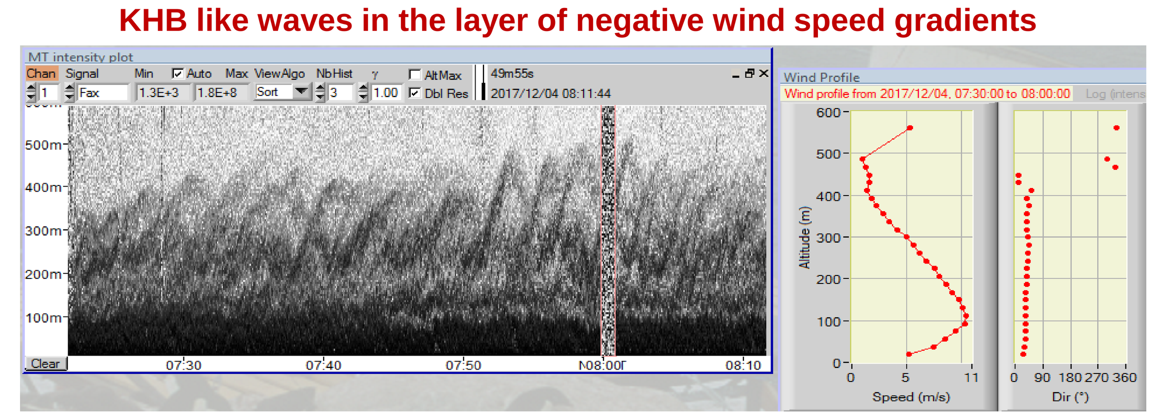
Examples of wavelike internal structures within LLJ

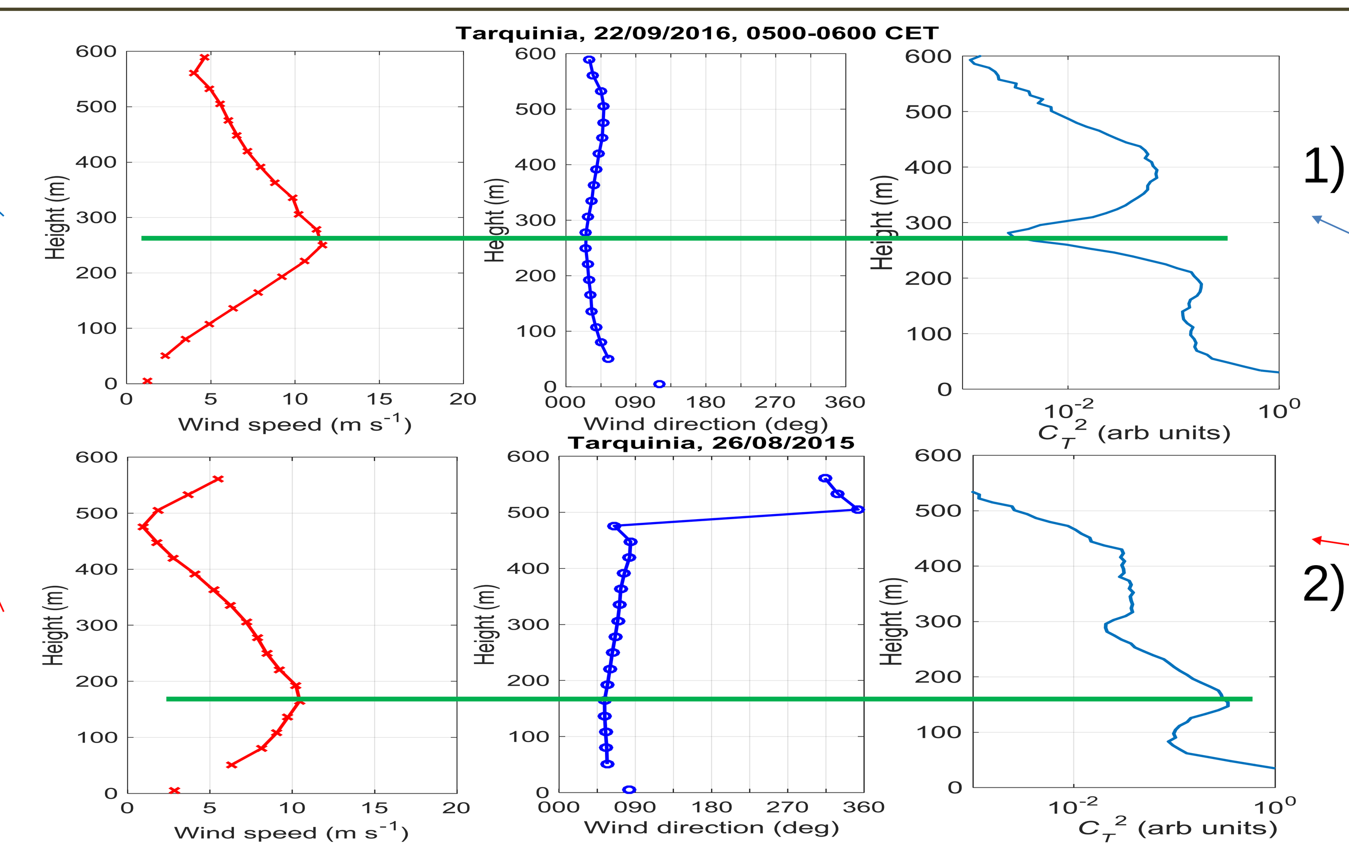
Echogram close-up showing the presence of KHBs below and above the height of the wind speed maximum. Braids are tilted in **opposite directions** depending on the vertical gradient of wind speed



The grey-scale intensity is proportional to lnC_T^2 . NB! Waves are not distinguishable on echograms with conventional time scales (**above panel**).

KHB like waves in the layer of negative wind speed gradients

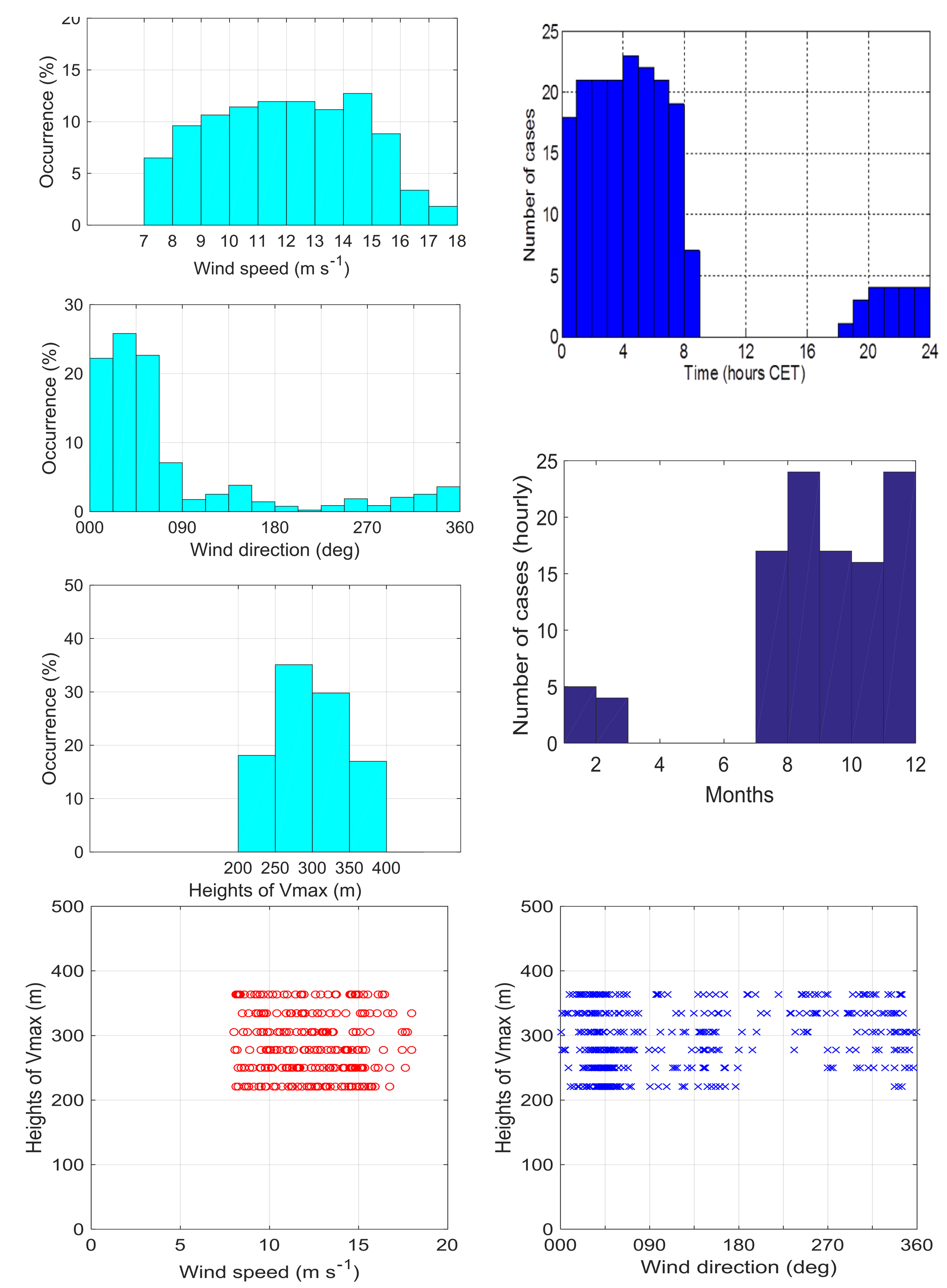




Characteristics of the waves in LLJs:

Characteristic	Method of determination	
1. Period P of following (time distance between separate fine-scale layers)	1) Visually (manually) from sodar echograms or time series at different heights 2) with spectral analysis	100-200 s
2. Wavelength $\lambda = V P$, V is wind speed	Taylor's hypothesis	500-1500 m
3. Vertical thickness of individual fine-scale layers	Visually from sodar echograms or instant profiles of the signal intensity	30-50 m
4. Entire depth of the turbulent layer dH_{fl}	Visually from sodar echograms	300-600 m

STATISTICS of LLJ EVENTS OCCURRENCE during 2015-2017



CONCLUSIONS

DIFFERENT diurnal cycles of the ABL turbulence structure were documented using sodar and *in situ* measurements during long-term experiment from May 2015 to March 2017 at the coastal zone. This diurnal course indicates three main types of the diurnal behaviour of the ABL turbulence structure:

1) The typical for middle-land areas alternation of the nocturnal surface-based temperature inversion layer (with LLJ or without it) and the convective-plume layer (capped by the inversion layer in the morning hours);
2) the presence of the surface-based temperature inversion layer during both the night- and daytime;
3) the presence the convective-plume layer (capped by the inversion layer or without it) during both the night- and daytime.

The often occurrence of low-level jets (LLJ) characterizes the nocturnal ABL at the coastal zone during late-summer and autumn seasons. Winds with maxima of 8-15 m/s from N-NE at heights of 200-350 m are typical for these LLJs.

There are two patterns of turbulence within LLJs: 1) At the region of the wind-speed maximum, the minimum!!! of turbulence occurs. 2) At the region of the wind-speed maximum, the maximum!!! of turbulence occurs. Below and above this zone, turbulent layers occur. Inside the both below and elevated turbulent layers, the regular wavy fine-scale layers forming the braid (or, herring-bones) pattern (Kelvin-Helmholz billow like) in the sodar echogram are present.

The periods of the observed wavy structures range between 100 and 200 s. Wavelengths λ estimated using Taylor's hypothesis are of ≈ 500- 1500 m. The vertical thickness of individual braids layers was of 30-50 m. The entire depth dH_{fl} of the turbulent layer containing waves varied from 300 to 600 m..

The presented results call for the development of new theoretical approaches taking into account the interaction of turbulence and wave processes occurring simultaneously. The challenging problem in atmospheric physics concerning the vertical transfer from the near-surface to the overlying atmosphere unlikely can be resolved without consideration of wave processes. The presented results could be used for verification of some (including large eddy simulations) computational experiments.

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