A Study on the Nocturnal Atmospheric Boundary Layer: SABLES2006

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ABSTRACT:
Preliminary results from SABLES2006 field campaign (Stable Atmospheric Boundary Layer Experiment in Spain) are shown. This campaign took place from 19 June to 5 July 2006 at the CIBA (Research Centre for the Lower Atmosphere) site, which is located at Valladolid on a fairly homogeneous terrain. Different instrumentation was available on a 100m tower (cups and sonic anemometers, thermometers, humidity sensors and three high resolution microbarometers). Additionally, a triangular array of microbarometers close to surface was also deployed in order to characterize wave events. Moreover a tethered balloon was used to get vertical profiles of the atmosphere up to 1000 m. Mean micrometeorological variables, stability and turbulent parameters (all of them 5 minute averaged) have been analysed for 10 consecutive nights, showing the main characteristics of the stable nocturnal boundary layer: surface-based inversions, intermittent turbulence, katabatic winds, low level jets, developing gravity waves, etc. The boundary layer height in stable conditions is also evaluated from different definitions. The range of values found is analysed.
Key words: stable boundary layer, field campaign, turbulent parameters, katabatic winds, intermittent mixing.

Estudio de la Capa Límite Atmosférica Nocturna: SABLES2006

RESUMEN:
En este trabajo se muestran resultados preliminares de la campaña SABLES2006 (Experimento en Capa Límite Atmosférica Estable en España). La campaña tuvo lugar entre el 19 de junio y el 5 de julio en el CIBA (Centro de Investigaciones en la Baja Atmósfera), localizando en la provincia de Valladolid sobre terreno homogéneo. En una torre de 100 m se dispuso de diferente instrumentación (anemómetros de cazoletas y sónicos, termómetros, sensores de humedad y tres microbarómetros de alta sensibilidad). Adicionalmente, se utilizaron tres microbarómetros dispuestos en un triángulo junto a la superficie con el objeto de caracterizar eventos ondulatorios. Además se empleó un globo cautivo para obtener perfiles de la atmósfera hasta 1000 m. Se han analizado variables micrometeorológicas

medias, parámetros de estabilidad y turbulentos (todos promediados en 5 minutos) para 10 noches consecutivas, mostrando las principales características de la capa límite estable nocturna: inversiones junto al suelo, turbulencia intermitente, vientos catabáticos, chorros a bajo nivel, desarrollo de ondas de gravedad, etc. La altura de la capa límite en condiciones de estabilidad fue evaluada según diferentes definiciones. Los rangos de valores encontrados han sido analizados.

Palabras clave: capa límite estable, campaña de campo, parámetros turbulentos, vientos catabáticos, mezcla intermitente.

1. INTRODUCTION

One of the main characteristics of the atmospheric boundary layer (ABL) is its degree of stratification. The convective and neutral boundary layers have been deeply studied in the past, however the stable boundary layer (SBL) has remained less investigated and many of the relevant processes involved are not fully understood. The stable boundary layer is formed when the surface is cooler than the air (Stull, 1988), and this is often produced at night over land, which is also known as the nocturnal boundary layer (NBL). Along the night, the relative importance between the mechanical generation of turbulence and the damping produced by stability can change quite quickly, leading to different ranges of turbulent mixing, sometimes being intermittent. Among others, the main processes studied in the SBL have been: radiative flux divergence, intermittent and patchy turbulence, slope flows, Low-Level Jets, elevated turbulence, shear instabilities, wave generation and breaking, wave-turbulence interactions, etc. In the last decade much effort, both experimental and modelling, has been paid in the specific research of the SBL. In the experimental side several field campaigns have taken place both in mid-latitudes (Cuxart *et al*., 2000; Poulos *et al*., 2002) and polar sites (Grachev *et al*., 2005). With regards to simulations, in Beare and McVean (2004) a summary of the main Large Eddy Simulations (LES) done during the 90's can be found. Recently, intercomparison of both 1-D single column models (Cuxart *et al*., 2006) and LES (Beare *et al*., 2006) have been carried out simulating a moderately stratified Arctic case. The LES results are consistent with observations and local scaling theories (Nieuwstadt, 1984) and are used to compare the 1-D results which show large spread.

The parameterization of the vertical mixing in stable conditions is not well resolved, however it is fundamental for obtaining realistic simulations. Knowledge of SBL processes is essential for improving the representation of the atmospheric boundary layer in regional and large-scale climate models (Holtslag, 2006). The stability functions play an important role in these parameterizations (Viterbo *et al*., 1999; King *et al*., 2001), and these functions depart from the most commonly used in the literature (Businger *et al*., 1971; Högström, 1988) as the stable stratification increases (Yagüe *et al*., 2006).

This paper presents the Stable Atmospheric Boundary Layer Experiment in Spain 2006 (SABLES2006) which took place at CIBA (Research Centre for the Lower Atmosphere) from 19 June to 5 July 2006, and was intended to further extend our knowledge of the SBL overlying a relatively flat, homogeneous terrain, acquired in SABLES98 (Cuxart *et al.*, 2000). In the 2006 campaign, besides the standard instrumentation deployed in a 100m tower (allowing the evaluation of mean variables and turbulent parameters) and vertical soundings (tethered balloon) of the low atmosphere up to 1000m, 6 high accuracy microbarometers (3 in the 100m tower and 3 forming a triangular array at the surface) were deployed in order to detect gravity waves and their interaction with turbulence (see in this issue Viana *et al.*, 2007). As stability increases, vertical turbulent motions are suppressed, but buoyant oscillations can occur as gravity waves. Turbulence can be suppressed or enhanced by the passage of gravity waves, can ride up and down hundreds of meters on these waves, and can nonlinearly interact with them (Nappo, 2002).

In section 2 the main characteristics of the site and the instrumentation used will be described. In section 3 some preliminary results (stability, turbulent parameters and depth of the SBL) of this campaign will be shown and we will finish with the main conclusions. In Appendix A the definitions of the main parameters evaluated are listed.

2. DESCRIPTION OF CIBA'S SURROUNDINGS AND INSTRUMENTATION

The Research Centre for the Lower Atmosphere (CIBA in Spanish, 41º49'N, 4º56'W, 840m) is located around 30 km NW from Valladolid city in the Northern Spanish Plateau, on relatively flat, homogeneous terrain.

The measurements collected in SABLES2006 come from three sources:

a) Permanent instrumentation installed in a 100m tower comprising sonic anemometers and conventional sensors measuring wind speed and direction, temperature, relative humidity, soil temperature and pressure at surface (see Table I for details). This instrumentation was installed by the National Risoe Laboratory in 2001, as part of a project in which the main objective was to upgrade the 100m tower, which has been active since the 80s.

b) Six Paroscientific microbarometers (3 installed at 20, 50 and 100m on the tower, and 3 deployed at z=1m on a triangular array of 200m side approx.). These devices measure the absolute pressure at 2 Hz sample rate (which ensures a resolution around 0.002 hPa); this is a compromise between having a good temporal resolution and having the ability to register sufficiently small enough pressure perturbations. The records of these microbarometers are ideal for observing the propagation of wave-like structures and for calculating the wave parameters (see in this issue Viana *et al.*, 2007).

c) A tethered balloon sounding was operated during nighttime when wind conditions were suitable. A total of 70 vertical soundings were obtained with a maximum height ranging between 300 and 900m.

Table 1.- Main instruments deployed at the 100m tower.

Instrument	z (m)	Sampling rate (Hz)
Metek USA-1 Sonic anemometers	3-20-100	20
Wind vanes	10-35-75-100	5
Cup anemometers	2-10-35-50-75-100	5
Platinum resistance thermometers	2-10-20-35-100	1
Microbarometers	20-50-100-surface array	2

3. RESULTS

In this section the evolution of the main parameters evaluated for ten consecutive nights of SABLES2006 campaign are presented along with the stable boundary layer depths obtained from the vertical soundings using different definitions.

3.1. MAIN STABILITY AND TURBULENT PARAMETERS EVOLUTIONS DURING SABLES2006

Ten consecutive nights from the SABLES2006 campaign (from 21 to 30 June) have been analysed in order to study the behaviour of the main average and turbulent variables affecting the SBL.

For each night the chosen time period has been from 1800 to 0600GMT, which includes the transition from the late daily conditions to the nocturnal ones (sunset at CIBA was around 2000GMT at this time of the year and sunrise around 0500GMT). In Figs. 1 to 4 single tick separation indicates a time interval of three hours. A double tick in the x-axis indicates the change of night (discontinuity in the temporal sequence, as only time periods from 1800 to 0600 GMT a represented).

Figures 1-4 show the evolution of mean meteorological variables, stability and turbulent parameters (5 minute means. See Appendix A for definitions).

Significant cooling affects the air near the surface as can be seen in Fig. 1c (more than 15ºC over the night for most of them), although different degrees of stability are reached on different nights. Sometimes sharp changes are observed. There is a similar evolution for many nights of the campaign (21, 22 and 26-29 June), in which an early temperature inversion is developed close to the surface (Fig. 2c), starting before sunset, along with westerly light winds and a reduced wind shear (Figs. 1a & 1b).

This situation lasts until a certain time after sunset, when the temperature inversion is deeply eroded (Fig. 2c), wind speed and wind shear increases, and wind direction veers, having a significant NE direction. This transition is sharp during some nights (27-28-29 June around 2000GMT), and is produced more slowly other nights (21-22 June). Katabatic winds (radiatively cooled air descending along local

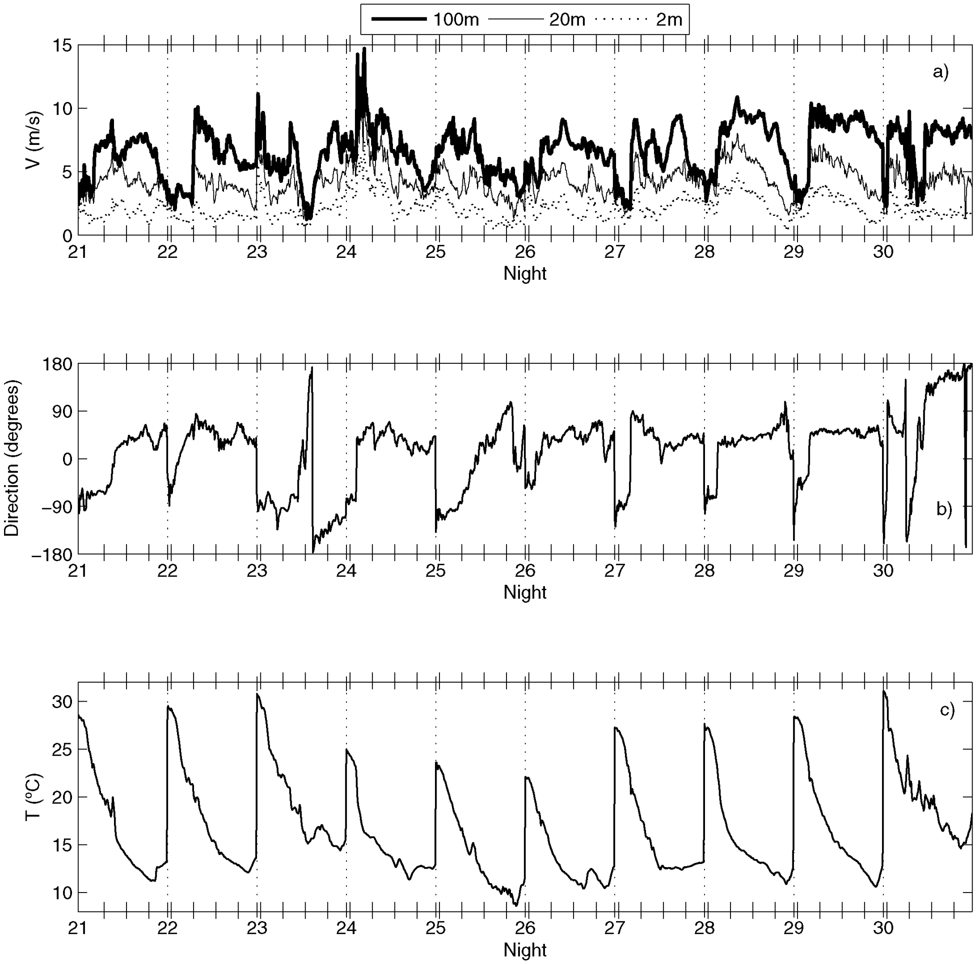

Figure 1.- Evolution for 10 consecutive nights (21-30 June 2006) of: a) wind speed at z=2, 20 and 100m, b) wind direction at z=10m and c) temperature at z=2m.

slopes) are the most probable cause for this behaviour. Although CIBA is located on a fairly levelled terrain, there are two small slopes (Cuxart *et al.*, 2000): one in the NW-SE direction (1:6000) and the other in the NE-SW direction (1:1660). Even shallow slopes such as these could produce drainage flows in stable conditions that affect the thermal and dynamical characteristics of the CIBA boundary layer. Brost and Wyngaard (1978) and Mahrt (1981) found that even slopes as small as $\Delta z/\Delta x$=0.001-0.01 over a large area can produce drainage flows of 1-2 m s^{-1}. Slopes at the Wangara field site (Australia) are of the order of 0.007 and the average slope of the Great Plains in the USA is around 0.001 (Stull, 1988). Derbyshire and Wood (1994) concluded that even shallow slopes can have an important influence on the

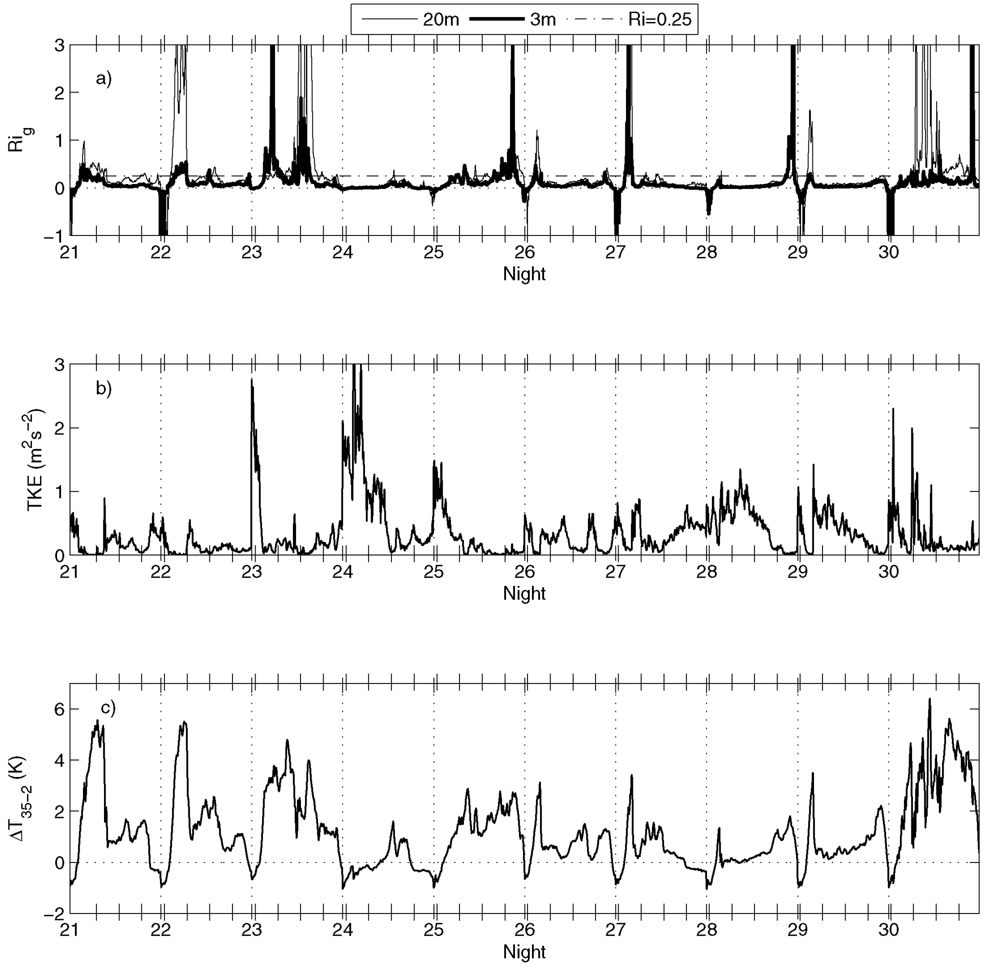

Figure 2.- Evolution for 10 consecutive nights (21-30 June 2006) of: a) Gradient Richardson number at z=3m, b) Turbulent Kinetic Energy at z=3m, and c) Inversion strength between 35m and 2m.

physical processes affecting the SBL. Maguire *et al.* (2006) investigate through theoretical arguments the influence of shallow slopes of the order of 1:1000 on the SBL. Consistently with the arrival of the katabatic flow, the cooling speed increases, as can be seen from the descending slope of the temperature evolution (Fig. 1c), which is steeper during the change of the wind direction and the increase of the wind shear which marks the entrance of the easterly flow (compared to previous and subsequent periods). This is consistent with the idea that a katabatic flow will cool the ABL surrounding the CIBA site beyond the nocturnal cooling rate due to radiative effects. In addition, frequent bursts are observed in *TKE* and friction velocity during the onset of the katabatic flow (Figs. 2b and 4b), which produce turbulent mixing and large values (Fig. 4a) of downward sensible heat flux (> 40

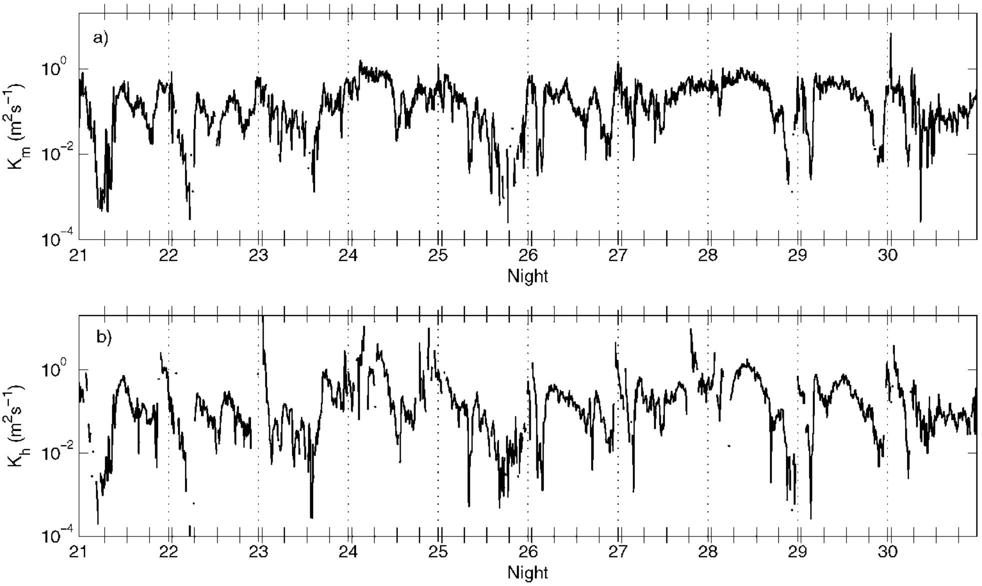

Figure 3.- Evolution for 10 consecutive nights (21-30 June 2006) at z = 3m of eddy exchange coefficients for: a) momentum *(K_m)* and b) heat *(K_h)*.

Wm^{-2}), eroding the surface inversion. The eddy exchange coefficients for momentum (K_m) and heat (K_h) also give information about the degree of mixing taking place in the SBL (Figs. 3a & 3b), and on the different orders of magnitude between them that sometimes are achieved (ranging from 10^0 to 10^{-4} m^2s^{-1}). Some discontinuities can be identified in Fig. 3, due to the presence of counter-gradient fluxes which give rise to negative values of the eddy exchange coefficients; some authors relate this fact to the presence of gravity waves in the SBL (see in this issue Viana *et al.*, 2007 for more details).

According to the observed katabatic winds and the evolution of the gradient Richardson number at z=3m and z=20m depicted in Fig. 2a, the nights during SABLES2006 field campaign can be grouped into two different sets. The first group (21, 22 and 26-29 June) comprises the nights in which the SBL was mostly weakly-moderately stably stratified, katabatic winds were important, and the Richardson number often took values below its critical value (Ri=0.25) except for the time period prior to the katabatic winds, in which the reduced wind shear (with friction velocity values less than 0.05 m s^{-1}, Fig. 4b) led to a stronger level of stability than during the rest of the night. In the second group, corresponding to the nights of 23, 25 and 30 June, the level of stratification developed ranges from moderate to strong stability, and Richardson number reached high values (Ri>0.25) during the central hours of the night. The night of 24 June was affected by some mesoscale instability; an intense rainstorm developed during the first hours of the night, producing a well mixed boundary layer with a neutral stratification for most of the night.

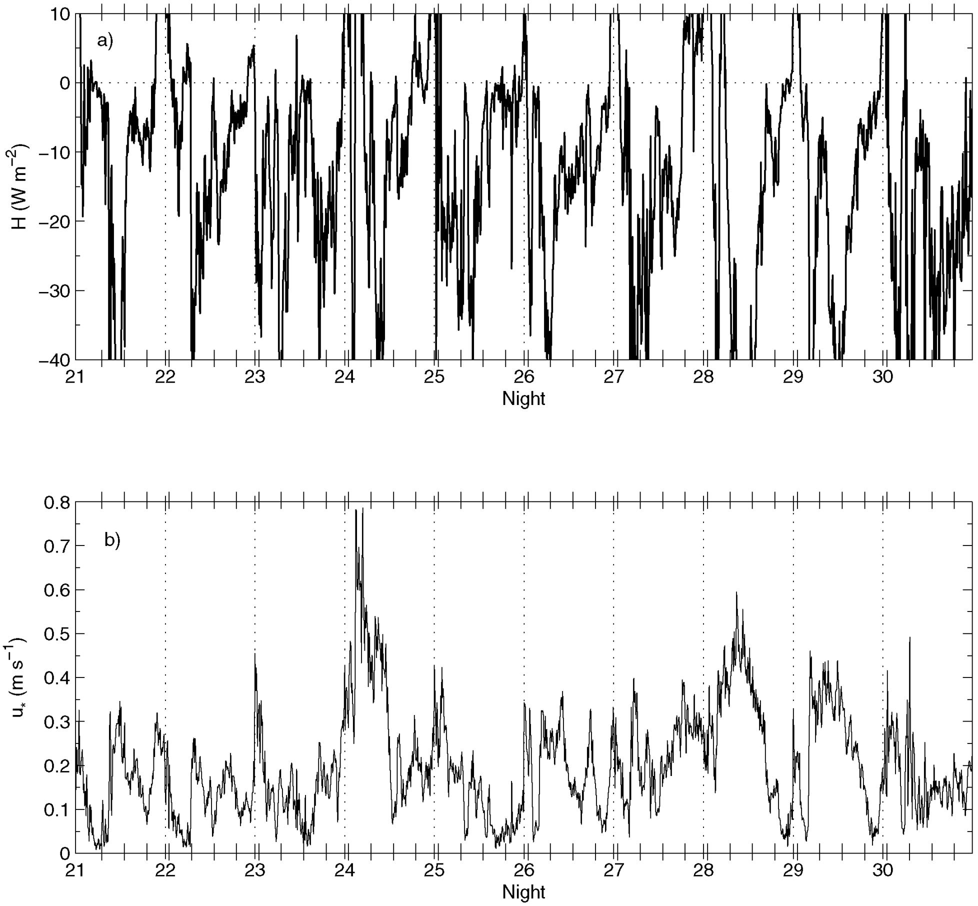

Figure 4.- Evolution for 10 consecutive nights (21-30 June 2006) at z=3m of: a) Sensible heat flux and b) friction velocity.

3.2. ANALYSIS OF THE NIGHT 25-26 JUNE

As was mentioned above, 3 of the 10 consecutive nights analysed (23, 25 and 30 June) presented moderate to strong stability conditions. Such cases are particularly interesting to study because

(i) intermittent turbulence is observed,

(ii) vertical transfer processes are strongly inhibited,

(iii) they exhibit a vertical structure of the turbulence that differs from that of weakly stable conditions,

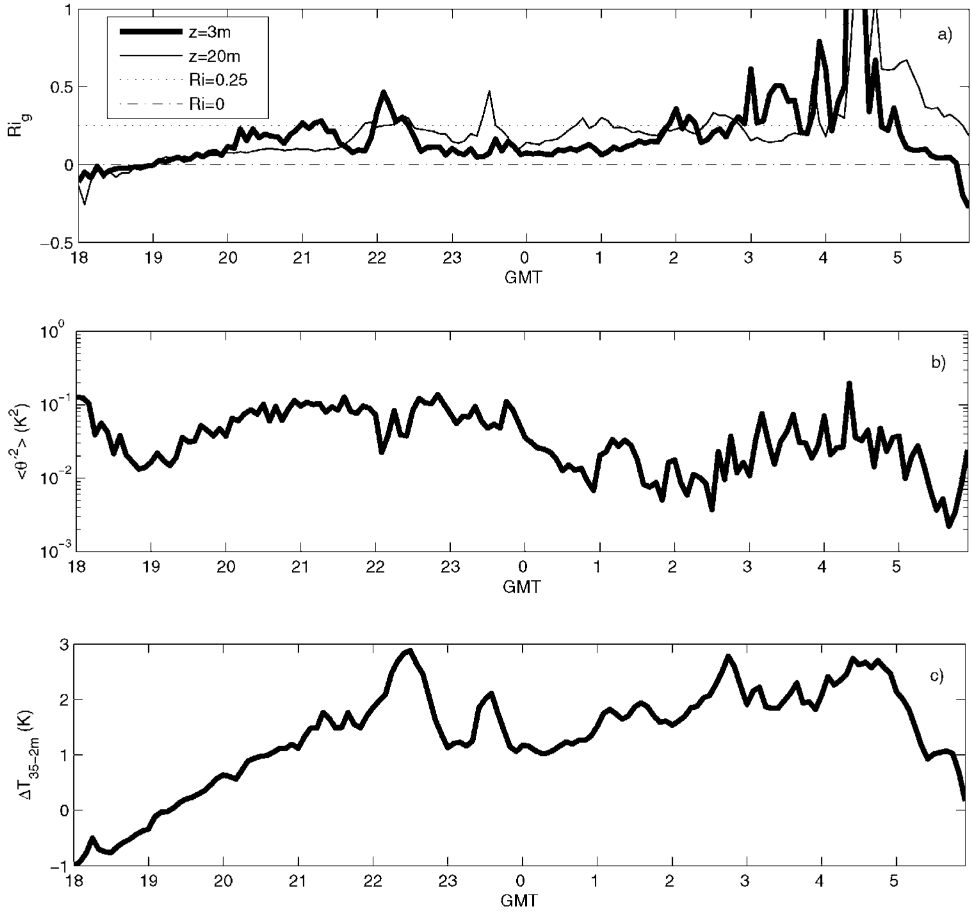

Figure 5.- Evolution along the 25-26 June night of: a) Gradient Richardson number, b) temperature variance, and c) Inversion strength between 35 and 2m.

(iv) the formation of gravity waves is favoured.

One of these nights (25 June) is analysed in this section. A detailed evolution of the gradient Richardson number, the temperature variance and the inversion strength for this night is shown in Fig. 5.

The night started with higher winds (around 4m s^{-1} at z=2m) than those from the first group (Fig. 1a), and a certain degree of wind shear, both progressively decreasing during the night, along with a surface inversion between 35m and 2m growing during the first hours and staying close to 2-3K until the end of the night (Fig. 5c). The veering of wind direction was produced very slowly this night. Accordingly, the Richardson number (Fig. 5a) progressively increased, being mostly subcritical during the first half of the night (1800-2400GMT), and frequently

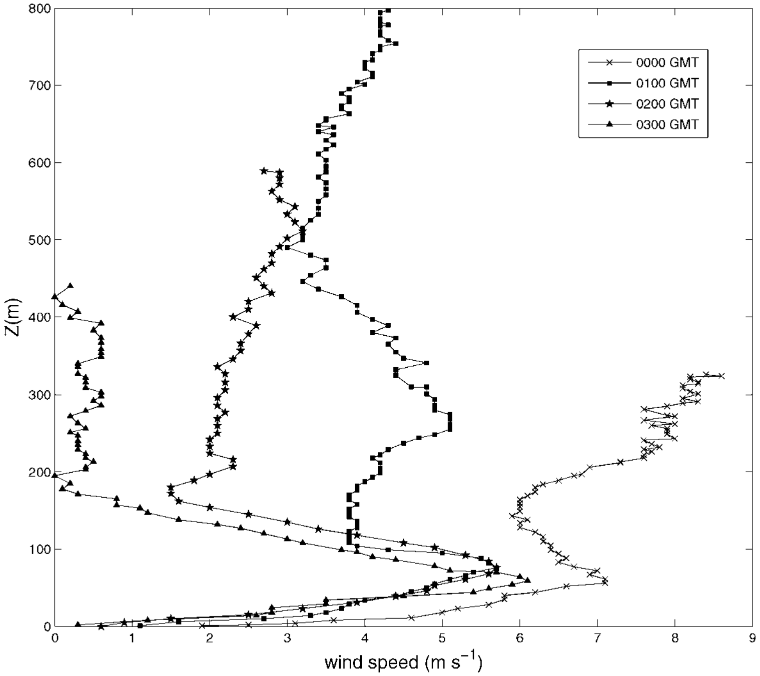

Figure 6.- Wind speed profiles for some hours of the 25-26 June night obtained from the tethered balloon soundings.

supercritical during the second half, especially from 0300GMT to 0500GMT, when some peaks of strong stability were produced along with oscillations of bigger amplitude in the temperature variance (Fig. 5b). In this stronger stable period higher values of Ri at z=3m than at z=20m were often observed, indicative of a decreasing stability with height. This corresponds to the situation described by Mahrt (1999) where the development and breaking of internal waves aloft produces elevated turbulence.

The soundings for this night show the presence of a low-level jet (LLJ) around z=80m at 0100GMT, which strengthened until reaching the characteristic nose-shape around 0300GMT, when the wind speed maximum (v=6 m s^{-1}) was located at z=70m. Note that winds tend to calm above the LLJ (Fig. 6). The soundings also indicate a well developed surface-based inversion with an average top around 250m (Fig. 7).

Eddy exchange coefficients (Figs. 4a&b) also show a progressive decrease as stability increases throughout the night. A sudden drop of both parameters is produced around 2200GMT, simultaneously with very low values of TKE and friction velocity (Figs. 2b & 4b). Starting around 0200GMT, counter-gradient fluxes (in which K_m or K_h<0, thus not appearing in these logarithmic plots) are produced. Counter-gradient fluxes of heat and momentum have been related in the literature to

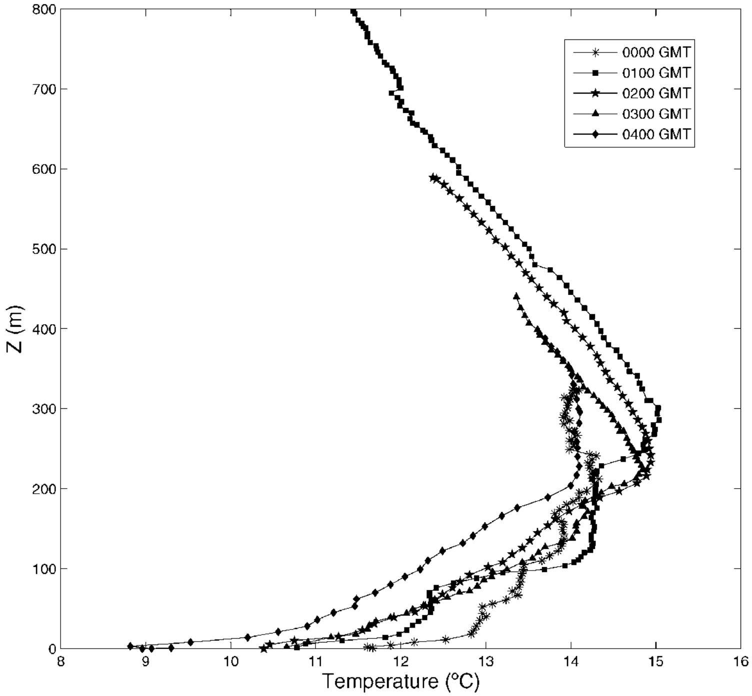

Figure 7.- Temperature profiles for some hours of the 25-26 June night obtained from the tethered balloon soundings.

the rolling up and breaking of internal gravity waves (Nai Ping *et al.*, 1983; Yagüe and Redondo, 1995), and also to the presence of Kelvin-Helmholtz instabilities (Ohya and Uchida, 2003).

3.3. STABLE BOUNDARY LAYER HEIGHTS IN SABLES2006

The stable boundary layer height (H_s) is not as easy to define as the height of the convective boundary layer. In this paper we have used 5 criteria. In the SBL, some definitions are based on the existence of a certain level of turbulence (criteria C1 and C2) evaluated from the bulk Richardson number (Garratt, 1982; Vogelezang and Holtslag, 1996). Two critical bulk Richardson numbers have been considered (0.25 for C1 and 0.5 for C2). Other definitions are based on the vertical reach of the radiative cooling produced at surface. Criterion 3 defines the SBL height as that layer where the vertical gradient of the potential temperature is $\geq$ 0.0035 K/m (Andre and Mahrt, 1982), while criterion 4 defines it as the inversion layer (Yu, 1978; Coulter, 1990). Finally criterion 5 is based on the location of the LLJ (Clarke, 1970). The results for the SABLES2006 soundings (Table 2) show that generally:

$$H_s\left(\partial\theta/\partial z > 0.0035\right) \geq H_s\,(H_{inv.\ sfc}) \geq H_s\,(LLJ) \geq H_s\,(R_{ibC} = 0.50) \geq H_s\,(R_{ibC} = 0.25)$$

So the SBL heights based on the turbulence criteria are lower than those coming form thermal criteria. Moreover, when the Richardson number criterion is applied, sometimes the critical value is exceeded from the first levels of the sounding.

Table 2.- Stable boundary layer heights obtained from the five different criteria used in this study.

Criterion	SBL height Observed (m)
C1	0-278
C2	0-108
C3	60-585
C4	20-500
C5	20-360

Figure 8 shows the evolution of the different SBL depths according to the different criteria for the 25-26 June night (0000GMT to 0500GMT). The depth where a certain level of turbulence exists (C1 & C2) is generally below 100m (except at 0300GMT for

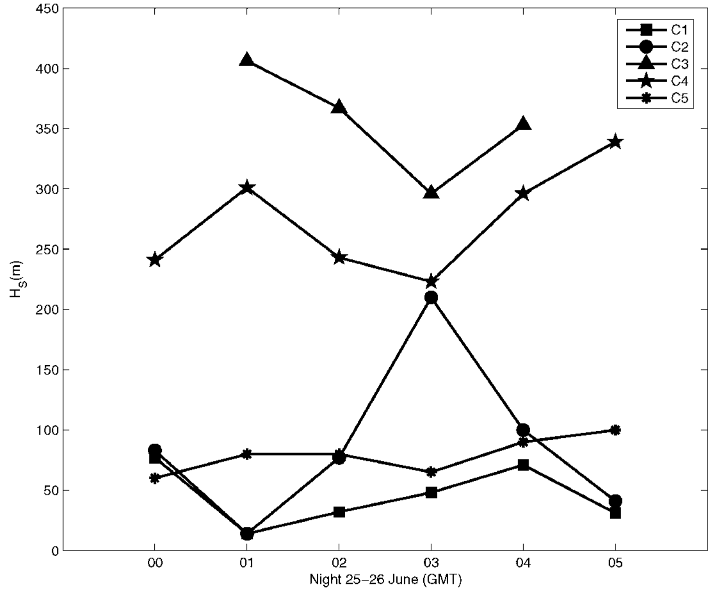

Figure 8.- Stable boundary layer heights along the 25-26 June night evaluated from different criteria.

the C2), as also the height of the LLJ (C5), which is really a very low value, indicating the stronger stability reached this night. If the surface layer can be estimated as 10% of the boundary layer height, this would imply having a constant flux or surface layer of only 10m. When the thermal criteria are applied (C3 and C4), greater SBL heights are found (between 250 and 400m) highlighting the vertical extension of the surface cooling. We can conclude that several length scales exist in the stable boundary layer, depending on the definition used to evaluate it, and this fact must be borne in mind when considering the application where this length scale is going to be used.

4. SUMMARY AND CONCLUSIONS

Some preliminary results from SABLES2006 are presented, regarding the overall level of stability and the turbulence developed during 10 consecutive nights, as well as the evaluation of the stable boundary layer height from consideration of several different definitions. The night of 25-26 June, which developed moderate to strong stability and wave-like structures, has been selected for making a more detailed analysis. The main conclusions from this study are:

— The NBL during SABLES2006 showed stratification with a level of stability which ranged from neutral to strong stratification. Many of the nights were affected by easterly katabatic winds which increased the wind shear and eroded the surface inversion, soon after the sunset. Bursts of turbulence (with maximum values of TKE and friction velocity) were frequent during the onset of the katabatic winds (more intense when the change of the wind direction was more abrupt).

— During the most stable nights (23, 25 and 30 June), the influence of the katabatic winds is less significant, higher values of the gradient Richardson number are achieved and minimum values of the turbulent parameters (K_m, K_h, TKE, u_*, H) are found with intermittent turbulent mixing present during the course of the night.

— During the night of 25 June, the level of stability increased progressively and the turbulent parameters decreased accordingly due to the inhibition of turbulence. From 0300 to 0500GMT the gradient Richardson number was supercritical, and the SBL developed a well defined LLJ and a surface-based inversion up to 300m. These conditions allow the formation of gravity waves, which are associated with elevated turbulence (Richardson number decreasing with height) and high amplitude oscillations of the temperature variance.

— The SBL height has been evaluated from different definitions (based on turbulence or surface cooling considerations). Relatively shallow depths (less than 100m most of the times) are predicted when the turbulence criterion is used compared to the degree of stratification present in the lower atmosphere (up to 500m)

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APPENDIX A

In this appendix the different definitions of the turbulent and stability parameters used in section 3.1 are listed:

— Gradient Richardson Number (*Ri*): This stability parameter comprises information about the dynamic and thermal processes contributing to stability (wind shear and gradient of potential temperature):

$$Ri = \frac{\frac{g}{\theta_0}\frac{\partial\bar{\theta}}{\partial z}}{\left(\frac{\partial\bar{U}}{\partial z}\right)^2 + \bar{U}^2\left(\frac{\partial\bar{\alpha}}{\partial z}\right)^2} \qquad \text{(A1)}$$

To evaluate the gradients of wind velocity and temperature, log-linear fits (Nieuwstadt, 1984) were made to the different levels data. The wind direction gradient is evaluated using simple linear fits:

$$\begin{aligned} \bar{u} &= az + b\ln z + c \\ \bar{T} &= a'z + b'\ln z + c' \\ \bar{\alpha} &= a''z + c'' \end{aligned} \qquad \text{(A2)}$$

— The turbulent kinetic energy (*TKE*), which is the portion of kinetic energy associated with turbulence, evaluated from the variances of the along-wind, cross-wind and vertical components of velocity:

$$TKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \qquad \text{(A3)}$$

— Inversion strength. This stability parameter is defined as the temperature difference between 35m and 2m.

$$\Delta T_{35\text{-}2} = T_{35m} - T_{2m} \tag{A4}$$

— The turbulent exchange coefficients of momentum and heat (K_m, K_h), which are the turbulent counterpart to the molecular kinematic viscosity and thermal diffusivity coefficients:

$$K_m = -\frac{\overline{u'w'}}{(\partial \overline{U}/\partial z)} \qquad K_h = -\frac{\overline{\theta' w'}}{(\partial \overline{\theta}/\partial z)} \tag{A5}$$

— Friction velocity, related to the vertical shear of the wind speed:

$$U_* = \left((\overline{-v'w'})^2 + (\overline{-u'w'})^2\right)^{0.25} \tag{A6}$$

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