P28 **WAVE-LIKE EVENTS DETECTED FROM MICROBAROMETERS MEASUREMENTS DURING BLLAST CAMPAIGN**

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1. INTRODUCTION

The Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) field campaign was carried out during the summer of 2011 (14^{th} June to 8^{th} July) in Lannemezan (France). The main objective of the campaign (Lothon et al., 2012) was to improve the knowledge of the late afternoon transition in the planetary boundary layer (PBL). Fair weather days were preferred to analyze due to the better development of the convective boundary layer and a better view of the evolution of the residual and stable boundary layers later developed. However, several rainy and stormy days were observed during the campaign. In this study, two different types of days have been analyzed, taking advantage of the large instrumentation deployed over the zone. One of the objectives of the field campaign was to learn more about gravity waves (Gupta and Sunil, 2001; Manasseh and Middleton, 1994) that can be developed during this transition and during the whole night and their interaction with turbulence. For this purpose, three high resolution microbarometers were deployed at 1m a.g.l. in a zone known as Supersite 1. The wave event 1 occurred on a rainy and stormy day (21^{st} June).

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Storms are one of the possible mechanisms generators of gravity waves (Gedzelman, 1983), and they have shown to be an important hazard for aircrafts (Miller, 1999). These gravity waves could also affect the fluxes of different magnitudes by the oscillation in different meteorological parameters (Carruthers and Moeng, 1987).

The wave event 2 corresponds to gravity waves found in a fair weather day (2^{nd} July), one of the Intensive Observation Period (IOP) of the campaign. Wavelet analyses and wave parameters evaluations (Viana et al., 2009) have been carried out in order to draw some conclusions about the features and the possible origin of these wave-like disturbances.

During the wave event 1, periodic oscillations in pressure were found during the passage of a storm over the zone. A clear high amplitude signal with a repetition of some cycles is observed in these records. Evaluated wave parameters showed a short range of values, indicating a good near monochromatic wave. Similar fluctuations in other parameters (temperature, wind speed and wind direction) have been found at different heights and they have been correlated with the pressure fluctuations. These oscillations agree relatively well in some cases (wind) with the Taylor-Goldstein's polarization equations from the linear wave theory (Nappo, 2002). We relate the origin of this wave to descending vertical currents associated to rainfall acting over a stable layer near the surface, previously formed by the surface cooling caused mainly by the evaporation of the drops close to the ground.

The wave event 2 was composed by two clear waves developed close to the ground. These waves travelled in the same direction than the wind and they could be formed by the action of the flow over a nearly obstacle or just by the action of this katabatic stronger wind above a stable layer near the ground with weaker winds.

2. DATA AND SITE

Data used for this study were taken from different instrumentation deployed over CRA (Centre for Atmospheric Research) in Lannemezan (France), near the Pyrenees Mountains, during the BLLAST campaign. This campaign took place from 14 June to 8 July 2011, and it was the result of an effort of several international researchers with the aim of improving the knowledge of the late afternoon transition in the PBL (see http://bllast.sedoo.fr for further details on the project). Data employed for this specific study are listed below:

1. A triangular array of three high resolution Paroscientific microbarometers (Model 6000-16B) separated about 150m (Fig. 1) and at 1m a.g.l. with the objective of detecting small scale surface pressure fluctuations. This triangular configuration was used to characterize wave events by means of methods based on wavelets decompositions, allowing the calculation of wave parameters (period, wavelength, phase speed and direction of propagation of these waves). A sampling rate of 2 Hz was used, enabling a resolution of around 0.002 hPa. A high pass filter (Butterworth) has been applied to the pressure records in order to eliminate those periods higher to 45 minutes, i.e. removing the synoptic tendency and the daily cycle. Applying this filter, fluctuations in pressure due to waves are easily observed in the time series.

2. Temperature, wind and rainfall data from instrumentation placed at different heights in two nearly towers (60m and 8m).

3. Temperature from a set of thermocouples close to the ground.

4. RADAR and IR satellite images, helping to relate some found waves with storms near the zone.

5. Vertical velocity measurements from UHF wind profiler, used to give an idea of the vertical motions in the lower troposphere.

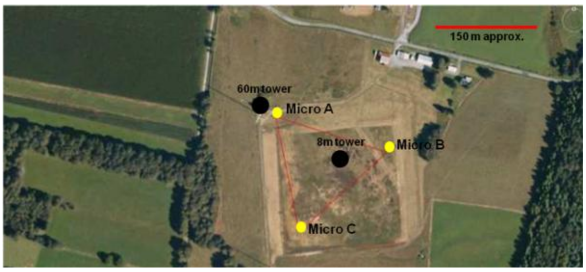

FIGURE 1. *Deployment of the microbarometers array in BLLAST campaign (Supersite 1). The positions of the 60m and 8m towers are also shown. Picture from Google Earth.*

3. RESULTS

3.1 Wave event 1

Figures 2a and 2b show filtered pressure and wavelet analysis respectively for the wave event 1, occurred during July 21st. This day was dominated by storms around the zone and in the nearly Pyrenees Mountains. A clear spectral energy peak is seen in the wavelet map from 21:15 UTC to 21:55 UTC, with a wave period of 8-11 minutes and corresponding with several cycles observed in the pressure records. These fluctuations in pressure reached almost 0.5 hPa in a few minutes which are values of remarkable importance compared to those usually produced by waves in the stable boundary layer (one order of magnitude smaller, see wave event 2).

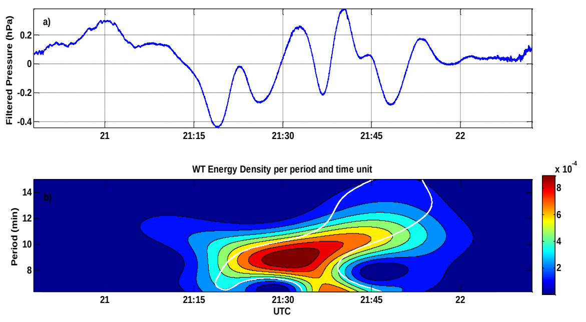

FIGURE 2. *a) Filtered pressure (hPa) for wave event 1. b) Wavelet transform energy density per period and time unit for wave event 1.*

Figure 3 indicates the rainfall record (a) and the vertical velocity obtained from UHF wind profiler (b) for this period. It can be seen how there existed a rainy period from 20:10 UTC to 21:35 UTC with strong negative vertical velocities (-6 m s^{-1} to -10 m s^{-1}). The indirect effect of the rain in the temperature profile was to create a stable stratification in the lower layers, with a decrease of temperature near the surface due to the effect of the latent heat absorbed by the evaporation of the fallen drops on the ground, as it can be seen in Figure 4a (temperature profile up to 60m height). Brunt Väisälä frequencies (N_{BV}) have been calculated for different layers up to 60m, and their values are also shown in Figure 4b. The condition for the persistence of gravity waves in a stable layer is that the frequency of the waves must be lower than N_{BV} (Stull, 1988). In the present case study, the minimum frequency of the wave was 0.0021 s^{-1} (It corresponds to a 8 minutes period). It can be seen how N_{BV} remained well above this value after 20:15 UTC except for the layer 45-60m. This made it possible the hypothesis that the wave was trapped in the lower layers, below 45 meters approximately.

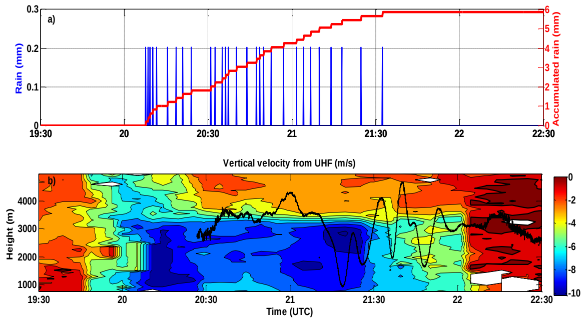

FIGURE 3. *a) Rainfall (blue) and accumulated rainfall (red) in mm. b) Vertical velocity (m/s) from UHF wind profiler (Filtered pressure is overlying this figure (black line) to show the wave event from 21:15 UTC to 22:00 UTC)*

This assumption is also supported by the relations found between the pressure fluctuations and other meteorological parameters measured in the 60m tower. Moreover, the UHF image (Figure 3b) shows how the rain seems to reach altitudes of more than 3km, and no stable layers were expected at these heights. Unfortunately, no radiosoundings are available for this day at this time because it was not an IOP day.

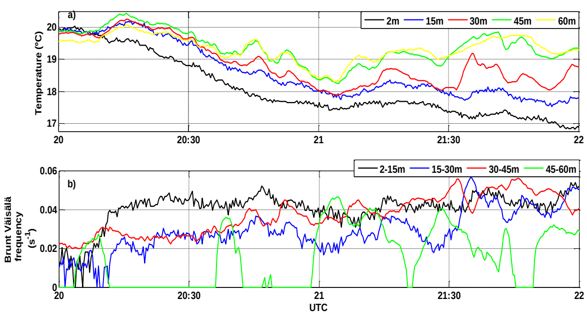

FIGURE 4. *a) Temperature (ºC) at different heights in the 60m tower from 20:00 UTC to 22:00 UTC. b) Brunt Väisälä freq. (s^{-1}) at different layers for the same period as in a).*

Figure 5 shows RADAR images from 20:00 UTC to 22:00 UTC. It can be seen how the wave was detected in the final part of a storm system passing through the zone, and not ahead the storm with a cold current or gust front as it is sometimes observed in thunderstorms (Bedard and Cairns, 1977).

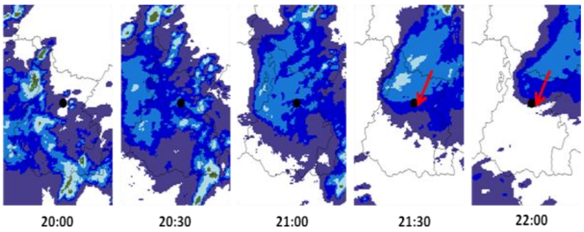

FIGURE 5. *RADAR images for wave event 1 (time in UTC). Black point indicates Lannemezan and red arrows indicate the approximated direction of propagation of the waves.*

The hypothesis of the wave trapped in a layer near the ground is also supported by the relationships found between the pressure fluctuations and other parameters measured at different heights in the 60m tower (Figure 6). This figure is an example of these relationships. It specifically shows the pressure records and the wind speed at 45m (left side). At the right side, wavelet analysis of this wind speed (up) and pressure (down) are shown and their similitude can be observed. Comparison to other parameters at different heights have also been calculated (not shown here), and the best relations have been found between wind (direction and speed) at 15m, 45m and 60m (specially at 45m) and with oscillations in temperature at 30m and 45m.

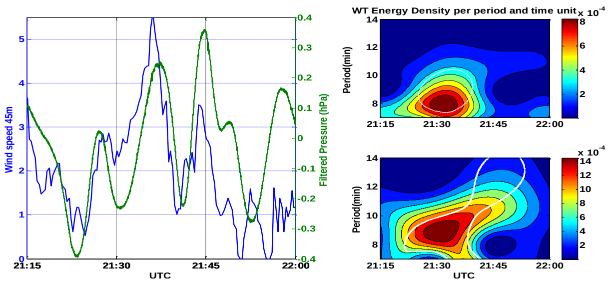

FIGURE 6. *Left - Wind speed (m s^{-1}) at 45m (blue) and filtered pressure (hPa) (green). Right – Wavelet analysis for wind speed (up) and for pressure (down)*

Wave parameters have also been calculated and they are shown in Figure 7. This figure shows how for this period we obtain a well defined wavelength between 500m and 550m, a phase speed of approximately 1 m s^{-1} and a well marked direction of propagation of 216º (i.e. the wave came from 36º, near the NE direction). These values and the 8 minute wave period indicate the wave to be a microscale event and are slightly lower to other gravity waves related to thunderstorms reported in different works (Miller,1999).

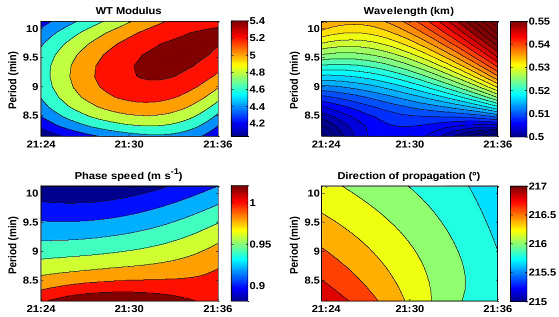

FIGURE 7. *Wave parameters (WT modulus, wavelength, phase speed and direction of propagation) for a period within the wave event 1. (Note that direction of propagation is direction of origin + 180º).*

Strong downdrafts due to precipitation could impinge over the stable layer previously created and generate these gravity waves.

Different wave-like disturbances in the pressure records were found the same day. Unlike the previously studied wave, these other gravity waves were related to storms away from the site, with higher periods, higher wavelengths and higher speeds. The origin of them was more difficult to find out, because of the remoteness of the waves. There did not exist stable layers near the ground during these waves and they were probably formed higher in altitude due to thermals currents acting upon some stable layers up in the PBL (the radiosoundings showed an inversion in temperature between 800m and 1000m agl). The study of these gravity waves is not shown here.

3.2 Wave event 2

Figure 8 shows filtered pressure and wavelet analysis for July 2nd from 20:00 UTC to 22:00 UTC.

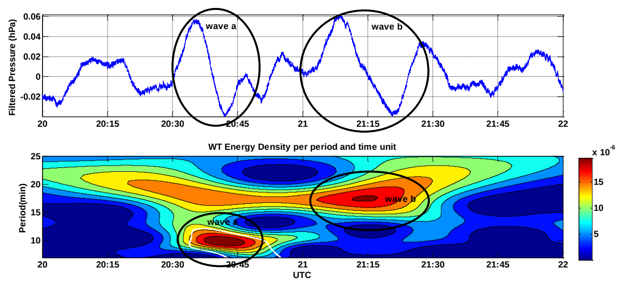

FIGURE 8. *a) Filtered pressure for wave event 2. b) Wavelet transform energy density per period and time unit for wave event 2. The two different waves analyzed are marked with circles.*

Two different wave-like disturbances are analyzed; the first one (wave a) has a period of 8-10 minutes approximately and occurred between 20:30 UTC to 21:00 UTC. The second wave (wave b) could be formed slightly higher in altitude, with a period around 18-20 minutes from 20:00 UTC to 22:00 UTC approximately. The wavelet analysis shows higher wavelet energy from 21:00 UTC to 21:30 UTC and for this reason, the studied period has been limited to this shorter one. The variations in pressure for the wave a) and the wave b) were up to 0.06 hPa, values much lower than those for wave event 1.

July 2nd was a different day compared to June 21st. In this case, the fair weather predominated and a surface-based thermal inversion layer was formed up to 45m-60m from 17:00 UTC onwards due to radiative surface cooling (temperature not shown). According to the calculated Brunt Väisälä frequencies (not shown), waves larger than 2 minutes of period are supported in the layer below 45m for this period. Looking at the radiosounding launched at 20:00 UTC (not shown) in the same site, there exist some light stable layers, but these were not characterized by temperature inversions and the stability was much weaker than those for the surface layer.

The wind was mainly blowing from S-SE direction and it increased in speed at 20:20 UTC above 4.8m (Fig. 9), which could be an indication of a katabatic wind. This increase in wind speed was more intense above 45m.

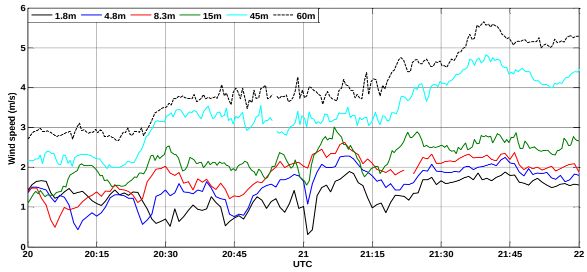

FIGURE 9. *Wind speed at different heights from 8m and 60m towers.*

Relations between pressure fluctuations with other meteorological parameters have also been found (Figures 10 and 11). For the wave a), the best relations were found in temperature from 1.5cm (thermocouple close to the ground) up to 2m and in wind until 4.8m. For the wave b), similar relations were found, but in this case these relations were observed from surface until slightly higher levels.

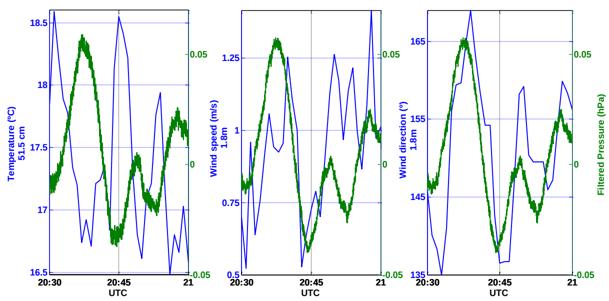

FIGURE 10. *Relations for wave a between filtered pressure (green) and other parameters (blue): temperature at 50.1cm (a), wind speed at 1.8m (b) and wind direction at 1.8m (c).*

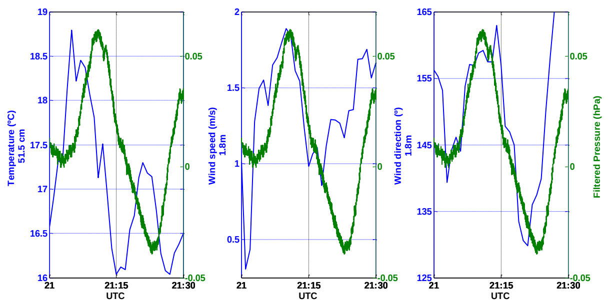

FIGURE 11. *Relations for wave b between filtered pressure (green) and other parameters (blue): temperature at 50.1cm (a), wind speed at 1.8m (b) and wind direction at 1.8m (c).*

Good relations have been found between the oscillations in pressure and the oscillations in wind speed. These relationships agree relatively well with the Taylor-Goldstein´s polarization equations from the linear wave theory, which establish no phase lag between these parameters. For the temperature variation it is difficult to explain these relations with the equations from the linear wave theory. The Taylor-Goldstein´s equations suggest a π/2 phase lag between the pressure fluctuations and the temperature ones, but due to the non monochromatic nature of the wave (something normal in the atmosphere) and to the noise in the temperature records, these relations are difficult to completely fulfill. Moreover, the temperature sensors were not installed at the same location than the microbarometers. Despite of this, further study related to the wave linear theory applied to this case has to be done.

Wave parameters have also been calculated for these two waves. A short range of these values was found: wavelength of around 1.4km (wave a) and 2.1km (wave b), a phase speed of 2.2 m s^{-1} (wave a) and 1.8 m s^{-1} (wave b). The directions of propagation of the waves were similar for the two ones, indicating an origin from south, near the wind direction at these heights.

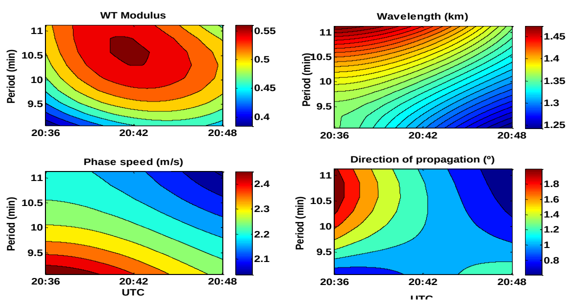

__FIGURE 12.__ Wave parameters (WT modulus, wavelength, phase speed and direction of propagation) for a period within the wave event 2a. (Direction of propagation is direction of origin + 180º).

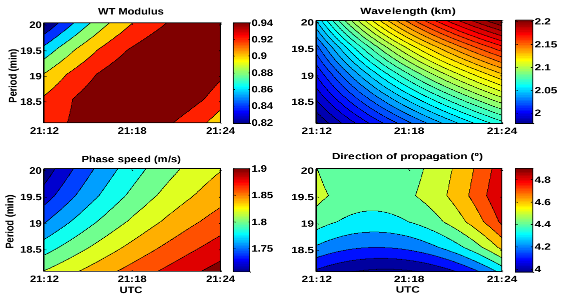

__FIGURE 13.__ Wave parameters (WT modulus, wavelength, phase speed and direction of propagation) for a period within the wave event 2b.

4. CONCLUSIONS

Two days with different gravity waves observed over Lannemezan (France) during the BLLAST campaign have been deeply studied.

The wave event 1 (June 21st) was a gravity wave associated to thunderstorms, particularly to downdrafts acting over a stable layer near the surface. This stable layer was previously created by the action of the latent heat absorbed by evaporation of the rain droplets fallen during the precipitation event (a convective system crossed through the zone for almost 2 hours). The magnitude of the oscillations in pressure was higher than those related with typical stable boundary layers developed during fair weather nights (like wave event 2) and they achieve values of almost 0.5 hPa of variation, being values of remarkable importance

The wave event 2 was associated to the wind (probably katabatic) acting over a stable layer near the surface formed by radiative cooling and generating oscillations in pressure of almost 0.06 hPa.

These oscillations in pressure were related to oscillations in other parameters (temperature, wind speed, wind direction, vertical velocity) and it has been made an attempt to relate them with the equations of the linear wave theory.

Gravity waves like that for wave event 1 with important amplitudes in pressure fluctuation could be an important hazard for aircrafts. This danger is due to high variations in pressure that can produce important wind shear and because they occur very close to the surface, increasing their importance during the landing and takeoff of the planes. This danger could increase if these oscillations persist in the space and they propagate away from the precipitation zone.

These gravity waves could also affect the fluxes of different magnitudes due to the observed variations in temperature, wind and vertical velocity.

5. ACKNOWLEDGMENTS

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