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A study of local turbulence and anisotropy during the afternoon and evening transition with an unmanned aerial system and mesoscale simulation

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1 authors' response

The whole manuscript has undergone significant changes as a result of the three referees' suggestions. A further analysis of the BLLAST observations during the afternoon and evening transition has been made for 2 July 2011. Now UHF, soundings and tower measurements (all of them at Site 1) are taken, apart from observations from M^2AV (Site 1) and frequent soundings (Site 2) already shown in the previous version of the manuscript. Furthermore, results from high-resolution mesoscale simulations are used to better describe the evolution of the LLJ and the anisotropy ratio during the evening transition of 2 July 2011 in Lannemezan. The main changes in the revised version of the manuscript are the following:

- The 3 new co-authors (M.A. Jiménez, J. Cuxart and D. Martínez) have performed numerical simulations and data analysis, apart from contributing to the discussion of the new results.
- The manuscript has a different organization. The introduction is re-written according to the reviewers' requests (now the turbulence and anisotropy during the evening transition is described, as well as the low-level jet). The next section is devoted to the observations and model setup. The atmospheric situation is described in Section 3, and in section 4 turbulence and anisotropy are evaluated. Finally, the discussion of the results is shown in Section 5 and the conclusions in Section 6.
- The title has now changed into "A study of local turbulence and anisotropy during the afternoon and evening transition with an unmanned aerial system and mesoscale simulation"

There has been further substantial work involved since uploading the answers to the three anonymous referees. In this summarising text, we stick to the already published answers. Due to the large changes, involving changes in equations and figures, we did not succeed in compiling the "latexdiff" file which should mark up the differences of the original and the new manuscript.

We are confident that the revised version of the manuscript has improved significantly, and kindly ask the editor to consider our contribution for publication in ACP.

2 answers to referee 1

The authors would like to thank the anonymous referee for his/her suggestions. According to your and the other reviewers requests, a further analysis of the BLLAST observations during the afternoon and evening transition has been made for the 2nd July 2011. Now UHF, soundings and tower measurements (all of them in site 1) are taken, apart from observations from M^{2}AV (site 1) and frequent soundings (site 2) already shown in the previous version of the manuscript. Furthermore, results from a high-resolution mesoscale simulations are used to better describe the evolution of the LLJ and the anisotropy ratio during the evening transition of the 2nd July 2011 in Lannemezan. As a result, find below the main changes in the revised version of the manuscript, some of them directly answering your requests.

- The 3 new co-authors (M.A. Jiménez, J. Cuxart and D. Martínez) have performed the numerical simulations and data analysis, apart from interviewing in the discussion of the new results.

- The manuscript has a different organization. The introduction is re-written according to the reviewer requests (now the turbulence and anisotropy during the evening transition is described, as well as the low-level jet, LLJ). Next section is devoted to the observations and model setup. The atmospheric situation and the features of the observed LLJ are described in sections 3 and 4, respectively and in section 5 the anisotropy is evaluated. Finally, the discussion of the results is shown in section 6 and the conclusions in section 7.

- The title has now changed into "A study of a local turbulence and anisotropy during the afternoon and evening transition with an unmanned aerial system and a mesoscale simulation"

Find below the answer or your requests point by point. The text from the review is given in italic letters, the answers are provided in normal letters. Changes to the text of the manuscript are indicated in quotation marks.

3 Answers to major comments

The use of unmanned aerial vehicles in the study of meteorology is still novel. To this end, manuscripts such as this one are to be encouraged as the scientific potential of UAVs seems to be large.

We are happy that the referee acknowledges the potential of UAS in the field of meteorology and totally agree with the importance of UAS.

However, whilst the manuscript contains some interesting and tantalizing data, and its methodology is sound, its conclusions are not robust because the dataset is too small. This is clear from a basic statistical viewpoint alone.

The UAS data set is forcefully small, due to its mode of operation. Therefore, to supplement it in order to have a broader picture of the events and mechanisms in place, we have tried to use most of the available data during that BLLAST IOP1. Now UHF, soundings and tower measurements (all of them in site 1) are analysed in depth, apart from observations from UAS (site 1) and frequent soundings (site 2) already shown in the previous version of the manuscript. The analysis is complemented by the model outputs from a high-resolution mesoscale simulation obtained from the MesoNH model (model setup is described in section 2.3 and in more detail in Jiménez and Cuxart (2014)). All sources of data are giving consistent results as it is seen in current Figure 5. The model is able to reproduce the LLJ formation reported from the observations (Figure 2). For the evening transition, there are only UAS observations of turbulence at higher levels (up to 300m AGL) and for this reason this case is taken in this work. The studied case of 2nd July is described in section 3 and 4 pointing the similarities and differences to the other IOPs during the BLLAST campaign. Turbulence and anisotropy of the IOPs during the BLLAST campaign are further analysed in Canut et al. (2015) from tethered balloon observations.

In addition, the presence of a low-level jet on this occasion leaves the reader asking: what would have happened to the anisotropy ratio if the LLJ had not been there ? If you can so much as answer this question, then the paper will be vastly improved.

We see that in the daytime the anisotropy ratio (A) provided by the sources are very similar and slightly above 1, in coherence with a dry sheared convective boundary layer. At the evening transition, A takes larger values (a factor between 2 and 5), very likely because the contribution of the convection weakens significantly and the eddies become progressively shallower and more elongated. The beginning of the Inertial Subrange (IS) of the spectrum shifts to the right, and after sunset the eddies have relatively shallow dimensions and are elongated along the main wind direction (Mason and Thomson (1987)), showing large values of anisotropy at these scales. If a LLJ is present (maximum of wind speed at lower levels and close to the top of the temperature inversion), eddies are even more elongated and therefore A increases. Now Figure 7b shows the anisotropy ratio computed from tower observations of the studied case (2nd July) and the one of 1st July (no LLJ during the evening transition). It is found that the anisotropy is larger when the LLJ is present, although in both cases the anisotropy increases during the evening transition when the eddies are more elongated in the wind direction (Mason and Thomson, 1987).

At night the values of A diverge depending on the scale and the source of data (new figure 7a). The model resolved motions at the height of the LLJ is just as anisotrope as in the transition, not feeling significantly the effects of thermal stratification at those levels. Instead, M2AV and the tower, that measure at smaller scales, provide much higher values of anisotropy, indicating that at the smaller scales variability in the horizontal is significantly larger than at the vertical, therefore indicating that thermal stratification may be playing an important role, moving the upper limit of the IS to very small eddies.

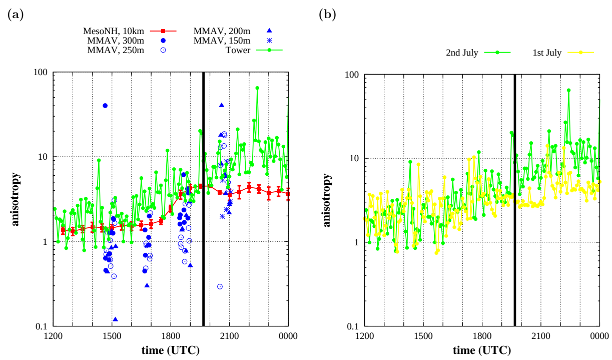

Figure 7. (a) Time series of the anisotropy computed from different sources: M^{2}AV flight observations during the four flights for different heights (in blue); tower measurements at 60 m AGL every 5 min (in green); and model results averaged between 150 m and 300 m AGL to be close to the altitudes of the M^{2}AV observations considering a spatial area of 10 km x 10 km centered at Lannemezan (in red). The same in (b) but computed from tower observations during the IOP9 (1st July, no LLJ) and IOP10 (2nd July, with LLJ). The time of sunset is represented with a black vertical line. Note the logarithmic scale on the y-axis.

If the LLJ was present on all available measurement days, then of course this is important too, and more flight data will in any case boost the statistical base. Fig 10 in particular could be added to and improved. I see from Lothon et al that three other days are potentially available from the M2AV dataset. For this reason, it is probably best to label such a revision as major although it is difficult for me to know how much work is involved.

There are only available observations of turbulence from M^{2}AV during the afternoon and evening transition of the day studied here (2nd July). For this reason the data analysis is limited to the 2nd July. Nevertheless, the results obtained here are compared to those reported from other IOPs where LLJ was not present during the evening transition. It is found that the IOPs with clear skies and weak wind conditions the anisotropy ratio increases during the evening transition but this ratio increases even more when the LLJ is present (only for IOP10, 2nd July). This is further explained in section 6 with the help of the new figure 7.

The conclusions section is also very small, as mentioned below. This should be improved with a larger dataset for a better range of meteorological conditions.

The conclusion section is re-written to incorporate the new analysis (extra sources of data and model outputs). The main findings of the work are: (1) during the afternoon transition, TKE decreases as time progresses and it is minimum close to sunset. Afterwards it increases due to the presence of a LLJ. (2) the shear generated by the presence of a LLJ is the responsible of the increase of the anisotropy during the evening transition, being larger than if no LLJ is present. (3) the anisotropy ratio computed from difference sources of data (model and observations) shows that A depends on the scale (spatial and temporal) of motions included in the data.

A bit of an overhaul of the figures is required too, as described in detail at the bottom of the details below.

We would like to thank the referee for the suggestions. For the revised version, new figures were created, taking into account the additional sources of observations and mesoscale simulation.

4 Answers to minor comments

In general:Stick to either local time or UTC. Do not keep changing from one to the other. But state, both in the abstract and in the main body of the paper, that local time = UTC+2hr.

We will stick to UTC time. As the longitude of Lannemezan is almost the same as Greenwich, in solar time Lannemezan has the same UTC hour as Greenwich. We now comment on this in the manuscript.

Abstract. Line 1 "We analyse airborne observations..." Line 1-2 "directions" Line 2 "turbulently-mixed", "stably-stratified" Use local times in the abstract (but state local= UTC+2hr) Line 5. "...anisotropy ratio, defined here as the ratio of the variance of horizontal to vertical wind speed, changes..." Line 7. "...mean value of about 1 to a mean value of 2 about one..." Line 8. "...a mean value of about 8 one hour after sunset."

We thank the referee for the improvements and changed the text accordingly.

Introduction. Line 28. "...is described in two distinct consecutive phases:" Lines 33-35. Is this typical ? Do you see it here for the case studied ?

Previous works show that the evolution of the TKE during the afternoon and evening transitions can be described in two consecutive phases according to the decrease of the surface heat flux (**?**). This is now clarified in the introduction: "The combined inspection of observations (LITFASS-2003 experiment) and a mixed layer model performed by Nadeau et al. (2011) show that the TKE decay phase could be separated in two stages: a slow decay of TKE during the afternoon transition followed by a rapid collapse during the evening transition. Similar results were obtained from **?** from observations (CASES-99) and LES simulations." Similar results are obtained from the BLLAST dataset (Lothon et al., 2014) and this is now clarified in the results. Observations from M^2AV are not a proper dataset to check this two-phase process (observations available only at some vertical levels during some instants during the afternoon and evening transitions) but results from the mesoscale simulations evidence this decaying of turbulence (see new figure 4d).

Section 2.1 Line 61. The proximity to the Pyrenees I found initially worry because of effects such as gravity waves on the measurements. Given the wind directions during the measurements, this probably isn't an issue. But I would recommend stating the likelihood, or not, of the effect of the mountains on flow. I see gravity waves are not mentioned in Lothon et al (2014) at all !!

We completely agree with your point. Now the complex terrain area is better described, as well as the organization of the flow at lower levels (new section 3) with a deeper analysis of the observations and the mesoscale simulation during the studied transition (2nd July 2011). The general NE flow on 2nd July in the BLLAST site co-existed with the plain-mountain system that generated northerly flows in the daytime over the foothills of the Pyrenees (see for instance new Figure 2a), and the Aure valley -just South of Lannemezan- presented a well developed upvalley wind system. As sunset approached, downslope flows appeared in the Aure valley and generate a down-valley flow which blew underneath the decaying upvalley flow. The down-valley flow will increase its depth and intensity during the first hours of the night and will progress towards Lannemezan reaching it around midnight (Figure 2d). Similar results were obtained by Jiménez and Cuxart (2014). As sunset approached, the wind veered clockwise in the BLLAST site, generating after sunset a well defined LLJ from SE, with maximum wind values around 6 m s^{-1} at heights between 150 m and 300 m AGL. That structure was sampled by the M^2AV's last flight.

About your question of the presence of gravity waves, during the first 3 flights, stably stratified conditions were not present yet in the ABL (they are during the afternoon and early evening transition, when surface cooling starts) and therefore no ambient conditions were favourable to develop gravity waves in the ABL. However, during the last flight (about 2100 UTC) cooling is stronger and Román-Cascón et al. (2015) found gravity waves between 2030-2130 UTC close to the surface (they are analysing surface pressure and other atmospheric magnitudes up to 2 m AGL). Figure 8 in Román-Cascón et al. (2015) (vertical profile of the observed Brunt-Vaisala frequency) shows that gravity waves can be found up to about 100m AGL but not at higher levels (where the M^2AV sampled). Later on (from 2100 UTC to midnight), gravity waves could be found but the presence of the LLJ does not allow a strong nocturnal cooling (strongly stably stratified conditions), departing from

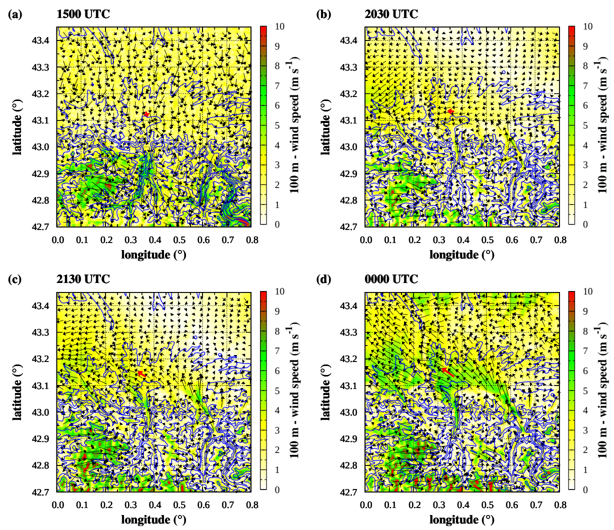

Figure 2. Modelled 100 m AGL wind vectors together with wind speed (in colours) and the topography lines (in blue) at different instants (a) 1500 UTC, (b) 2030 UTC, (c) 2130 UTC, (d) 0000 UTC. The 60 m wind vector observed by the tower is plotted with a red arrow.

the favourable conditions for the development of the gravity waves. About the model. It is not able to capture these observed gravity waves (Román-Cascón et al. , 2015) since they are attached to the ground. In fact, the model is not seen this maximum of wind at 2 m AGL that they report since the first grid level is at 1.5m. A comment on the presence of gravity waves is included in section 4, when the description of the processes during the studied transition is made. We do not consider that the possible presence of Internal Gravity may alter the discussion on the other relevant issues treated in the paper and we just mention them and refer to (Román-Cascón et al. , 2015) for further information.

Line 65. "...with sides about 3-4km long were equipped..." Line 69. "ultra-high" Line 70. "...which provide a measure of the boundary layer depth..."

We changed the text as suggested.

Lines 73-75. No need to describe what a sonde measures, this is standard. State what type of sondes were used e.g. RS92.

We changed the text to: "Standard GRAW and MODEM radiosondes were launched from site 1 during the intensive operation period (IOP) days at least 4 times per day at 0500, 1100, 1700 and 2300 UTC (launching times). In particular, on 2 July, additional radiosondes at 0200 and 2030 UTC were performed. The frequent radiosonde consists of a conventional Vaisala receiver and a global positioning system (GPS) radiosonde RS92SGP, that is tied to a couple of inflated balloons. "

Line 80 "M2AV flight tracks"

OK. Corrected.

Line 84. "...partially controlled..."

We changed the text to "It is started and landed manually, and can be fully controlled during the mission by an autopilot system. For this case study, most ascents and descents as well as the race track pattern with straight horizontal legs were flown with the autopilot."

Section 2.2 Line 108-109 spelling: "temperature" Line 120 "calculated by two different methods" Line 121 "removing the zero offset and a linear detrend of the time..."

OK. Corrected.

Lines 125-130 gravity waves might be seen in such data. Is there any evidence for this ?

This is already answered in 5 points above.

Line 150. Need to define LLJ in the body text (it was defined only in the abstract).

ok, thank you.

Section 2.3 Line 160. No need to define geostrophic wind, remove words "determined by the...centrifugal force" Line 163. "especially at night" Line 164. "observed LLJ occurrence between 30 and 60 % of all nights" Line 171. "Further, for particular interest for the present study, it creates wind shear..."

OK. Corrected.

Section 3: maybe turn section 3 into Section 2.4 as it?s quite small?

We completely revised the structure of the manuscript. Now it is as follows:

1. Introduction
2. Observations and model setup
2.1 Field site and instrumentation
2.2 M^{2}AV data processing
2.3 Model setup
3. Atmospheric situation
4. The nocturnal LLJ as observed and modelled
5. TKE and anisotropy during the afternoon-evening transition
6. Discussion
6.1 Turbulence properties
6.2 Low-level jet as source of enhanced turbulence
7. Conclusions

Section 4.1 Line 198. What are the typical ascent/descent rates of the UAV ? You can then state the typical SLOPE of the UAV profiles which will help the reader visualise the horizontal distance covered for a given height change.
We included in the text: "The profiles were performed with an ascent rate of about 3.5 m s−1, the descent rate was about 8 m s^{-1}."

Line 217. "For Flights 1 and 2" Line 218. "decreases"
OK. Corrected.

Line 246. Does it really indicate stability and hence also turbulence ?
Now an extended analysis of the turbulence is made at different levels: (1) up to 60m AGL from tower, (2) from 150-300m AGL from M^{2}AV and (3) for the whole ABL from the mesoscale simulation. Besides, the observed and modelled potential temperature in the ABL is inspected. As a result, there is no need to indicate the stability and turbulence with the Ri since the vertical profiles and time series of the modelled and observed TKE and potential temperature are enough. As a result, the definition of Ri in old section 2 is removed, as well as the comments on line 246. However, the stability and turbulence are further described in sections 4 and 5.

Section 4.2 Line 249. Define "Zi" here (you define it on line 299, but it needs to be here).
Right. z_i is now defined the first time that is used (new section 5).

Section 4.3 Line 290-291. Does this refer to the following day ? Best to make it clear.
Right. The observations and model results are restricted from 1200 to 0000 UTC. The information of old section 4.3 is now incorporated in section 4 where it is briefly commented that the LLJ remains in the site until sunrise of the next day (as it is seen from model and observations). But this is beyond the temporal scope of this study.

Section 5.1 Line 309. "In Fig. 9"
OK. Corrected although the number of the figure has changed.

Lines 310-314. This is even more reason for adding more flight data to the analysis, as explained in the main comments section above. Statistically, the analysis given is barely acceptable and firm conclusions cannot be drawn.
With the limited number of flights, all them corresponding to different flow regimes, it is not possible to make a well-posed statistical analysis. The approach taken, instead, is to analyze case by case, using the UAS data as another source of information together with all others.

Line 322. "flux reduces to zero..."

OK. Corrected.

Section 5.2 Line 327 and 330. No need to put m s-1 in italics. Lines 345-346. "...leads to a thermodynamic decoupling of the air that is in direct contact with the surface from the atmosphere above." Line 353. Do not use "A" notation; use the phrase anisotropy ratio in full throughout. Line 363. "within the scale of a few km."

OK. Corrected.

Section 6. This section is too short. The use of UAV data for meteorological research is still novel. How can future studies of turbulence and the anisotropy ratio be improved upon in the light of BLLAST ? Would you change the flight patterns or the layout of the ground sites ?

The conclusion section is now re-written to incorporate the new analysis of the observations (UHF, tower and extra soundings) and the mesoscale model results. The main findings of the current work are:

(1) the results presented here show that the use of UAS for meteorological research complements the information given for other sources of data (soundings, tower, ...) to better characterize the lower atmosphere. Furthermore, turbulence measurements in the lower atmosphere can be performed with M^2AV.

(2) M^2AV observations are giving consistent results to those reported during the BLLAST experimental field campaign (observations from tower, UHF and soundings) and those obtained from a mesoscale simulation.

(3) During the day, a well developed CBL favour the isotropy conditions and the anisotropy ratio remains nearly constant. However, during the afternoon and evening transitions the stably stratified conditions and the general wind favour the elongation of the eddies in the prevailing wind direction, resulting in a loosing of isotropy. Therefore, the anisotropy ratio increases and specially due to the presence of a low-level jet, generated by the interaction between the large-scale winds and the nocturnal mountain-plain circulations.

(4) Once the anisotropy ratio is computed from different sources of observations and model, the spatial and temporal scales included there might induce differences in its value, highlighting which are the relevant processes included in the observations and in the mesoscale simulation results.

Besides, to improve the understanding of anisotropy probably flights well defined along and across the turbulent elongated structures of longer track would bring much more supplementary information. To do so, efficient use of available information should be made beforehand and determine the high of the flight to use the batteries as optamally as possible to get long tracks.

Line 368. "radiosondes" Line 371. "...vertical component coincided with the evolution of a LLJ."

OK. Corrected.

Figures. (i) Fig 1. Add on a distance scale of 1km, or perhaps 5 km, whatever seems best ? The UAV flight patterns here are very small. Could you make the present figure Fig 1a and add a Fig 1b to the right showing a zoom-in of the flights in nice detail ?

We replaced the figure with another two, showing the topography as represented in the model, and superimposed the observation sites and the flight tracks.

(ii) You should combine Figures 3 and 4, using potential temperature (Kelvin) on the x-axis. With suitable line styles/point symbols the distinction between radiosonde and M2AV profiles should be clear. Add profile times to the key for the M2AV data.

We replaced the figures with a new one (now Figure 5, see bellow), consisting of 4 subfigures, showing data of M^2AV, sounding, tower and simulations for each time a flight is available.

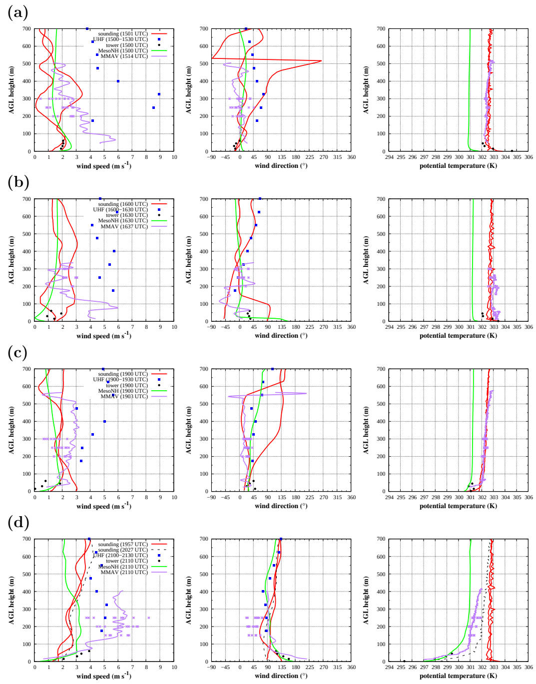

Figure 5. Vertical profiles of wind direction (in °) on the left, wind speed (in $\mathrm{m\,s^{-1}}$) in the center and potential temperature (in K) on the right, from $\mathrm{M^2AV}$ (in violet) for the four flights of 2 July 2011: (a) 1500, (b) 1630, (c) 1900 and (d) 2110 UTC. Vertical lines and dots correspond to instantaneous values from the vertical profiles and to mean values for each horizontal leg, respectively. $\mathrm{M^2AV}$ data are compared against instantaneous observations from UHF (blue squares), tower (black dots), and frequent (red) and standard soundings (black) together with mesoscale simulation results (green). Legend indicates the corresponding times to each data source.

(iii) You should use "mid-profile times" for all profiles, regardless whether M2AV or radiosonde.

ok

(iv) Fig 8. Use same x-axis as Fig 7. Also add "W", "N", "E", "S" direction labels to the x-axis.

OK. See the changes in the new Figure 5 (two answers above).

(v) Figs 11, 12, 13. I can't help feeling that your interpolated contour plots are disturbing the real data. Please try using "pixel" plots to show true data only.

The plots regarding the UHF observations are improved according to you comment.

(vi) Add annotations showing the astronomical sunrise and sunset times, as appropriate, to Figs 10-13.

We included a vertical black line to indicate the sunset time in the time series and it is properly described in the caption of the figure.

5 answers to referee 2

The authors would like to thank the anonymous referee for his/her suggestions. According to your and the other reviewers' requests, a further analysis of the BLLAST observations during the afternoon and evening transition has been made for 2 July 2011. Now UHF, soundings and tower measurements (all of them in site 1) are taken, apart from observations from M^{2}AV (site 1) and frequent soundings (site 2) already shown in the previous version of the manuscript. Furthermore, results from high-resolution mesoscale simulations are used to better describe the evolution of the LLJ and the anisotropy ratio during the evening transition of 2 July 2011 in Lannemezan. As a result, find below the main changes in the revised version of the manuscript, some of them directly answering your requests.

- The 3 new co-authors (M.A. Jiménez, J. Cuxart and D. Martínez) have performed the numerical simulations and data analysis, apart from contributing to the discussion of the new results.

- The manuscript has a different organization. The introduction is re-written according to the reviewers' requests (now the turbulence and anisotropy during the evening transition is described, as well as the low-level jet, LLJ). The next section is devoted to the observations and model setup. The atmospheric situation and the features of the observed LLJ are described in sections 3 and 4, respectively, and in section 5 the anisotropy is evaluated. Finally, the discussion of the results is shown in section 6 and the conclusions in section 7.

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Find below the answer to your requests point by point. The text from the review is given in italic letters, the answers are provided in normal letters. Changes to the text of the manuscript are indicated in quotation marks.

6 Answers to general comments

The research topic as well as the available data could provide an interesting contribution to the field of boundary layer research. From the title I expected a comprehensive analysis of the conditions and processes during AT relating turbulent and mean quantities. Unfortunately, the presented analysis and discussion do not fulfil my expectations.

We appreciate that the referee considers our research topic and data as interesting. In the revised version of the manuscript a deeper analysis of the processes that take place during the AT is made. Data from other sources (soundings, UHF and tower) and a mesoscale simulation of this case further characterise the mean quantities and the turbulence in the lower atmosphere.

I am missing a clearly formulated research question and motivation for this study.

The scientific questions are now stated at the end of the introduction. M^2AV measurements taken during the BLLAST experimental field campaign, together with other sources of data and results from a mesoscale simulation, are used in this work to further understand the processes involved during the afternoon and evening transitions with special attention to:

(1) characterize the evolution of the ABL, specially in the lower levels (up to 400 AGL),

(2) evaluate the changes in the turbulent scales and their implication in the isotropy of the fields and

(3) study the influence of a nocturnal low-level jet on the turbulence properties.

The quality of the analysis is fairly poor. The authors describe profiles of temperature and horizontal wind in an unnecessary longish way (separately for the various instruments without a critical discussion/explanation of the existing differences).

In the revised version, the description of the ABL development is shortened substantially, but it includes additional data and numerical simulations with the model MesoNH. The differences between the datasets due to their location (there were two main sites during the BLLAST experimental field campaign) is now included in the description of the results.

The turbulence quantities, which are the new and interesting part of the analysis, are described very briefly. The discussion of these should be more detailed.

Now sections 5 and 6 are devoted to describe the observed and simulated turbulence. Turbulent M^2AV observations are now complemented with the tower observations and the mesoscale simulation results, with the three sources of data producing consistent results. On the other hand, the anisotropy ratio (A) is now computed from the tower and the model results and they are compared to those already computed from the M^2AV observations.

We see that in the daytime the anisotropy ratio (A) provided by the sources are very similar and slightly above 1, in coherence with a dry sheared convective boundary layer. At the evening transition, A takes larger values (a factor between 2 and 5), very likely because the contribution of the convection weakens significantly and the eddies become progressively shallower and more elongated. The beginning of the Inertial Subrange (IS) of the spectrum shifts to the right, and after sunset the eddies have relatively shallow dimensions and are elongated along the main wind direction (Mason and Thomson, 1987), showing large values of anisotropy at these scales. If a LLJ is present (maximum of wind speed at lower levels and close to the top of the temperature inversion), eddies are even more elongated and therefore A increases. At night the values of A diverge depending on the scale and the source of data (new figure 7a). The model resolved motions at the height of the LLJ is just as anisotrope as in the transition, not feeling significantly the effects of thermal stratification at those levels. Instead, the M^{2}AV and the tower, that measure at smaller scales, provide much higher values of anisotropy, indicating that at the smaller scales variability in the horizontal is significantly larger than at the vertical, therefore indicating that thermal stratification may be playing an important role, moving the upper limit of the IS to very small eddies.

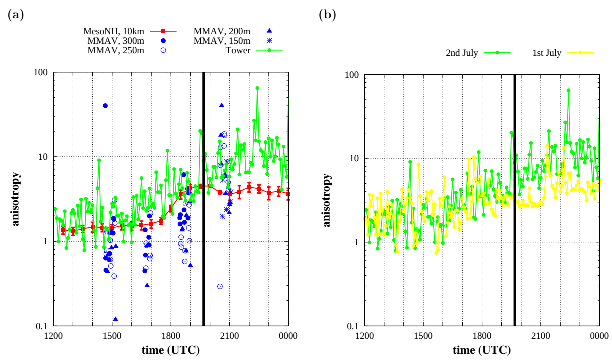


Figure 7. (a) Time series of the anisotropy computed from different sources: M^{2}AV flight observations during the four flights for different heights (in blue); tower measurements at 60 m AGL every 5 min (in green); and model results averaged between 150 m and 300 m AGL to be close to the altitudes of the M^{2}AV observations considering a spatial area of 10 km x 10 km centered at Lannemezan (in red). The same in (b) but computed from tower observations during the IOP9 (1 July, no LLJ) and IOP10 (2 July, with LLJ). The time of sunset is represented with a black vertical line. Note the logarithmic scale on the y-axis.

The authors claim that a nocturnal low-level jet develops after sunset and affects TKE and anisotropy. Although this might be the case, the analysis of the jet including its formation and spatial inhomogeneity is not complete and raises more questions instead of answering them.

We agree with your comment. Now the analysis of the low-level jet and the anisotropy is extended and sections 5 and 6 are focused on this. Now Figure 7b (see above) shows the anisotropy ratio computed from tower observations of the studied case (2 July) and the one of 1 July (no LLJ during the evening transition). It is found that the anisotropy is larger when the LLJ is present, although in both cases the anisotropy increases during the evening transition when the eddies elongate in the wind direction, as it was described in Mason and Thomson (1987).

The quality of the figures is not sufficient and English should be checked by a native speaker.

All figures have been replaced according to the detailed suggestions of the three referees, and also incorporating the additional data and simulations. A native speaker has gone through the English.

Much to my regret, I think that the current version of the manuscript is not suitable for publication in ACP. However, I encourage the authors to revise their manuscript introducing a clear research questions and significantly improving the presentation quality. Below I provide specific comments to the major flaws of the manuscript, which could help the authors to provide a new version.

We would like to thank the referee again for his valuable and detailed comments and the encouragement to submit an improved revised version.

7 Answers to specific comments

1. The title does not match the analysis conducted in the manuscript. As the title is promising I recommend revising the manuscript to match the title.

We suggest to change the title to "A study of local turbulence and anisotropy during the afternoon and evening transition with an unmanned aerial system and mesoscale simulation" The new version of the manuscript includes numerical simulations to expand the airborne observations to a larger scale. With these additional results, the analysis of the observations are better embedded in the atmospheric context, and more concise conclusions can be drawn from the additional data sources.

2. Introduction and motivation

If the authors analyse the relation between a low-level jet and turbulence I would expect a paragraph on previous work related on this topic in the Introduction. Instead Section 2.3 could be removed as it just recalls text-book knowledge. The authors should keep in mind that with the reduction of surface friction in the evening wind speed above the inversion increases and that not always a low-level jet involves.

According to the deeper analysis of the observations and the mesoscale simulations for the afternoon and evening transitions of 2 July 2011, the structure of the manuscript has now completely changed to:

1. Introduction
2. Observations and model setup
2.1 Field site and instrumentation
2.2 M^{2}AV data processing
2.3 Model setup
3. Atmospheric situation
4. The nocturnal LLJ as observed and modelled
5. TKE and anisotropy during the afternoon-evening transition
6. Discussion
6.1 Turbulence properties

6.2 Low-level jet as source of enhanced turbulence

7. Conclusions

Now in the introduction the low-level jet and turbulence are introduced and the current work is put in context regarding the previous ones. Some parts of old section 2.3 are now in the introduction. We agree with your comment on the shear in the lower atmosphere but for the studied case observations and model agree that during the evening a low-level jet was generated at the foothills of the Pyrenees due to the combined effect of the eastern large-scale wind and the mountain-plain circulation. This is further described in section 3.

Furthermore, a clear research question needs to be formulated, .e.g. how do turbulence characteristics change during AT and in the stable boundary layer? Or, what is the relation between turbulence characteristics and stability and/or energy balance at the Earth's surface?

The scientific questions are already listed on page 2 of this document.

3. Section 2

The use of UAV measurement to derive turbulence quantities in the boundary layer is a promising approach. As the technique is still fairly new and not every reader is familiar with UAV measurements, I would wish for a rather detailed description of the method and especially giving information about flight legs (length, duration, ground speed) ideally including clear figures or a scheme of the conducted flights. At the moment, some information about the flight legs are given at various parts in the manuscript which makes it a little confusing (e.g. l. 313).

We agree with the referee that all information on the M^2AV should be in the same place. It is now all included in the Section "Field site and instrumentation". The figure illustrating the flight path is now included in a topographic map used for the simulations, as also suggested by another referee. The information about the UAV is now as follows:

"The M^2AV is an unmanned aerial vehicle with a wing span of 2 m and a weight of 6 kg. It is started and landed manually, and can be fully controlled during the mission by an autopilot system. For this case study, most ascents and descents as well as the race track pattern with straight horizontal legs were flown with the autopilot. The flight track is shown in Fig.1b. The M^2AV is equipped with a miniaturized turbulence measurement payload comprising a 5-hole probe for deriving the angle of attack and sideslip in the aerodynamic coordinate system. The data can then be converted to the 3D wind vector in the geodetic coordinate system using precise information on position and attitude of the aircraft obtained by GPS and an inertial measurement unit (IMU). The application of the method for unmanned aircraft is demonstrated by van den Kroonenberg et al. (2008). Further, the payload comprises a slow and accurate as well as a fast temperature sensor, and a capacitive humidity sensor (Martin et al., 2011). The parameters measured by the M^2AV (profiles of temperature, humidity, wind speed and wind direction, as well as turbulent fluxes of sensible heat) have been validated extensively against other airborne data sets (Spiess et al., 2007), as well as in situ meteorological tower and remote sensing observations (Martin et al., 2011; Cuxart et al., 2012). The system has been deployed for high resolution atmospheric profiling (Martin et al., 2011; Jonassen et al., 2015) and for deriving turbulent parameters (van den Kroonenberg et al., 2012; Martin et al., 2014; Martin and Bange, 2014) worldwide at various locations.

The analyses focus on a case study for 2 July 2011. For this study, the M^{2}AV performed vertical profiles, and followed race track patterns of about 1 km length for deriving turbulent parameters of the 3D wind vector. The profiles were performed with an ascent rate of about 3.5 m s^{-1}, the descent rate was about 8 m s^{-1}. The race track pattern consisted of three legs at one altitude (300 m) oriented in East-West and West-East direction, then three legs at a second altitude (250 m) and two legs at a third altitude (200 m). The same pattern was repeated three times for each flight. Note that the time for one flight leg is only about 45 s at the aircraft speed of 22 m s^{-1}, therefore providing an instantaneous snapshot of the turbulence properties. The same flight track was employed during four distinct flights starting around 1430 UTC, 1630, 1830 and 2030 UTC. A single flight lasted approximately 40 min. Only Flight 2 was shorter due to a failure of the autopilot around 20 min after takeoff. The exact times for takeoff and landing are given in Table 1. During the last flight, the altitudes for the race track pattern were reduced by 50 m in response to the lower ABL height."

Also the impact of the different filtering methods could be illustrated using figures. What are these slowly changing structures? Gravity waves require stable stratification? Is this given?

To avoid confusion, we just present the method that was used for data processing in the revised version:

"Visual inspection of the time series of v' and w' revealed several cases with wave like slowly changing structures (wavelength around 2 km) of relatively large amplitude compared to the fast fluctuations. They have a high impact on the variance calculation. The variances of wind speed σ_v^2 and σ_w^2 were calculated by employing a high pass Butterworth filter of third order, with different cutoff frequencies tested, which resulted in more realistic values than linear detrending. By the high pass filtering technique, these longwave features disappeared. In any case, the flight legs were not long enough for obtaining statistically relevant information about wavelengths larger than the double of the flight leg. Therefore, a 0.01 Hz high pass filtering was finally applied in this case study, instead of removal of a linear trend from the wind components."

About your question of the presence of gravity waves, during the first 3 flights, stably stratified conditions were not present yet in the ABL (they are during the afternoon and early evening transition, when surface cooling starts) and therefore no ambient conditions were favourable to develop gravity waves in the ABL. However, during the last flight (about 2100 UTC) cooling is stronger and Román-Cascón et al. (2015) found gravity waves between 2030-2130 UTC close to the surface (they are analysing surface pressure and other atmospheric magnitudes up to 2 m AGL). Figure 8 in Román-Cascón et al. (2015) (vertical profile of the observed Brunt-Vaisala frequency) shows that gravity waves can be found up to about 100 m AGL but not at higher levels (where the M^2AV sampled). Later on (from 2100 UTC to midnight), gravity waves could be found but the presence of the LLJ does not allow a strong nocturnal cooling (strongly stably stratified conditions), departing from the favourable conditions for the development of the gravity waves.

The model is not able to capture these observed gravity waves (Román-Cascón et al. , 2015) since they are attached to the ground. In fact, the model does not see this maximum of wind at 2 m AGL that they report since the first grid level is at 1.5 m. A comment on the presence of gravity waves is included in section 4, when the description of the processes during the studied transition is made. We do not consider that the possible presence of Internal Gravity may alter the discussion on the other relevant issues treated in the paper and we just mention them and refer to (Román-Cascón et al. , 2015) for further information.

The contents of Figure 1 which aims to give and overview of the measurement area are hard to see. I recommend providing two subfigures, one giving a general overview of the area including UHF site 1 and 2 and the launch site of the frequent radiosondes and the UAVS and the other one zooming in on the UAV site showing the flight tracks.

We changed former figure 1 to a new one with two panels. One is showing the topography as represented in the model and the other one the observation sites and the flight tracks. We think that now the sampled area is better described with the plots and the corresponding comments in section 2.

As mentioned above the section about low-level jets is out of place here and should be moved to the introduction.

We agree with your comment and we have re-structured the manuscript (see above), and the LLJ section is now part of the introduction, as suggested.

4. Analysis of the measurements Sections 3 and 4 should be reorganized.

We agree with the referee, see new structure presented above.

In the following I propose a possible outline for an analysis:

- The detailed description of synoptic conditions even including a figure is not necessary for the analysis. In my opinion, a brief narrative description of synoptic conditions is sufficient.

We agree with your comment and we have removed the figure of the synoptic conditions. The description of the synoptic conditions is made in section 3.

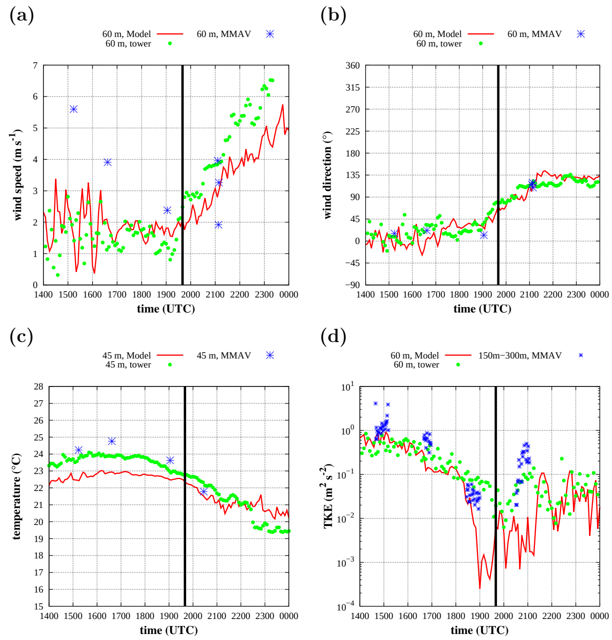


Figure 3. Modelled and observed time series for (a) wind speed (in $\mathrm{m\,s^{-1}}$), (b) wind direction (in $^{\circ}$), (c) temperature (in $^{\circ}$C) and (d) TKE (in $\mathrm{m^2\,s^{-2}}$) from 15:00 UTC until midnight on 2 July 2011. Tower observations are in green circles, model results in red lines and M^{2}AV data in blue asterisks. The temporal evolution of wind and temperature data from M^{2}AV is constructed with the values of the vertical profiles taken at the corresponding height of the tower measurements. For TKE, all the M^{2}AV legs where TKE is derived, at 150 m, 200 m, 250 m and 300 m AGL, are included in the plot. The time of sunset is represented with a black vertical line.

- As AT is defined via the surface sensible heat flux, the authors could start with showing a time series of the energy balance components at the Earth's surface. At the moment it is not quite clear which of the flights are within AT and which are not.

We agree with your comment. The time series of the model results, together with the M^{2}AV and the 60 m tower observations, are shown in the new figure 3 (see below). The sunset time is also indicated. By inspecting the temporal evolution of the wind, temperature or TKE it is possible to characterise the period when the M^{2}AV flights were performed and we think that it is not necessary to add the observed energy balance components at the Earth's surface.

- To show the evolution of the boundary layer during the afternoon and evening, the authors could show profiles of potential temperature and horizontal wind for specific times. Instead of showing profiles separately for each instrument, the different instruments (UAV, UHF and frequent radiosondes) could be shown together in one plot. This would allow to compare the instruments as well as eventual spatial differences. So, Figs. 3-8 could be combined in a few precise figures combining the information.

We composed new figures as suggested. For each M^{2}AV flight time, subplots are shown that include data of UAV, UHF, radiosondes, tower, and numerical simulations. We did this for potential temperature, horizontal wind speed, and wind direction. See below new figure 5.

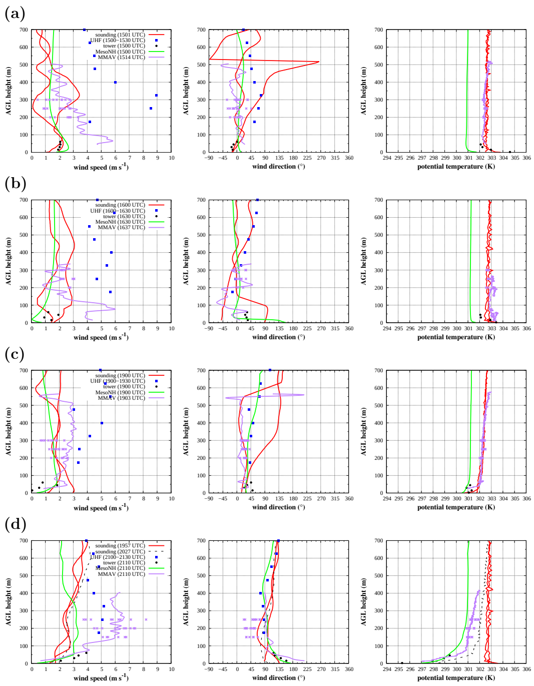


Figure 5. Vertical profiles of wind direction (in °) on the left, wind speed (in m s^{-1}) in the center and potential temperature (in K) on the right, from M^{2}AV (in violet) for the four flights of 2 July 2011: (a) 1500, (b) 1630, (c) 1900 and (d) 2110 UTC. Vertical lines and dots correspond to instantaneous values from the vertical profiles and to mean values for each horizontal leg, respectively. M^{2}AV data are compared against instantaneous observations from UHF (blue squares), tower (black dots), and frequent (red) and standard soundings (black) together with mesoscale simulation results (green). The legend indicates the corresponding times to each data source.

For better visibility wind direction could be plotted as dots or even as vectors (Figure 8 is a mess). Also, the data should be quality checked and outliers should be removed, e.g. for the frequent radiosondes. It is hard to believe that the wind speed of more than 10 m/s near the ground measured by the UAV at 2027 UTC is realistic, given that it is not measured by any of the other instruments.
As mentioned above, these plots are now put together in the new figure 5. We agree that the M^{2}AV observed wind speed at 2027 UTC seems not realistic in comparison to the sounding and UHF observations, although the wind direction is comparable to the other sources of data. Therefore, only the last M^{2}AV profile at 2110 UTC is used (new figure 5d) where the observations are comparable to the other sources of data and the model results.

Wind speed measured during the ascent and descent of the frequent radiosondes vary a lot, which suggests an impact of vertical motion of the sonde on the measurements. This should be discussed.

We included in the text:

"Differences between profiles of an ascent and consecutive descent might arise from a temporal development of the atmosphere, with a typical time span of 10 min between half of the ascent and half of the descent, and the different location (up to 10 km from launching to landing site during BLLAST). In contrast to the standard radiosonde technique, the use of double balloon systems tends to stabilize the ascent of the payload, as it reduces pendulum motion (**?**)."

- When showing profiles of potential temperature the evolution of the boundary layer height zi could be illustrated.

During the afternoon and evening transitions z_i changes as time progresses and for this reason the height where M^2AV sampled is indicated with "m AGL". More information about the evolution of z_i for the different IOPs during BLLAST are shown in Lothon et al. (2014).

Line 183-185: what does it mean that the residual layer is lower than the ABL top? Normally, the top of the residual layers coincides with the top of the former ABL top. The bottom of the residual layer is indicated by the top of the surface inversion

We agree that the text was unclear and this sentence is removed in the revised version. The height of the residual layer and the depth of the surface inversion are clearly seen in Figure 5.

- The evolution of a low-level jet could be shown in this paragraph as well where the mean conditions are analysed. In this context the wind profiles should be checked for the criterions used to identify low-level jets (e.g. Stull, 1988), as a wind speed of 6 m/s is not very strong.

The description of the observed low-level jet features is made now in section 4, together with the mesoscale simulation results. We agree that a wind speed of 6 m s^{-1} is not very strong. However, we explain now in the introduction that we use the criteria of Baas et al. (2009), where a LLJ is defined according to the wind speed difference between the maximum wind speed and the minimum wind speed above:

"There are different criteria in the literature for identifying a wind profile as LLJ, e.g. taking into account the maximum wind speed, or a specific decrease of the wind speed above the altitude of the maximum wind speed (Bonner, 1968; Banta, 2008). In this article the definition of Baas et al. (2009) is applied, with the following LLJ criteria: the difference of the wind speed between the maximum and the closest minimum above has to exceed 2 m s^{-1} and has to be larger than 25% of the maximum wind speed. These criteria have to be met for at least 30 min in time."

Fig. 11-13 should be optimized using the same scale on the y-axis and the some color scale. Also Fig. 12 and 13 should be combined. Why do the authors not show measurement of the UHF at site 2 for the whole night? The differences between the various wind speed profiles should be discussed more thoroughly. For me the LLJ establishes only after midnight. Around 2000 UTC there is much temporal variation of the wind speed (e.g. Figure 12) ? quite similar to the period between 1000 to 1900 UTC.

These figures are plotted with the same color scale and vertical axis in the new figure 4. Besides, the same plot is made with the mesoscale model results, indicating that both UHF and model are giving similar patterns. The attention is now focused on the period from 1500 to 0000 UTC on 2 July 2011 and all the temporal series shown in the manuscript are now within this interval.

- The figure of TKE profiles should be improved as it is hard to see the different dots.

We agree with the referee. The figure was replaced by a new figure, including also TKE from tower observations and numerical simulations for the same times as the M^{2}AV flights.

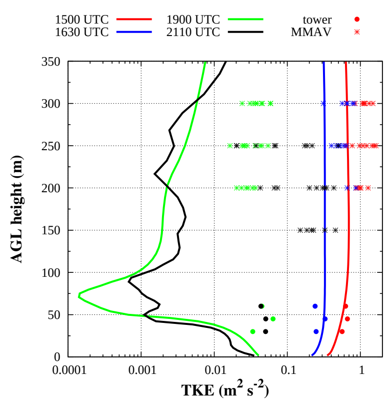


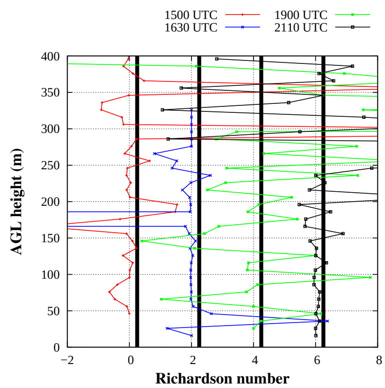
Figure 6. Vertical profiles of the simulated TKE (in lines) at different instants during the M^{2}AV flights (see legend). Tower (in dots) and M^{2}AV (in asterisk) observations are also included. Note the logarithmic scale on the x-axis.

It might also be interesting for the reader to see a time series of instantaneous wind measurements which were used for TKE calculation. The turbulence characteristics could then be described relating them to the different mean conditions in the ABL, e.g. to stability, wind speed or the Richardson number.

The time series of v' and w' revealed several cases with wave like slowly changing structures (wavelength around 2 km) of relatively large amplitude compared to the fast fluctuations. They have a high impact on the variance calculation. The variances of wind speed σ_v^2 and σ_w^2 were calculated by employing a high pass Butterworth filter of third order, with different cutoff frequencies tested, which resulted in more realistic values than linear detrending. By the high pass filtering technique, these longwave features disappeared. In any case, the flight legs were not long enough for obtaining statistically relevant information about wavelengths larger than the double of the flight leg. Therefore, a 0.01 Hz high pass filtering was finally applied in this case study, instead of removal of a linear trend from the wind components.

Currently, the authors calculate the Richardson number from the race track patterns. Why do they not use the profiles of wind and temperature?

We agree with your point that Ri could be also computed from the M^2AV profiles to have a better description of the turbulence in the lower ABL (see figure below). Nevertheless, in the current version of the manuscript the observed vertical profiles from TKE (tower and M^2AV) and those obtained from the model outputs are further described (see section 5) and for this reason the Ri number to identify when and where turbulence takes places is not longer used. The definition of Ri is removed from old section 2 and the lasts sentences of sections 4.1 and 4.2 are adapted to describe the turbulence without the use of Ri (and in some cases it says Ri, not shown).



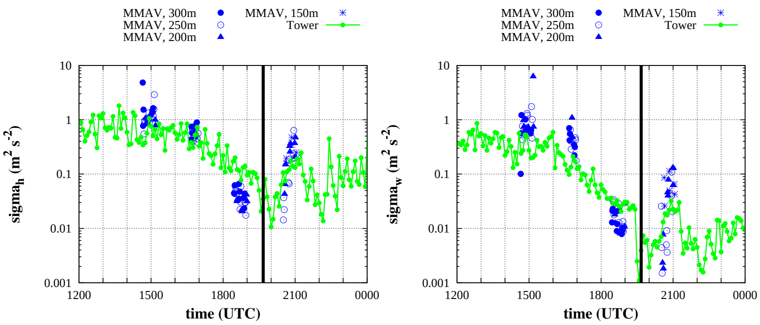
Profiles of Ri computed from the M^2AV profiles. To have a better representation, the x-axis is shifted by 2 to the right every instant. The vertical black line indicated Ric=0.25.

The turbulence characteristics could also be related to the surface fluxes.

We agree with your point. The M^2AV TKE is now compared to model outputs and tower observations (see new figure 6 showed above).

Additionally, it would be helpful to provide sigma-w and sigma-u separately in order to see what causes the change in anisotropy sigma-w decrease or sigma-v increase or vice versa. This allows also to see if sigma-w becomes too small at all.

Find below a time series of sigma-u and sigma-w separately computed from M^2AV and the 60 m tower observations. It is seen that the increase of the anisotropy after sunset is related to a decrease of sigma-w. This figure is not included in the current version of the manuscript but this result is mentioned in section 5.



sigma-u and sigma-w separately computed from M^{2}AV and the 60 m tower observations.

- Why do the authors not use information on turbulence from the UHF? It would be interesting to compare them to the turbulence parameters derived from the UAV. Also the UHF data are available during the night and could provide turbulence parameters during the time of the fully developed low-level jet.

UHF provides a qualitative estimation of turbulence, but not TKE to compare to. Data from the 60 m tower and mesoscale simulation are now used instead.

5. Discussion and conclusions

The discussion section could include differences in mean profiles derived with different instruments, problems with the UAV measurement when deriving turbulence quantities, on the dependency of TKE to mean conditions on spatial inhomogeneity in atmospheric conditions, etc.

Differences in mean profiles and turbulence properties are now discussed in the manuscript based on a larger data set of UAV, tower, radiosonde, frequent radiosonde, UHF data, and numerical simulations. The organization of the flow at lower levels is now further explored from the mesoscale simulation with a special attention to the locally-generated winds that are specially important in such a complex terrain region. Besides, problems with the UAV measurement when deriving turbulence quantities are also mentioned. To improve the understanding of anisotropy probably flights well defined along and across the turbulent elongated structures of longer track would bring much more supplementary information. To do so, efficient use of available information should be made beforehand and determine the high of the flight to use the batteries as optimally as possible to get long tracks. This is now mentioned in conclusions as a suggestion of further work.

The conclusions should be precise and pick up the research questions formulated in the introduction. The authors could also combine the Discussion and Conclusion section.

The conclusion section is re-written to incorporate the new analysis (extra sources of data and model outputs). The main findings of the work are:

(1) during the afternoon transition, TKE decreases as time progresses and it is minimum close to sunset. Afterwards it increases due to the presence of a LLJ.
(2) the shear generated by the presence of a LLJ is the responsible of the increase of the anisotropy during the evening transition, being larger than if no LLJ is present.
(3) the anisotropy ratio computed from difference sources of data (model and observations) shows that A depends on the scale (spatial and temporal) of motions included in the data.

6. Literature
The reference list should be adapted more precisely to the research done in the manuscript.
We agree that the reference list in the previous version of the manuscript could be improved substantially. Since the introduction is re-written, the references are also updated, for instance those related to turbulence observations, isotropy conditions and studies of LLJ, in all cases from the observation and modelling perspectives.

7. The quality of the figures has to be improved significantly. At the moment, they are not sufficient for publication in a peer-reviewed journal.
We agree with your comments. Now all figures are improved, adding the new analysis considering extra observations and the mesoscale simulations results and also taking into account the reviewers' suggestions.

8. As the manuscript deals with observations sensitive to the time in relation to sunrise, I highly recommend using local time instead of UTC.
We explain why we prefer to use UTC instead of the official time:
"Throughout the article, times are given in UTC, as the study area has the same longitude as Greenwich and therefore the same solar time. The official local time is UTC + 2 h."

8 Answers to minor comments

Introduction
Lines 20 to 23: The surface sensible heat flux normally decreases shortly after noon. I.e., it is more than 160 min until sunset.
You are right. We changed the text to:
"The afternoon transition (AT) is defined differently in the literature, depending e.g. on the observational techniques and available data sets. Lothon et al. (2014) use the definition of Nadeau et al. (2011) for the BLLAST (Boundary-Layer Late Afternoon and Sunset Turbulence) experiment, which is also used in this study. According to this definition, the AT begins when the surface sen-

sible heat flux starts to decrease, and ends when the surface sensible heat flux becomes negative, corresponding to the time before sunset. Another definition of the afternoon-evening transition is based on the time from the beginning of a decrease in wind speed variance until the beginning of the building of a temperature inversion, which takes around 160 min during summer (Busse and Knupp, 2012)."

Line 25: why does the mixing ratio increase at this time?

The phenomenon is described in detail in Fitzjarrald and Lala (1989). He explains it as the convergence of turbulent moisture fluxes in the surface layer, with a simultaneous heat flux divergence. An easy explanation is that vegetation stops photosynthesis and starts breathing around sunset. As we do not at all discuss humidity in the article, we prefer not to explain the phenomenon in detail, but we added another reference in the text:

"The transition usually includes several consecutive changes of near surface parameters: a decrease of the vertical and horizontal wind speed variance, temperature, thermal fluctuations, and wind speed, as well as a rapid increase of the mixing ratio (Fitzjarrald and Lala, 1989), and finally the formation of a temperature inversion, e.g. Acevedo and Fitzjarrald (2001); Busse and Knupp (2012); **?**."

Lines 31-35: Why do you mention turbulent flux profiles in Oct and Febr at all? Additionally, BLLAST was in summer.

We agree with the referee the sentence is now removed.

Section 2

Refer to the launching time: is this valid for the descents, too?

The time of the soundings refer to launching time. Regarding the soundings on site 1, they reach levels of about 12 km AGL and the sonde was lost afterwards. As a result, only ascents are taken in the analysis here. On the other hand, frequent radiosoundings on site 2 reach typically heights of about 2 km with vertical wind speeds of 6 m s^{-1} for the ascent and 3 m s^{-1} for the descent. Soundings typical last 15 min and for this reason the ascents and descents are both considered in the plots of figure 5, labelled with the same time. This is now stated in section 2.1.

Line 112: what kind of spline function?

We used a linearly interpolated spline function to smooth the data.

Line 115: how good do the flight track and the mean wind direction agree?

The mean wind direction varies around N during the first three flights. The legs of the race track patterns were oriented directly in E-W-direction. This is now better indicated in new figure 1.

Line 121: you mention the method: 'removing the mean value' but you did not discuss the results compared to the other filter methods.

These paragraph is clarified and now read as: "Visual inspection of the time series of $v\prime$ and $w\prime$ revealed several cases with wave like slowly changing structures (wavelength around 2 km) of relatively large amplitude compared to the fast fluctuations. They have a high impact on the variance calculation. The variances of wind speed σ_v^2 and σ_w^2 were calculated by employing a high pass Butterworth filter of third order, with different cutoff frequencies tested, which resulted in more realistic values than linear detrending. By the high pass filtering technique, these longwave features disappeared. In any case, the flight legs were not long enough for obtaining statistically relevant information about wavelengths larger than the double of the flight leg. Therefore, a 0.01 Hz high pass filtering was finally applied in this case study, instead of removal of a linear trend from the wind components."

Line 130: Do you really eliminate advective contributions? Or large scale contributions? A spectral analysis would be helpful which could be compared with the spectrum of the UHF profiler.

You are right. With the method used we eliminate the larger scale contributions. This is now stated (see answer above).

Line 158: Do you need a minimum or just a reduction of the wind speed?

The LLJ definition according to Baas et al. (2009) uses a local minimum.

There are a lot of typos: attitude instead of altitude, temperatur instead of temperature, as instead of at (line 77)

We corrected the typo in temperature; however, it is really our intention to talk about the "attitude" of the aircraft (roll, pitch, yaw), not the altitude, and we use the "second balloon as a parachute", we do not employ a parachute for the frequent radiosonde technique.

Section 4

Line 199: How heterogeneous are the surface conditions?

Works of Lothon et al. (2014) and Cuxart et al. (2016) show that the surface characteristics and the topography are the responsible of the strong heterogeneity of surface fluxes and surface temperature sampled during the BLLAST campaign. The references to these works are now included in section 2.1.

Line 257-260: Why not use TKE in combination of isolines of the wind speed. This allows seeing directly the zones with strong wind shear and high TKE.

Figure 6 is improved (now tower and model results are used) and together with Figure 5 it is clearly seen the evolution of TKE together with the wind speed and direction.

Line 265: What means 'the lowest value of A'?

We now use the word "anisotropy ratio" instead of the notion A.

Figure 3 and 4: Either you should use temperature or potential temperature but not both. I would prefer potential temperature (in Figure 4, too).

We now use a plot combining data of different measurement systems, and use potential temperature. See new figure 5.

Section 5

Line 340: 'An LLJ increases the horizontal wind speed': the LLJ is the horizontal wind speed!

That sentence was confusing. The description of the evolution of the LLJ is now further explained in section 4 with the extra data analysis and model results.

Line 370: When you say that the 'LLJ was distributed inhomogeneously on a small scale of few km' it would be interesting to know why. There must be a lot of divergence and convergence. Did you see that in the UAV and/or UHF data?

The mesoscale simulation is now used to better describe the spatial distribution of the LLJ. See for instance new section 4 and figure 2.

9 answers to referee 3

The authors would like to thank the anonymous referee for his/her suggestions. According to your and the other reviewers requests, a further analysis of the BLLAST observations during the afternoon and evening transition has been made for 2 July 2011. Now UHF, soundings and tower measurements (all of them in site 1) are taken, apart from observations from M^2AV (site 1) and frequent soundings (site 2) already shown in the previous version of the manuscript. Furthermore, results from high-resolution mesoscale simulations are used to better describe the evolution of the LLJ and the anisotropy ratio during the evening transition of 2 July 2011 in Lannemezan. As a result, find below the main changes in the revised version of the manuscript, some of them directly answering your requests.

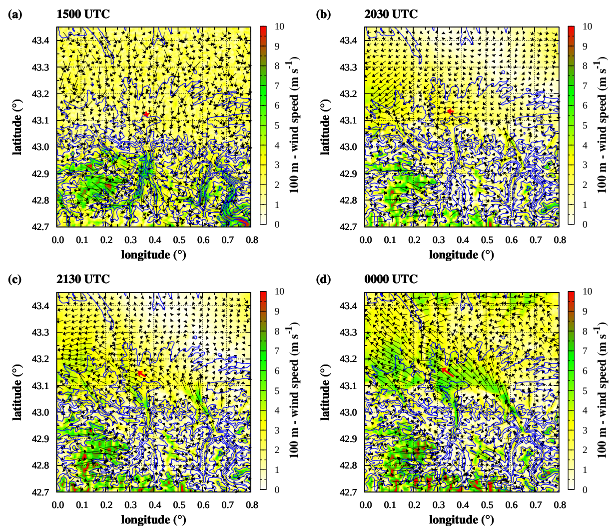


Figure 2. Modelled 100 m AGL wind vectors together with wind speed (in colours) and the topography lines (in blue) at different instants (a) 1500 UTC, (b) 2030 UTC, (c) 2130 UTC, (d) 0000 UTC. The 60 m wind vector observed by the tower is plotted with a red arrow.

- The 3 new co-authors (M.A. Jiménez, J. Cuxart and D. Martínez) have performed the numerical simulations and data analysis, apart from contributing to the discussion of the new results.

- The manuscript has a different organization. The introduction is re-written according to the reviewers' requests (now the turbulence and anisotropy during the evening transition is described, as well as the low-level jet, LLJ). The next section is devoted to the observations and model setup. The atmospheric situation and the features of the observed LLJ are described in sections 3 and 4, respectively, and in section 5 the anisotropy is evaluated. Finally, the discussion of the results is shown in section 6 and the conclusions in section 7.

- The title has now changed into "A study of local turbulence and anisotropy during the afternoon and evening transition with an unmanned aerial system and a mesoscale simulation"

Find below the answer to your requests point by point. The text from the review is given in italic letters, the answers are provided in normal letters. Changes to the text of the manuscript are indicated in quotation marks.

10 Answers to general comments

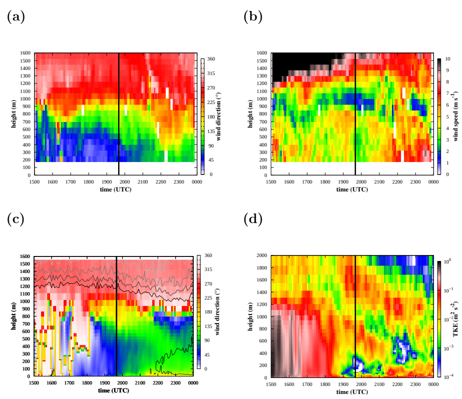
The afternoon-evening transition and anisotropy still need to be better understood so that they can be accurately represented in numerical models, so the topic is an important one and great contri-

butions could be made. However, the presented analysis raises questions as to the methodology and significance of the results. As the authors claim themselves, many of the TKE estimates are not statistically significant. As such, it is expected that the anisotropy results are not statistically significant in of themselves, as well.

M^{2}AV observations of turbulence after sunset are only available for the day studied here (2 July, IOP10 of the BLLAST campaign). For this reason the data analysis is limited to 2 July. Nevertheless, the results obtained here from M^{2}AV are now compared to those reported from other IOPs. It is found that during the IOPs with clear skies and weak wind conditions, the anisotropy ratio increases during the evening transition, but this ratio increases even more when the LLJ is present (only for IOP10, 2 July). Furthermore, TKE and anisotropy data derived from M^{2}AV are now compared to other data sources (tower and mesoscale simulations) and in all cases similar patterns are found.

Additionally, the analysis of the low-level jet is not adequate. Based on the data presented, it appears as though the LLJ itself did not develop until after the last flight was finished, and the main claim about a LLJ being present appears from suspicious data from the UAS itself that needs to be corroborated. Every major topic within this study has significant flaws, degrading the importance of the results.

Now section 4 is devoted to explain the observed LLJ through the mesoscale simulation results and a deeper analysis of soundings, UHF and tower data. According to the new Figure 4 (see below), UHF data indicates that the LLJ started at the begining of the last M^{2}AV flight and new Figure 5 shows the agreement of the different sources of data that are now analysed.



new Figure 4. Temporal evolution of the observed (UHF) and modelled vertical profiles for (a) UHF wind direction (in °), (b) UHF wind speed (in $\mathrm{m\,s^{-1}}$), (c) MesoNH wind direction (in colours) and wind speed (in lines, for values $\geq 4\,\mathrm{m\,s^{-1}}$, contour interval = $2\,\mathrm{m\,s^{-1}}$) and (d) MesoNH TKE (in $\mathrm{m^2\,s^{-2}}$). The time of sunset is represented with a black vertical line.

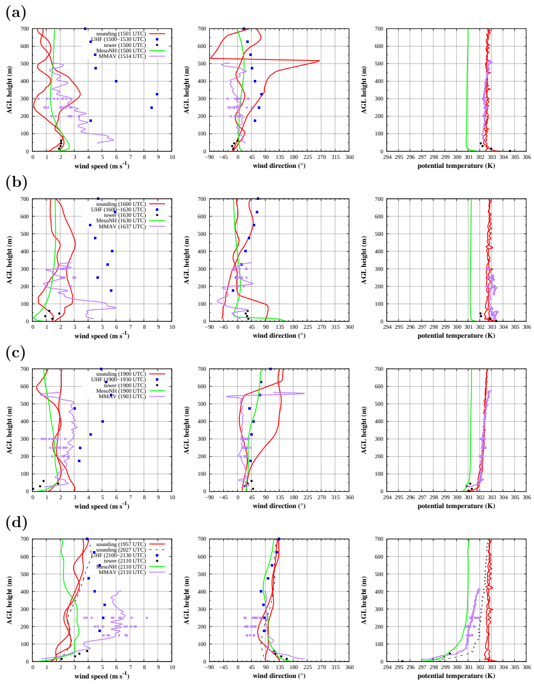


Figure 5. Vertical profiles of wind direction (in $^\circ$) on the left, wind speed (in $\mathrm{m\,s^{-1}}$) in the center and potential temperature (in K) on the right, from $\mathrm{M^2AV}$ (in violet) for the four flights of 2 July 2011: (a) 1500, (b) 1630, (c) 1900 and (d) 2110 UTC. Vertical lines and dots correspond to instantaneous values from the vertical profiles and to mean values for each horizontal leg, respectively. $\mathrm{M^2AV}$ data are compared against instantaneous observations from UHF (blue squares), tower (black dots), and frequent (red) and standard soundings (black) together with mesoscale simulation results (green). Legend indicates the corresponding times to each data source.

Additionally, much of the paper needs to be rewritten. The section on the M2AV data processing is confusing, as it presents multiple ways in which the data could be processed but ultimately states that only one of the methods was used.

We agree with your point. We completely revised the structure of the manuscript. Now it is as follows:

1. Introduction

2. Observations and model setup

2.1 Field site and instrumentation

2.2 $\mathrm{M^2AV}$ data processing

2.3 Model setup

3. Atmospheric situation

4. The nocturnal LLJ as observed and modelled

5. TKE and anisotropy during the afternoon-evening transition

6. Discussion

6.1 Turbulence properties

6.2 Low-level jet as source of enhanced turbulence

7. Conclusions

Particularly, the data processing in section 2.2 has been changed to:

"Visual inspection of the time series of $v\prime$ and $w\prime$ revealed several cases with wave like slowly changing structures (wavelength around 2 km) of relatively large amplitude compared to the fast fluctuations. They have a high impact on the variance calculation. The variances of wind speed σ_v^2 and σ_w^2 were calculated by employing a high pass Butterworth filter of third order, with different cutoff frequencies tested, which resulted in more realistic values than linear detrending. By the high pass filtering technique, these longwave features disappeared. In any case, the flight legs were not long enough for obtaining statistically relevant information about wavelengths larger than the double of the flight leg. Therefore, a 0.01 Hz high pass filtering was finally applied in this case study, instead of removal of a linear trend from the wind components."

Within the results section, too much text (and figures) are dedicated to describing how the mean profiles of wind and temperature changed over time and how they were observed by different instrumentation. Instead, the authors should dedicate more time and figures to the anisotropy discussion, as that (by the title) seems to be the focus of the paper.

We agree with your point. Now a deeper analysis on the turbulence and anisotropy is made in sections 5 and 6, as well as the comparison of the M^{2}AV results to those obtained from the 60 m tower and the model. Besides, the M^{2}AV profiles are compared to those sampled by tower, UHF and soundings and those obtained from the model (see new Figure 5 above). It is found that the different sources of data are able to reproduce similar patterns although the spatial and temporal scales of the eddies depend on the sources of data.

It might be helpful to include analysis of the spectra, especially since the authors mention that wave-like features were observed.

The inspection of the spectra for the flights shows that, as stratification develops in the evening, there is more energy at scales below 2 km, but there is no hint of the expected shape of the spectrum in the presence of gravity waves. Román-Cascón et al. (2015) indicated the likely presence of gravity waves that evening, but this is not confirmed by our data at the levels where M^{2}AV was flown. Therefore inspection of the spectra is inconclusive and we prefer to refrain to develop this point in the manuscript.

The conclusions section needs to be expanded upon to focus on the main results of the study.

The conclusion section is re-written to incorporate the new analyses (extra sources of data and model outputs). The main findings of the work are:

(1) during the afternoon transition, TKE decreases as time progresses and it is minimum close to sunset. Afterwards it increases due to the presence of a LLJ.

(2) the shear generated by the presence of a LLJ is responsible for the increase of the anisotropy during the evening transition, being larger than if no LLJ is present.

(3) the anisotropy ratio A computed from difference sources of data (model and observations) shows that A depends on the scale (spatial and temporal) of motions included in the data.

Throughout the whole paper, the authors need to more clearly define what the motivation for the study and their significant findings as they relate to previous studies.

Previous works devoted to turbulence measurements, anisotropy and LLJ are described in the introduction to properly describe the state of the art. Besides, the scientific questions addressed in this work are now stated at the end of the introduction. M^{2}AV measurements taken during the BLLAST experimental field campaign, together with other sources of data and results from a mesoscale simulation, are used in this work to further understand the processes involved during the afternoon and evening transitions with special attention to:

(1) characterize the evolution of the ABL, specially in the lower levels (up to 400 m AGL),

(2) evaluate the changes in the turbulent scales and their implication in the isotropy and

(3) study the influence of a nocturnal low-level jet on the turbulence properties.

Considering all of the aforementioned problems with the manuscript, I recommend that the manuscript is not acceptable for publication in ACP. However, I recommend that the authors continue to strengthen their analysis of the data, and rewrite/restructure much of the paper for resubmission (these changes to be too significant for 'major revisions').

We improved the manuscript by analyzing additional data sets and we have also incorporated the results from a mesoscale simulation. The whole manuscript was revised and re-structured to strengthen the M^{2}AV findings.

11 Answers to specific comments

In addition to revising the paper to address the aforementioned issues, the author could significantly improve the manuscript by addressing the following specific concerns: Abstract:

a) Line 4: Define BLLAST within the abstract.

ok

b) Line 5: Either provide flight times in UTC, or sunset in local time (and throughout the entire paper, stick to one convention).

We use UTC throughout the text, as the longitude of the field site is the same as of Greenwich. Therefore, solar time is the same as UTC. We comment on this in the revised manuscript.

c) Line 10: Low-level jet is typically not capitalized

We changed to "low-level jet" throughout the text.

d) In general: Provide the main results/conclusions of the study within the abstract.

We have included in the abstract that the TKE derived from M^2AV is similar to the one obtained from other sources of data (UHF, sounding, 60 m tower and mesoscale simulations). Besides, all sources present an increase of anisotropy after sunset, related to the presence of a low-level jet. The differences of the values of the anisotropy ratio are linked to the different spatial and temporal scales sampled by the 60 m tower, M^2AV and model.

Introduction: e) Line 19: It is stated that there are different definitions for the afternoon-evening transition, but only one is given. Please indicate if the provided definition is the one used here (as the reader assumes it is). It could also be useful to provide an alternative definition, and why it would be used differently.

We now give the definition used in the study, and present an alternative definition:

"The afternoon-evening transition of the atmospheric boundary layer (ABL) describes the processes converting a convective ABL into a stably stratified nocturnal ABL. The afternoon transition (AT) is defined differently in the literature, depending e.g. on the observational techniques and available data sets. Lothon et al. (2014) use the definition of Nadeau et al. (2011) for the BLLAST (Boundary-Layer Late Afternoon and Sunset Turbulence) experiment, which is also used in this study. According to this definition, the AT begins when the surface sensible heat flux starts to decrease, and ends when the surface sensible heat flux becomes negative, corresponding to the time before sunset. Another definition of the afternoon-evening transition is based on the time from the beginning of a decrease in wind speed variance until the beginning of the building of a temperature inversion, which takes around 160 min during summer (Busse and Knupp, 2012)."

f) Line 39 (and elsewhere): It is best to use 'larger' rather than 'stronger'.

We changed as suggested.

Also, the statement made here is not always true during unstable stratification. During daytime when the mean wind speed is large, the variance in the horizontal wind is often greater than the variance in the vertical. So please rephrase this statement.

That's true. We modified the text to:

"During unstable stratification and low wind speed, turbulence is mainly generated by buoyancy induced by heating of the Earth's surface, therefore the variance in the vertical wind component is larger than in the horizontal wind components."

g) Line 50: Change terminology from 'turbulently mixed' to 'convective', as turbulent mixing still continues (albeit weaker) during stably stratified conditions.

Thanks for the suggestion. It was taken into account.

h) Line 55: It would be useful to provide information about how the meteorology of the days in this study and the Darbieu case study is different.

We added in the text:

"The two case studies had similar weather conditions (clear skies, high pressure system nearby western Europe and weak wind speed) but the large-scale wind during the day (1200 UTC) was from W on 20 June and from NE on 2 July.

i) Overall, the introduction needs to be better structured. I suggest using the first paragraph to outline the main features of the AT leaving out the discussion of anisotropy (line 31).

The introduction section is also re-written. Firstly, the processes that take place in the afternoon and evening transitions are introduced, together with previous studies and main findings. Afterwards, the description is centered in describing the main processes related to a low-level jet and finally the eddies and turbulence scales are mentioned to introduce the anisotropy ratio. At the end the main scientific questions are stated.

In general, the first paragraph should be rewritten, as it seems unstructured at the moment.

We rewrote the paragraph, taking into account the comments of the three referees.

In the second paragraph, where the idea of isotropic/anisotropic turbulence is discussed, it would be beneficial to talk about past research and observed anisotropy during these conditions.

We included a paragraph about the LLJ and its influence on wind speed and wind speed variance. The next paragraph is about anisotropy in the atmosphere. Then we added a paragraph about numerical simulations and the capability to reproduce turbulence data.

The last paragraph should also be rewritten, as it does not flow well. I suggest first briefly describing the primary meteorology conditions of the day and the dataset used in this study. At the end of the paragraph, then you can compare and contrast instrumentation, meteorology, etc. between this and the Darbieu study.

As suggested, we conclude the Introduction with an overview of the atmospheric situation of the case study, and compare to the Darbieu conditions. The research questions and the scope of the manuscript are finally given. A more detailed description of this case is made in new section 3.

Background:

j) Line 69: Please provide an explanation for why this day was chosen as a case study.

We changed the text to:

"The analyses focus on a case study for 2 July 2011, for which M^2AV flight data after sunset are available."

k) Line 77: Provide a number for how slowly the second radiosonde typically descended. Also, what was the typical ascension rate? These may be important in determining how well they can resolve a developing inversion.

We added in the text:

"The mean ascent speed of the frequent radiosondes during BLLAST was $5.35\,\mathrm{m\,s^{-1}}$, the mean descent speed was $3.55\,\mathrm{m\,s^{-1}}$."

l) Line 93: State what quality about the M2AV has been validated against other datasets, as this statement seems vague.

We have included in the sentence that the parameters measured by the M^2AV (profiles of temperature, humidity, wind speed and wind direction, as well as turbulent fluxes of sensible heat) have been validated extensitvely against other airborne data sets (Spiess et al., 2007), as well as in situ meteorological tower and remote sensing observations (Martin et al., 2011). These intercomparisons show that M^2AV observations are similar to those observed from other sources, specially during the transitions, when temporal changes of the fields are slower than during the fully developed convective boundary layer.

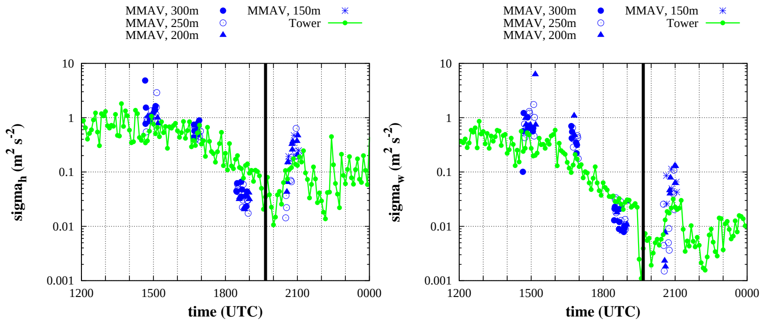
m) Line 120-123: Which method was used for each variance? Why were they not computed using a similar method?

The variances were all computed with the same method. The sentence is misleading, indeed. We changed to:

"The variances of wind speed σ_v^2 and σ_w^2 were calculated by employing a high pass Butterworth filter of third order". These variances are comparable to values computed from the 60 m tower observations (see figure below). It is seen that the increase of the anisotropy after sunset is related to a decrease of sigma-w. As suggested from rewiewer 2, these results are now described in section 5.

n) Line 127: So a high pass filter was used for the calculation of the horizontal wind variance? This sounds opposite of what is stated earlier that the variance values were simply detrended.

A high pass filter is applied, yes. We changed the text to:



sigma-v and sigma-w separately computed from M^2AV and the 60 m tower observations.

"Visual inspection of the time series of v' and w' revealed several cases with wave like slowly changing structures (wavelength around 2 km) of relatively large amplitude compared to the fast fluctuations. They have a high impact on the variance calculation. The variances of wind speed σ_v^2 and σ_w^2 were calculated by employing a high pass Butterworth filter of third order, with different cutoff frequencies tested, which resulted in more realistic values than linear detrending. By the high pass filtering technique, these longwave features disappeared. In any case, the flight legs were not long enough for obtaining statistically relevant information about wavelengths larger than the double of the flight leg. Therefore, a 0.01 Hz high pass filtering was finally applied in this case study, instead of removal of a linear trend from the wind components."

o) Lines 120-133: This section needs to be rewritten, as it is currently very unclear how these calculations were performed differently for v2 and w2.

We agree with the referee that this paragraph is confusing. We omitted the tests we performed, and just present the method that was used in the end (text see above).

p) Line 135: Explain why you assume isotropy in the horizontal direction. With the data from the 5-hole probe, it's possible to calculate u2 as well. Do these values (compared with the v2) support your statement of horizontal isotropy? Previous research shows that this assumption is not valid (see Luhar (2010), Banta et al. (2006) among many others). This may cause a large overestimate of the TKE.

We agree that a sheared boundary layer does not have isotropic turbulence, since the eddies are elongated following the direction of the main wind, as described in Mason and Thomson (1987). However, since the eddies in the transversal direction have scales of the order of the kilometer, which is comparable to the leg size of M^2AV, we may assume that isotropy apply for the sampled scales. This information will be included in the paper.

q) Line 157, 158: Note that the maximum/minimum are local, not absolute.

We changed the text to "The LLJ consists of a local maximum in the vertical profile of horizontal wind speed in the ABL, followed by a local minimum of wind speed."

r) Line 169: Include citation to Bonner (1968) as he was one of the first to come up with criteria for a LLJ to be classified.

Thanks for the suggestion. It is now included in the manuscript.

Atmospheric Situation:

s) Line 185: How is the residual layer lower than the boundary layer height? By definition, during a well-developed convective boundary layer, the temperature inversion is at the top of the ABL. Thus, what here is referred to as the bottom of the residual layer is likely the ABL height.

We agree that the text was unclear and this sentence is removed in the revised version. The height of the residual layer and the depth of the surface inversion are clearly seen in Figure 5.

t) Figure 2: The title and text within Fig. 2 should be in English. It would also be useful to put a symbol on the map marking where BLLAST took place.

We replaced this figure with a topographic map. The BLLAST sites are marked, and the flight path is included.

Results:

u) Section 4.1: This section could be substantially condensed, as the level of detail is not necessary in the context of the rest of the manuscript.

We agree with the suggestion, the section is now much shorter (see the new organization of the sections above).

v) Figure 3 (and in text): Potential temperature is typically provided in K. It would also be helpful to indicate the time of the flights in either the legend or caption, making it easier for the reader to understand the evolution.

We now provide potential temperature in K. The time the data was obtained is now indicated in the legend for each figure. See new figure 5 shown above.

w) Line 198: Move sentence ('Note that : : : may influence the temperature profiles') to after 'They were all obtained during a descent'. Also, indicate how long the descents took? Was it long enough for the boundary layer to evolve during the time, or was stationarity safely assumed?

We added in the description of the M^2AV

"The profiles were performed with an ascent rate of about $3.5\,\mathrm{m\,s^{-1}}$, the descent rate was about $8\,\mathrm{m\,s^{-1}}$."

x) Line 220 and Fig. 5: The 10 m/s wind speed at 40 m seems to be a large outlier, when compared to the rest of the profiles (and the rest of that profile itself). The authors should carefully evaluate this measurement before reporting it, to ensure that it is a valid measurement. It looks like an outlier, and that there may have been an issue with the measurement. With such a large number of instruments taking data during BLLAST, there should be another source that corroborates this measurement.

We removed this particular wind speed profile from the figure, as the other profiles of this flight are in better agreement with the other data sets. However, we consider that we observed a process of changing conditions, as also the wind direction changes dramatically within the same profile. These changes probably occurred on a time scale below minutes, which were not captured by the other observations, and which might be caused by the horizontal translation during the ascent (probing different air masses). See also answer to Referee 2, page 6.

y) Fig 4/6/8: With so much information provided on these plots, it is difficult to see much of the data that is actually being plotted. I suggest only plotting times that are actually used in the analysis (1500-2000) and using a similar color scheme to those used in the M2AV plots, for comparing radiosonde profiles with those of similar times. For example, color the 15:01 radiosonde blue, 19:03 magenta, etc. For those that don't have similar times, use separate colors / line types in the two plots.

We now provide profiles of wind speed, wind direction and potential temperature for each flight separately, including in the same figures also simultaneous data of radiosonde, UHF, tower and numerical simulations (see new figure 5 above).

z) Fig. 8: I suggest changing the x-axis to be similar to that in Fig. 7, to make the plot easier to see. Also, x-label should be 'wind direction' not wind speed!

We now plot all data (tower, radiosonde, UHF, M^{2}AV and numerical simulations) together in one figure for each time of a flight. This makes the data easier to compare.

aa) Fig. 10: Use a line to mark sunset instead of a dot, as a line would be much easier to see.

For all the time series included in the new version of the manuscript a vertical black line indicates the sunset time. See for instance new figures 3 and 7 below.

bb) Section 4.3: Based on the discussion and results in Fig. 11-13, it appears as though the LLJ did not really develop until after 21 UTC. Additionally, the altitude of any developing LLJ appears to be much higher than the flight levels, especially during the 20:30 UTC flight where it is claimed that the flight is affected by a LLJ. As mentioned earlier, the high wind speeds recorded by the M2AV at the low height seem suspicious, and it appears that the claim that the flight was affected by a LLJ is mostly supported by that measurement. In fact, at site 1 (which is closer to the flight track), no LLJ

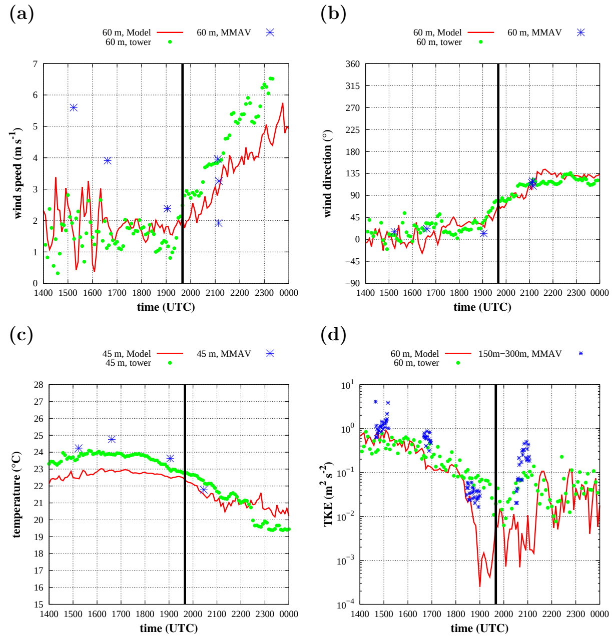


Figure 3. Modelled and observed time series for (a) wind speed (in m s^{-1}), (b) wind direction (in $^\circ$), (c) temperature (in $^\circ$C) and (d) TKE (in m^2 s^{-2}) from 15:00 UTC until midnight on 2 July 2011. Tower observations are in green circles, model results in red lines and M^{2}AV data in blue asterisks. Temporal evolution of wind and temperature data from M^{2}AV is constructed with the values of the vertical profiles taken at the corresponding height of the tower measurements. For TKE, all the M^{2}AV legs where TKE is derived, at 150 m, 200 m, 250 m and 300 m AGL, are included in the plot. The time of sunset is represented with a black vertical line.

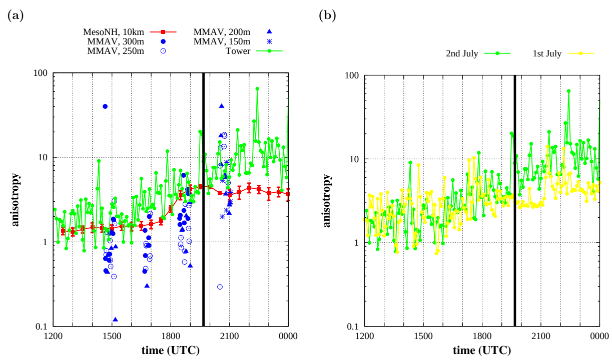


Figure 7. (a) Time series of the anisotropy computed from different sources: M^{2}AV flight observations during the four flights for different heights (in blue); tower measurements at 60 m AGL every 5 min (in green); and model results averaged between 150 m and 300 m AGL to be close to the altitudes of the M^{2}AV observations considering a spatial area of 10 km x 10 km centered at Lannemezan (in red). The time of sunset is represented with a black vertical line. Note the logarithmic scale on the y-axis.

was really observed until after 00 UTC, well after the last flight. With the data presented, I question *whether a LLJ was apparently during the flight periods and affected the results.*

A further inspection of the UHF observations and the model results for Lannemezan show that the initiation of the LLJ took place after 2000 UTC and the last M^2AV flight could sample under the influence of the LLJ. We agree that the vertical profile of wind speed at 20:30 seems not realistic (comparing to other sources of observations and model) and for this reason we have not considered it in the analysis.

Discussion:

cc) The authors correctly identify that the TKE measurements are likely not representative and statistically insignificant. If the TKE measurements are statistically insignificant, than other parameters such as the anisotropy likely are as well, since they are computed from the same variables. The authors should further discuss these limitations as well. These issues are significant, and cast doubt on the conclusions drawn from this study.

We do not consider the TKE measurements as non-significant, we just state that with a flight length of 1 km we are not able to draw conclusions about eddies of sizes larger than 2 km. Anyway the ABL height is below 2 km, which should limit the size of the largest eddies. Both TKE and anisotropy measurements are in good agreement with data from tower and the output of numerical simulations, which now strengthen our observations.

dd) Fig 11-13: Consistently use the same colorbar across all of these images, as it makes it much easier to compare the wind speeds across locations/times.

We replaced the figures with new ones comparing model results and simulations, and used the same colorbars. See new figure 4 showed above.

Conclusions:

ee) The conclusions section is very short and not very informative about the main results of the study. It reads as if it was written in a very rushed manner. I suggest rewriting the section to include the specific results, and relate the results to previous research to highlight any new findings. As it stands now, it reads as if no new results are found, as all of the findings are within previous research to some extent.

The conclusion section is re-written to incorporate the new analyses (additional sources of data and model outputs). The main findings of the work are:

(1) during the afternoon transition, TKE decreases as time progresses and it is minimum close to sunset. Afterwards it increases due to the presence of a LLJ.

(2) the shear generated by the presence of a LLJ is the responsible of the increase of the anisotropy during the evening transition, being larger than if no LLJ is present.

(3) the anisotropy ratio A computed from difference sources of data (model and observations) shows

that A depends on the scale (spatial and temporal) of motions included in the data.

12 Answers to ediorial corrections

a) Line 50: TKE instead of 'turbulent kinetic energy'. b) Line 60: BLLAST already defined earlier in manuscript. Just put 'BLLAST' here. c) Line 70: Change 'to determine' to 'determination of'. d) Line 73: Use 'launched' or 'taken off' instead of 'started'. e) Line 109: Temperature misspelled. f) Line 325/330: Unitalicize m s-1.

We considered all editorial corrections.

Additional references to consider:

Acevedo, O., and D. R. Fitzjarrald. The early evening surface-layer transition: Temporal and spatial variability. J. Atmos. Sci., 58, 2650-2667.

Banta, R. M. Y. L. Pichugina, and W. A. Brewer. Turbulent velocity-variance profiles in the stable boundary layer generated by a nocturnal low-level jet. J. Atmos. Sci., 63, 2700-2719.

Bonner, W. D. Climatology of the low level jet. Mon. Wea. Rev., 96, 833-850.

Luhar, A. K. Estimating variances of horizontal wind fluctuations in stable conditions. Boundary-Layer Meteorol, 135, 301-311.

We thank the referee for the suggestions, and included all references in the manuscript.

13 revised version of the manuscript

Abstract. Observations of turbulence are analyzed for the afternoon and evening transition (AET) during the Boundary-Layer Late Afternoon and Sunset Turbulence (BLLAST) experimental field campaign that took place in Lannemezan (foothills of the Pyrenees) in summer 2011. The case of 2 July is further studied because the turbulence properties of the lower atmosphere (up to 300 m above ground level) were sampled with the Meteorological Mini Aerial Vehicle (M^2AV) from turbulently-mixed to stably-stratified atmospheric conditions. Additionally, data from radiosoundings, 60-m tower and UHF wind profiler were taken together with the model results from a high-resolution mesoscale simulation of this case. Weak large-scale winds and clear sky conditions were present on the studied AET case favouring the development of slope winds and mountain-plain circulations. It is found that during the AET the anisotropy of the turbulent eddies increases as the vertical motions are damped due to the stably-stratified conditions. This effect is enhanced by the formation of a low-level jet after sunset. Finally, the comparison of the anisotropy ratio computed from the different sources of observations allow to determine the most relevant scales of the motion during the AET in such a complex terrain region.

14 Introduction

The afternoon-evening transition (AET) of the atmospheric boundary layer (ABL) involves the processes of converting a convective ABL into a stably-stratified nocturnal ABL. The afternoon transition (AT) and evening transition (ET) are defined differently in the literature, depending, e.g., on the observational techniques and available data sets. Some definitions are based on the surface heat flux evolution (Caughey et al., 1979; Grant, 1997; Beare et al., 2006), as in Lothon et al. (2014), who apply to the BLLAST (Boundary-Layer Late Afternoon and Sunset Turbulence) campaign the definition of Nadeau et al. (2011). The AT begins when the surface heat flux starts to decrease and afterwards, the ET occurs when the surface sensible heat flux becomes negative (close to sunset), with the formation of a temperature inversion above the Earth's surface. This process finishes when a stably-stratified boundary layer is well established.

The AET usually includes several consecutive changes of near surface parameters that have also been used for alternative definitions: a decrease in wind speed (Mahrt, 1981) and temperature is typical, sometimes with a significant change of the wind direction (Stull, 1988), while the mixing ratio within the ABL rapidly increases (Fitzjarrald and Lala, 1989). Besides, the generation of a temperature inversion is responsible for a general drop in horizontal and vertical wind variances (Busse and Knupp, 2012) and thermal fluctuations. Consequently, the decay of the turbulence kinetic energy (TKE) occurs in two stages (Nadeau et al., 2011): a slow decay of TKE during the AT followed by a rapid collapse during the ET. The last stage of this evolution is often complemented with a change in turbulence characteristics like its spectral shape or anisotropy (Darbieu et al., 2015). Under unstable stratification and low wind speed conditions, turbulence is mainly generated by convection, and the variance in the vertical is similar to the one in the horizontal wind components, leading to isotropic turbulence and large values of TKE. Along the AET, turbulence anisotropy may arise from the effect of the thermal stratification that inhibits the extent of the vertical motions.

During the AET spatial inhomogeneities are created, which influence the development of the ABL through the night (Acevedo and Fitzjarrald, 2001; Cuxart et al., 2016). Over complex terrain, temperature gradients at local scales (Conangla and Cuxart, 2006) or larger-scale structures (Bonner, 1968) normally associated with topography are the responsible for the generation of a low-level jet (LLJ), firstly described in Blackadar (1957). This feature is described as a local maximum (Bonner, 1968; Banta, 2008) of wind speed with values $2\,\mathrm{m\,s^{-1}}$ larger than at lower and higher levels (alternatively, an LLJ is also considered if the wind decreases above and below at least 25% of the maximum, as in Baas et al., 2009). LLJs are frequently reported over land (Lenschow et al., 1988), initiated during the AET and reaching near-steady-state conditions at night, when the ABL decouples from the ground as the surface temperature cools down and a temperature inversion layer is formed. Some climatologies report LLJ occurrence between 30 and 60% of all nights (Song et al., 2005; Baas et al., 2009; Emeis, 2014; Lampert et al., 2015), with the exact percentage depending on the local features and ambient conditions. When an LLJ is present, the wind shear between the surface and the wind maximum is enhanced and the corresponding turbulent mixing (Cuxart and Jiménez, 2007; Kallistratova et al., 2013) decreases the intensity of the surface temperature inversion. Besides, the wind shear associated to the LLJ favours the elongation of the eddies along the main wind direction (Mason and Thomson, 1987; Mauritsen and Svensson, 2007), leading to larger values of anisotropy compared to areas where the LLJ is weaker or non existent.

The aim of this work is twofold: first, to evaluate the changes in the turbulence characteristics during the AET for the lower ABL, with special regard to the isotropy of turbulent eddies and, second, to study the influence of a nocturnal LLJ on these turbulence properties. A case from the BLLAST experimental field campaign (Lothon et al., 2014) is taken where clear-sky and weak pressure gradient conditions were present to favour the formation of a mountain-plain circulation, as previously reported in Jiménez and Cuxart (2014). An LLJ was generated during that ET, when turbulent measurements in the lower ABL were done by the Meteorological Mini Aerial Vehicle (M^2AV). The analysis is complemented with other sources of observations (standard and frequent radiosoundings, UHF and 60-m tower) and a high-resolution mesoscale simulation with the MesoNH model (Lafore et al., 1998). A detailed analysis of the increase in anisotropy during the AET for all the IOPs during BLLAST is reported in Canut et al. (2015), but here the case of 2 July 2011 is further studied with the help of M^2AV observations and mesoscale modelling. The manuscript is organized as follows. Section 2 is devoted to the observations and model setup. The organization of the flow at lower levels and a description of the turbulent motions are described in Sec. 3 and Sec. 4 evaluates the measured and modelled anisotropy ratio. Finally, discussion of the results and conclusions are shown in Sec. 5 and 6, respectively.

Throughout the article, times are given in UTC, as the study area has approximately the same longitude as Greenwich and therefore the same solar time. The official local time is UTC + 2 h.

15 Field site, instrumentation and model setup

The BLLAST experimental field campaign, conducted in summer 2011 in Southern France (Fig.1a), was dedicated to study the physical processes that take place in the AT (Lothon et al., 2014). Measurements were taken at three different sites spanning a triangle with sides about 3−4 km long close to Lannemezan, over a plateau at 600 m above sea level (ASL) approximately 20 km north of the Pyrenees mountain range. The experimental area was located following the exit of the Aure valley. The Aure valley is a narrow valley, 30 km long, with the main axis oriented approximately in the north-south direction. Data used here are from the main site (Site 1, asterisk in Fig.1b) and Site 2 (dot in Fig.1b), both equipped with various in situ and remote sensing instruments, whose main features are described below:

Standard GRAW and MODEM radiosondes were launched from Site 1 at least 4 times per day at 0500, 1100, 1700 and 2300 UTC during the intensive operation period (IOP) days. Additional radiosondes were launched at 2030 UTC on 2 July and at 0200 on 3 July 2011. At Site 2, frequent **Väisälä radiosoundings** (Legain et al., 2013) were performed every hour from 1300 UTC to 2000 UTC . Therefore, differences between simultaneous soundings can be attributed to different launching location and measurement technique.

An **ultra-high frequency (UHF) radar** was installed at site 1 for continuous monitoring of the atmosphere from 200 m to 3000 m above ground level (AGL). The UHF data have a vertical resolution of 75 m and were averaged over 30 min. Wind and potential temperature reported from the UHF are used in this work.

A **60-m tower** from Centre de Recherches Atmosphériques is permanently installed at Site 1, providing year-round turbulent measurements at 30, 45 and 60 m AGL . Other low-frequency sensors were also installed (Lothon et al., 2014) but they are not used in the current analysis.

15.1 The Meteorological Mini Aerial Vehicle M^2AV

Several unmanned aerial vehicles were operated within a radius of 2 km around Site 1 during the BLLAST campaign. This was the case as well for the **M^2AV**, that in particular took four distinct flights during the AET on 2 July 2011. The M^2AV is an unmanned aerial vehicle with a wing span of 2 m and a weight of 6 kg. It is started and landed manually, and can be fully controlled during the mission by an autopilot system. For this case study, most ascents and descents as well as the main flight, consisting of race track pattern with straight horizontal legs, were flown with the autopilot. The flight track is shown in Fig.1b.

The M^2AV is equipped with a miniaturized turbulence measurement payload comprising a 5-hole probe for deriving the angle of attack and sideslip in the aerodynamic coordinate system. The data can then be converted to the 3D wind vector in the geodetic coordinate system using precise information on position and attitude of the aircraft obtained by GPS and an inertial measurement unit (IMU). The application of the method for unmanned aircraft is demonstrated by van den Kroonenberg et al. (2008). Further, the payload includes both a slow but accurate (Pt1000) and a fast temperature sensor, as well as a capacitive humidity sensor (Martin et al., 2011). The static air temperature was derived from the Pt1000 thermometer measuring the stagnation point temperature by correcting the time lag effect and the total temperature effect as described in Stickney et al. (1994) using individual coefficients for the M^{2}AV. The dry potential temperature was then calculated according to Stull (1988).

The parameters measured by the M^{2}AV (profiles of temperature, humidity, wind speed and wind direction, as well as TKE and turbulent fluxes of sensible heat) have been validated extensively against other airborne measurements (Spiess et al., 2007), as well as in-situ measurements from a meteorological tower and remote sensing observations (Martin et al., 2011; Cuxart et al., 2012). The system has been deployed for high resolution atmospheric profiling (Martin et al., 2011; Jonassen et al., 2015) and for deriving turbulent parameters (van den Kroonenberg et al., 2012; Martin et al., 2014; Martin and Bange, 2014) worldwide at various locations.

For the present analysis, the M^{2}AV performed four distinct flights starting around 1430, 1630, 1830 and 2030 UTC. Flights lasted approximately 40 min except Flight 2, which was shorter due to a failure of the autopilot around 20 min after take-off. The exact times for take-off and landing are given in Table 1. Each flight combined vertical profiles followed by horizontal race track patterns of about 1 km length oriented in the east-west direction for deriving turbulent parameters. The profiles were performed with an ascent (descent) rate of about 3.5 (8.0) m s^{-1}. The profiles of wind speed were averaged over intervals of 10 m altitude for an individual ascent or descent, while wind direction was additionally smoothed using a linear interpolation function. The race track pattern consisted of three legs at 300 and 250 m AGL and two more legs at 200 m AGL. The same pattern was repeated three times for each flight. During the last flight, these altitudes were reduced by 50 m, corresponding to a lower observed ABL height. Note that the time for one flight leg is only about 45 s at the aircraft speed of 22 m s^{-1}, therefore providing an instantaneous snapshot of the turbulence properties.

Data from the horizontal legs of the race track pattern are used to calculate the turbulent properties at different heights of the lower ABL. Several legs provided time series of the fluctuation part of the wind components with a quasi-steady wave-like structure (wavelength around 2 km) of relatively large amplitude compared to the fast fluctuations. This structure had a high impact on the wind variances calculated with a linear detrending. Since the flight legs were not long enough for obtaining statistically relevant information about these longwave features, we decided to remove their impact by employing a high pass Butterworth filter of third order. After testing different cut-off frequencies, the variances were calculated using the high-pass filter with a frequency of 0.01 Hz.

The dynamic behaviour of the pressure sensors can be different depending on their orientation with respect to the aircraft track, providing discrepancies between the variances estimated for the wind components parallel and perpendicular to the race track. If isotropy is assumed in the horizontal plane, the wind variance parallel to the race-track σ_u^2 can be replaced by σ_v^2, according to the meteorological coordinate system. This is not in agreement with the results of Luhar (2010) but is a common approach for airborne data obtained at a high air speed compared to the wind speed (Paluch and Baumgardner, 1989; Gultepe and Starr, 1995; Meischner et al., 2001). A convective ABL generates isotropic turbulence, while in a sheared ABL, the eddies are elongated following the direction of the main wind, as described in Mason and Thomson (1987), and therefore they lose isotropy. However, in this case the eddy sizes in the transversal direction have scales of the order of one kilometre (Stull, 1988), which is comparable to the leg length of the M^{2}AV and, thus, we may assume that horizontal isotropy applies for the sampled scales. In addition, as the prevailing wind direction was from north during the day, the horizontal wind component v corresponds to the along-wind data, which has a higher coherence than the cross-wind component according to e.g. Thebaud (2004).

Assuming horizontal isotropy ($\sigma_u^2 = \sigma_v^2$), TKE is calculated for each flight leg as (Stull, 1988)

$$TKE = \frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) = \sigma_v^2 + \frac{1}{2}\sigma_w^2 \tag{1}$$

For investigating the turbulence anisotropy, the anisotropy ratio is defined in this study as the ratio of the horizontal to the vertical wind variances (Darbieu et al., 2015),

$$A = \frac{\sigma_u^2 + \sigma_v^2}{2\sigma_w^2} = \frac{\sigma_v^2}{\sigma_w^2} \tag{2}$$

where $\sigma_u^2 = \sigma_v^2$ is also assumed when calculating this parameter with airborne data. Equation 2 implies that isotropic turbulence is characterized with $A = 1$; that values lower than 1 correspond to day-time convection with a large vertical turbulence component; values exceeding 1 are caused by a dominating turbulence component in the horizontal direction induced by wind shear or by a decrease of the vertical variance under stably-stratified conditions. Despite the fact that here we use a different definition of the anisotropy ratio compared to other studies (e.g., Mauritsen and Svensson, 2007; Canut et al., 2015), all of them can be easily related.

15.2 Model set-up

The mesoscale model MesoNH (Lafore et al., 1998) was run in a similar manner as in previous studies, particularly in the Garonne river basin (see Jiménez and Cuxart, 2014, and the references therein). Two nested domains were used. The outer one, at 2 km x 2 km resolution, covered the Garonne river, and the inner one, at 400 m x 400 m resolution, was centered in Lannemezan (see Fig.1a). The vertical resolution is fine close to the surface (3 m) to properly represent of the physical processes that take place at lower levels, and coarser above. The initial and lateral conditions are taken from the European Centre for Medium-Range Weather Forecasts (ECMWF) every 6 hours.

For the case study, the simulation start time was set to 0000 UTC on 29 June 2011 so that rain observed during 30 June could be included, with the aim that soil moisture in the model would be more similar to the observations. The simulation end time was set to 1200 UTC on 3 July 2011. For the case study, attention is focused on describing the AET of 2 July 2011 (from 1500 UTC to 0000 UTC).

16 Flow at lower levels during the AET

The synoptic conditions during 2 July 2011 include a weak anticyclone (1025 hPa) over the British Isles, with lower values of the pressure field at the mean sea level on the western Mediterranean (1012 hPa) resulting in a weak north-easterly to east-north-easterly flow over southern France at low levels. This synoptic-scale flow co-existed with the plain-mountain system that generated northerly flows in the daytime over the foothills of the Pyrenees (Fig.2a). Additionally, the Aure valley, just south of Lannemezan, had a well developed up-valley wind system. At 2030 UTC, the wind in the plain blew from east-north-east (also over Lannemezan, Fig.2b), whereas the mountain valleys were generating down-valley flows that still did not reach the foothills where Lannemezan is located. Just one hour later (Fig.2c), the site was located in an area where the mountain to plain wind merged with the more general easterly wind, resulting in a local wind maximum over Lannemezan (an LLJ, as it will be described later), a structure that still stayed there, even reinforced at 0000 UTC (Fig.2d). The model reproduces very well the observed intensity and direction of the wind in Lannemezan (red arrow in Fig.2) for all the inspected instants.

Looking at the temporal series in Fig.3 from M^{2}AV, 60-m tower and mesoscale simulation, the wind speed at 60 m AGL decreases during the AET (with a higher rate for airborne observations) and increases again substantially after sunset, as wind turns from north to north-east direction, a behaviour that the model and the M^{2}AV observations successfully capture. Besides, the three sources are reproducing a similar temporal evolution of temperature, being the model 1 K warmer and 1 K colder than the observations during day and night, respectively. Although these biases are not large, similar values are found for other studies and they can be attributed to an enhanced mixing of the model at lower levels (Conangla and Cuxart, 2006) or to a misrepresentation of the surface heterogeneities (Cuxart et al., 2016).

To inspect the vertical characteristics of the LLJ, the profiles observed by the UHF profiler and those extracted from the model outputs are shown as Hövmoller plots (z,t) in Fig.4. Besides, in Fig.5 the observed vertical profiles (M^{2}AV, UHF, soundings and 60 m tower) at different instants are compared to those obtained from the model.

It is found that the observed and modelled wind direction are in good agreement with each other. Fig.4a shows that the UHF wind veers from north-east to south-east between 2000 and 2100 UTC above 200 m AGL and stays from that direction in the following hours. The model has a similar behaviour at those heights (Fig.4c) and indicates that, at lower levels, the south-easterly flow arrives earlier constricted to the first tens of meters AGL (as further confirmed with tower observations, Fig.3b). The TKE in the model decreases during the AET with a minimum close to sunset at about 200 m AGL and increases again when the LLJ is present due to its shear. It must be mentioned here that the values of the wind speed as provided by the UHF profiler are always significantly overestimated with respect to the soundings (Fig.5); instead the wind directions derived from both soundings and wind profiler are in very good agreement. Therefore, when making our assessment of other data and of the model, we will not give too much weight to the values of the UHF profiler for this particular case study. At 1900 UTC, before sunset, the thermal stratification is already stable at the site, with very weak winds from the north-east quadrant (Fig.5c). Profiles in Fig.4 indicate that, at 2000 UTC, already after sunset, there is a progressive formation of a south-easterly jet below 100 m AGL, that is clearly developed at 2300 UTC, detected by the tower measurements below 60 m and, according to the model, extending up to almost 300 m AGL with wind speed around 5 m s^{-1}. The reported LLJ has similar features as those described in Baas et al. (2009).

M^{2}AV profiles (Fig.5) show in general good agreement with the description just given using model and UHF profiler, indicating the increase in wind speed after sunset and the change of the wind direction. The airplane is also able to capture successfully the transition from thermally unstable to stable conditions as shown in the potential temperature profiles (Fig.5).

It seems therefore clear that the M^{2}AV flight just after sunset was able to capture the transition from a very weak wind regime to the establishment of a terrain-induced LLJ that was sustained for several hours (the simulation ends at 1200 UTC of the next day). Since flight legs were made to estimate turbulence intensities at heights that are probably located above and below the LLJ wind maximum, it is possible that we can infer some characteristics of the turbulence related to this structure using the last flight. Besides, knowing that an LLJ was present in the area sustainedly after sunset provides clues for the interpretation of the increase of anisotropy that will be described in the next section.

During the last flight (about 2100 UTC) ambient conditions were favourable to develop gravity waves in the ABL, especially at lower levels. Results from Román-Cascón et al. (2015) clearly show the presence of gravity waves close to the surface up to about 100 m AGL but not at higher levels (where the M^2AV sampled). The model results are not able to capture these waves since they are too attached to the ground.

17 Turbulence and anisotropy during the AET

Observations of the TKE (5-min averages from the tower and observations obtained with the M^2AV) and model results are similar during the AET, with a sustained decrease in turbulence, and very small values at sunset (Fig.3d). Once the turbulence collapses around sunset the observed values are very small in the whole column (tower and M^2AV reported TKE of around $0.05\,m^2\,s^{-2}$, Fig.6). As seen in this figure, the model produces even smaller TKE values throughout the vertical column, with a local minimum between 75 and 125 m AGL. Simulated results are closer to the observations at lower levels (as those observed by the 60-m tower) but clearly underestimate the results provided by the M^2AV at higher elevations. Modelled LLJs usually underestimate the intensity of turbulent mixing compared to observations (Conangla and Cuxart, 2006). Nonetheless, in this case, the local elevated turbulence usually associated to the LLJ wind maximum seems to be reproduced by the mesoscale simulation, as shown by a sustained TKE maximum near 400 m AGL between sunset and 2100 UTC (yellow and red colour, Fig.4d).

The anisotropy ratio for the afternoon and evening transition in this case study can be computed from the numerical model, M^2AV and the sonic anemometers in the 60-m tower (Fig.7). Each source samples different characteristic scales and therefore provides information about the anisotropy at different ranges of the TKE spectrum:

For the model, the columns of a box of 10 km side centered at Lannemezan are extracted, using the smallest domain that has a horizontal resolution of 400 m. The mean values of the horizontal and vertical wind speed are computed from the 25×25 columns, and the corresponding standard deviations are computed to obtain the anisotropy ratio. This is the anisotropy corresponding approximately to scales between 1 and 5 km as created by the model. Afternoon values are slightly below 1 since in summer prevailing dry-sheared convection typically has a turbulence spectrum with an inertial subrange (IS) starting at scales close to 1 km. As sunset approaches and convection weakens, anisotropy increases because the beginning of the IS shifts to the right. After sunset, the eddies have relatively shallow dimensions and are elongated along the main wind direction (as described in Mason and Thomson, 1987), showing large values of anisotropy at these scales. Anisotropy in the model is maximal close to the ground and decreases with height (not shown).

The M^2AV flew legs of 1 km length and resolves eddies down to sizes of typically a few meters (Martin et al., 2014). In the daytime the range of sampled eddies is almost all in the IS, and the anisotropy ratio has values close to 1. As sunset approaches and at night, the size of the largest eddies decreases and the airplane samples eddies larger than those in the IS, generating larger values of the anisotropy ratio. Statistical values over 5 minutes from a sonic anemometer at 60 m AGL are similar to those from the M^2AV (close to 10) in this case, representing typically scales of a few hundred meters (assuming a mean wind speed of $5\,\mathrm{m\,s^{-1}}$) to dissipation.

In the daytime the values of anisotropy provided by the different sources are very similar and close to 1, as expected with a dry-sheared convective boundary layer (Fig.7). During the evening transition, the anisotropy ratio is larger (by a factor of 2 to 5), likely because the contribution of convection weakens significantly and the eddies become progressively shallower and more elongated. At night the values of the anisotropy ratio differ depending on the scale and source of the data. At the height of the LLJ, the model produces the same values of anisotropy as during the transition, not significantly influenced by the effects of thermal stratification at those levels and the elongation of shear-driven eddies at those scales. Instead, the M^2AV and the tower, which measure at smaller scales, provide much higher values of the anisotropy ratio, indicating that thermal stratification and wind shear generated by the LLJ play a more important role at these scales, moving the upper limit of the IS to very small eddies.

18 Discussion

The TKE values observed with the M^2AV are compatible with other TKE values obtained on that particular day with ground-based, balloon and airborne observations (Canut et al., 2015). The time evolution of the TKE studied in the present case can be compared to the results obtained by Darbieu et al. (2015), that analysed the turbulence decay between 1200 and 2000 UTC for a similar day of the BLLAST campaign (20 June 2011, IOP 3) using observations and a large eddy simulation (LES). Observed TKE during Flights 1 and 2 are of the same magnitude than those values obtained in Darbieu et al. (2015) between 1500 and 1700 UTC (see their Fig.7). Two hours later, Flight 3 exhibits much lower values than in their study, suggesting that turbulence collapses faster and deeper in our case. Interestingly, the TKE produced by the numerical simulations is lower than the observations for both cases, despite the differences in the study cases and the numerical tools used. After sunset, Flight 4 observes a TKE increment with the arrival of the LLJ, with values between 0.02 and $0.6\,\mathrm{m^2\,s^{-2}}$. In the summary of Banta et al. (2006), TKE values around $0.1\,\mathrm{m^2\,s^{-2}}$ are reported for LLJs with a similar maximum wind speed around $5\,\mathrm{m\,s^{-1}}$, which is in the same order of magnitude as the observations presented here. However, the direct comparison of absolute TKE values with other values in the literature is often difficult due to the non-unique definition of TKE and data treatment, e.g. over what time were the data averaged, was a high pass filtering technique applied or was a linear trend removal done for determining the wind speed variances, (c.f. Banta et al., 2003).

The change of TKE with altitude does not provide a clear tendency (Fig.6). According to Banta (2008) a decrease in TKE with altitude is expected for an ABL where turbulence is created at the surface by thermal heating and then transported upwards. In contrast, when turbulence is induced by wind shear aloft, an increase in TKE with altitude is predicted by the theory (Banta, 2008) and produced by LES modelling (Nakanishi et al., 2014). In Fig.6, a large scatter of TKE values can be seen for M^{2}AV. This indicates that the individual flight legs for deriving turbulence properties were too short and the terrain was too inhomogeneous (Cuxart et al., 2016) to derive values which are statistically representative for the area (Lenschow et al., 1994).

The evolution of turbulence anisotropy, with larger values of the vertical wind variance during the afternoon and of the horizontal variances after sunset, is in accordance with other observations during the BLLAST campaign (Canut et al., 2015). Similarly, the numerical simulations of Darbieu et al. (2015) give a sustained anisotropy ratio around 1 at $z = 0.2\, z_i$ (z_i is the ABL height) until 1730 UTC, and a rapid increment up to 2.5 one hour later. These results are in accordance to our observations from Flights 1, 2 and 3 of the M^{2}AV, since the first two flights exhibit similar anisotropy results while the third one doubles its value (Fig.7). In addition, observations from Flight 4 suggest that the abrupt increment of the anisotropy ratio during the late afternoon, when the surface buoyancy flux reduces to zero (Darbieu et al., 2015), is enhanced after sunset.

In order to evaluate the impact of the LLJ on the turbulence anisotropy, this parameter is evaluated during IOP 9 (1 July) with data from the 60 m tower, and compared against our case study (2 July 2011, IOP 10). Similarly to IOP 10, in IOP 9 large-scale winds were weak, allowing the development of a mountain-plain circulation but without the arrival of an LLJ (Lothon et al., 2014). For both IOPs, the anisotropy ratio at 60 m AGL increases along the AET but, after sunset, it becomes larger for IOP 10 (not shown). Fig.8 shows the temporal evolution of the horizontal and vertical wind variances for both cases, separately. The results from M^{2}AV are also depicted for reference. During the day, all variances have similar values, remaining steady until 1600 UTC and decreasing afterwards, as sunset approaches. During this stage, the resulting anisotropy ratio is 1 for both cases. Close to the sunset time, the vertical wind variance decreases at a higher rate and thus the anisotropy ratio increases, as in Kallistratova et al. (2013). After sunset, the drop in σ_w is more significant for the IOP 10, coinciding with the arrival of an LLJ at the area. These results are in agreement with previous observations from Prabha et al. (2008) and Banta (2008). The wind shear generated by the presence of the LLJ and the stably-stratified conditions at lower levels (at 60 m AGL, see Fig.4) might be responsible for the drop in σ_w after sunrise, where the vertical motions are more damped than if an LLJ is not present.

19 Conclusions

This work focuses on the time evolution of turbulence properties at the lower ABL during the afternoon and evening transition (AET) for a case study of the BLLAST experimental field campaign in Southern France. The analysis has been carried out through airborne, tower, radiosonde and remote sensing (UHF wind profiler) observations. Besides, results from a high-resolution mesoscale simulation have been used to both characterize the organization of the flow at lower levels at the foothills of the Pyrenees (where the experimental campaign was located), and to complement the observations.

It is found that TKE decreases along the AET and reaches a minimum close to sunset, in agreement to other studied days of the BLLAST dataset. However, for the present study, an LLJ develops over the area afterwards as a combination of large-scale winds and the mountain-plain circulation generated due to the vicinity of the Pyrenees. This major feature remains nearly stationary during the whole night and is responsible for the increment of the TKE close to the surface and at higher elevations above the wind speed maximum after sunset. In addition to its intensity, the turbulence isotropy has been analysed for the AET. During the day, a well-developed convective boundary layer is characterized by isotropic turbulence (anisotropy ratio of 1) whereas after sunset vertical motions are damped due to the establishment of a stably-stratified ABL and the wind shear generated by the LLJ. A comparison with a similar day of the BLLAST campaign without the occurrence of an LLJ confirms that the anisotropy ratio is enhanced due to its presence. The increment of anisotropy is less pronounced in the mesoscale simulation probably due to the fact that the larger scales resolved by the model are less affected by thermal stratification and wind shear.

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Table 1. Takeoff and landing time for each flight of the M^2AV on 2 July 2011.

Flight	takeoff [UTC]	landing [UTC]
1	1431	1514
2	1636	1659
3	1823	1904
4	2026	2110

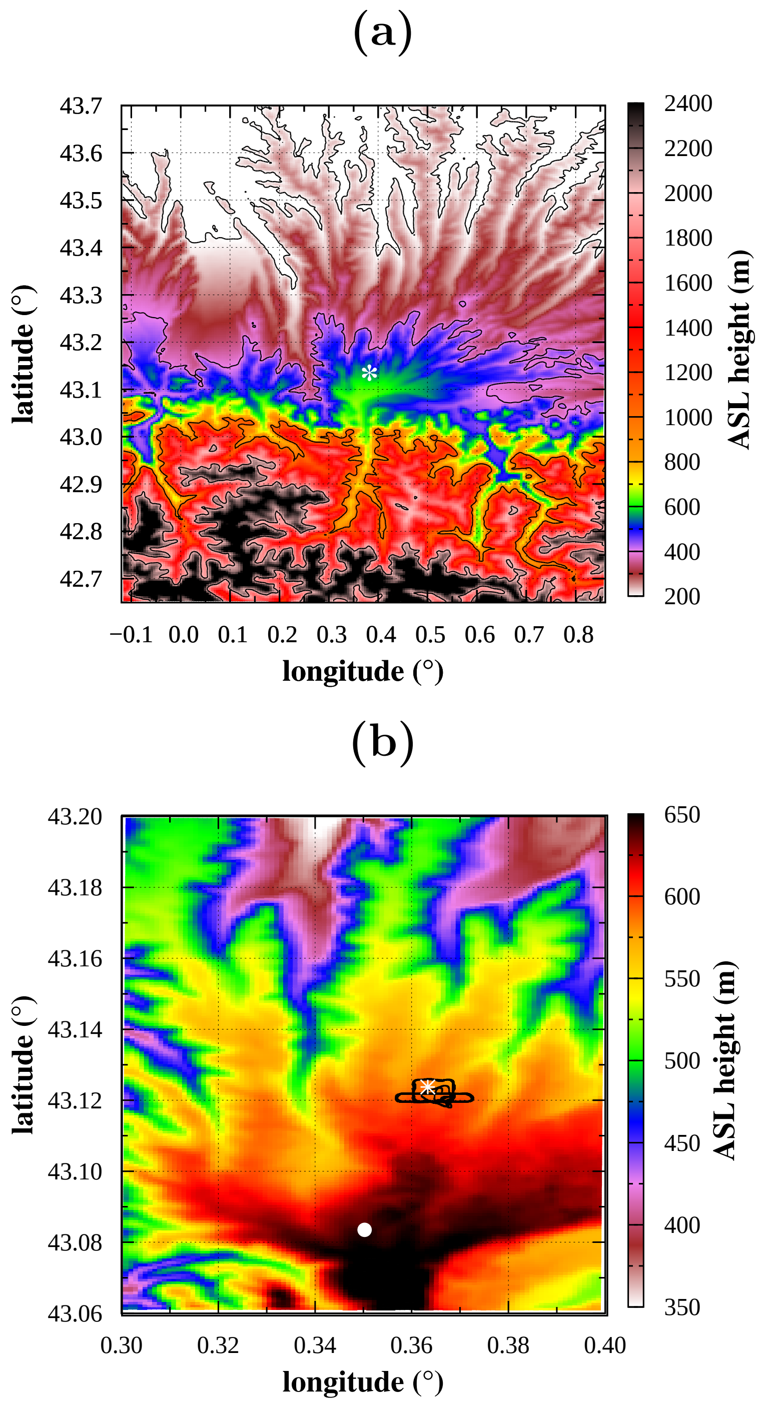

Figure 1. (a) Topography of the inner domain of the mesoscale simulation which covers the Pyrenees (mountains and foothills). The plateau where Lannemezan is placed is coloured in green and the Aure valley is at the south. Topography lines are labelled at 200, 400, 1000 and 2000 m (above sea level, ASL). (b) Zoom of (a) over the plateau where Lannemezan is placed together with the M^2AV flight tracks (black lines). The location of Site 1 (60-m tower, UHF radar and GRAW soundings) and Site 2 (frequent radiosoundings, MODEM) are indicated with an asterisk and a dot, respectively.

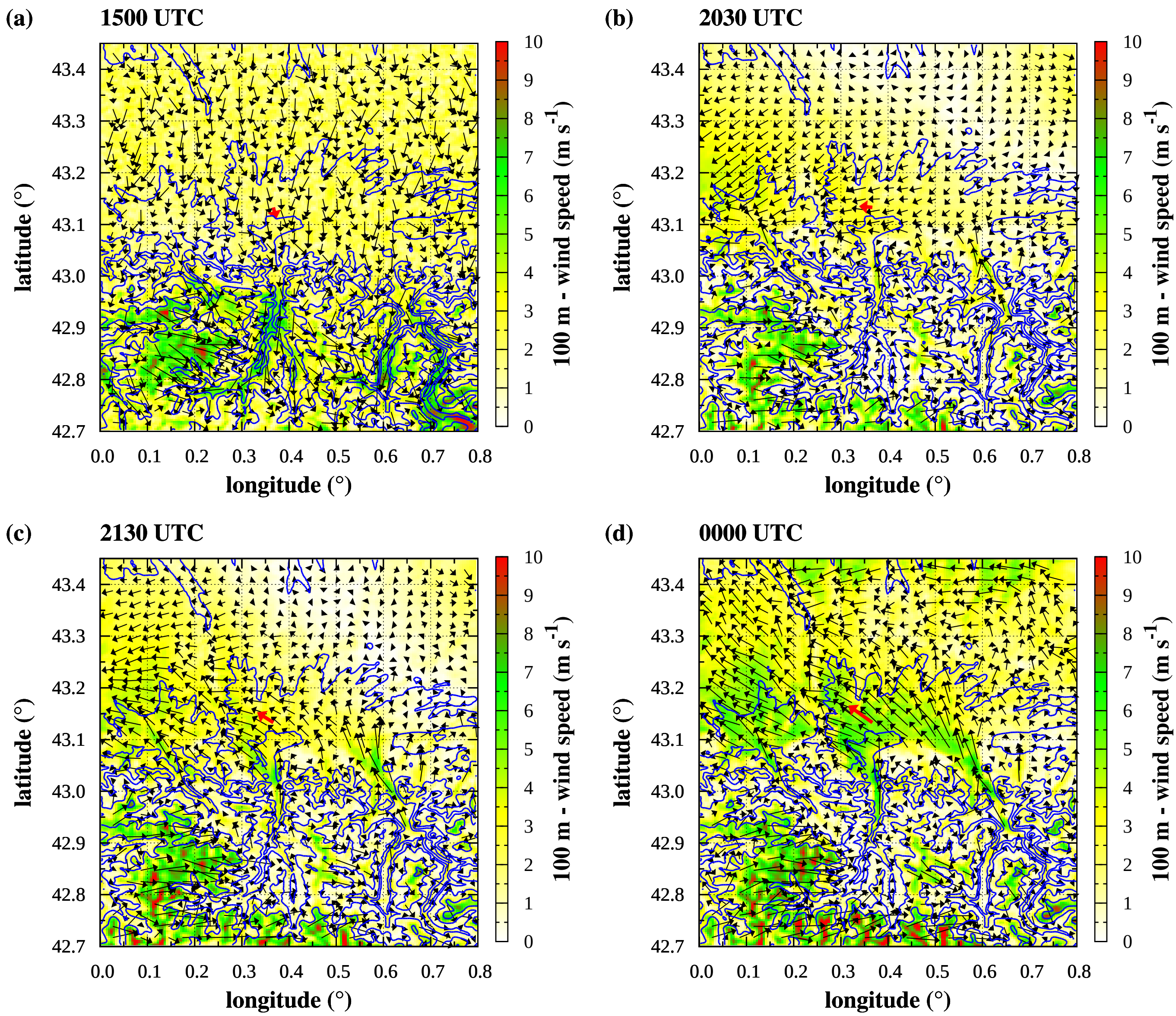

Figure 2. Modelled 100 m AGL wind vectors together with wind speed (in colours) and the topography lines (in blue) at different instants (a) 1500 UTC, (b) 2030 UTC, (c) 2130 UTC, (d) 0000 UTC. The 60 m wind vector observed by the tower is indicated with a red arrow.

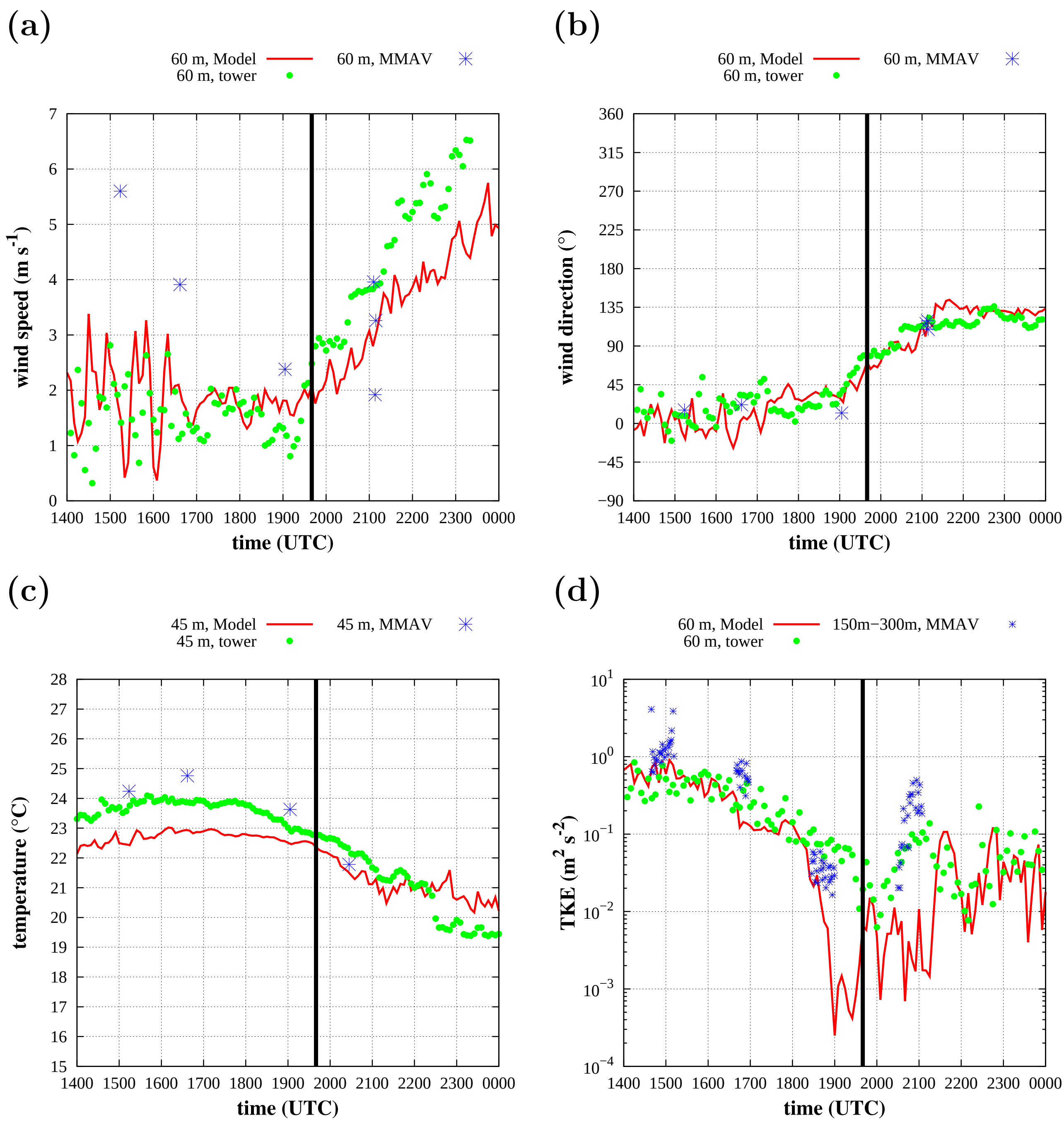

Figure 3. Modelled and observed time series for (a) wind speed (in m s^{-1}), (b) wind direction (in °), (c) temperature (in °C) and (d) TKE (in m^2 s^{-2}) from 1400 UTC until midnight on 2 July 2011. Tower observations are in green circles, model results in red lines and M^2AV data in blue asterisks. The temporal evolution of wind and temperature data from M^2AV is constructed with the values of the vertical profiles taken at the corresponding height of the tower measurements. For TKE, all the M^2AV legs where TKE is derived, at 150 m, 200 m, 250 m and 300 m AGL, are included in the plot. The time of sunset is represented with a black vertical line.

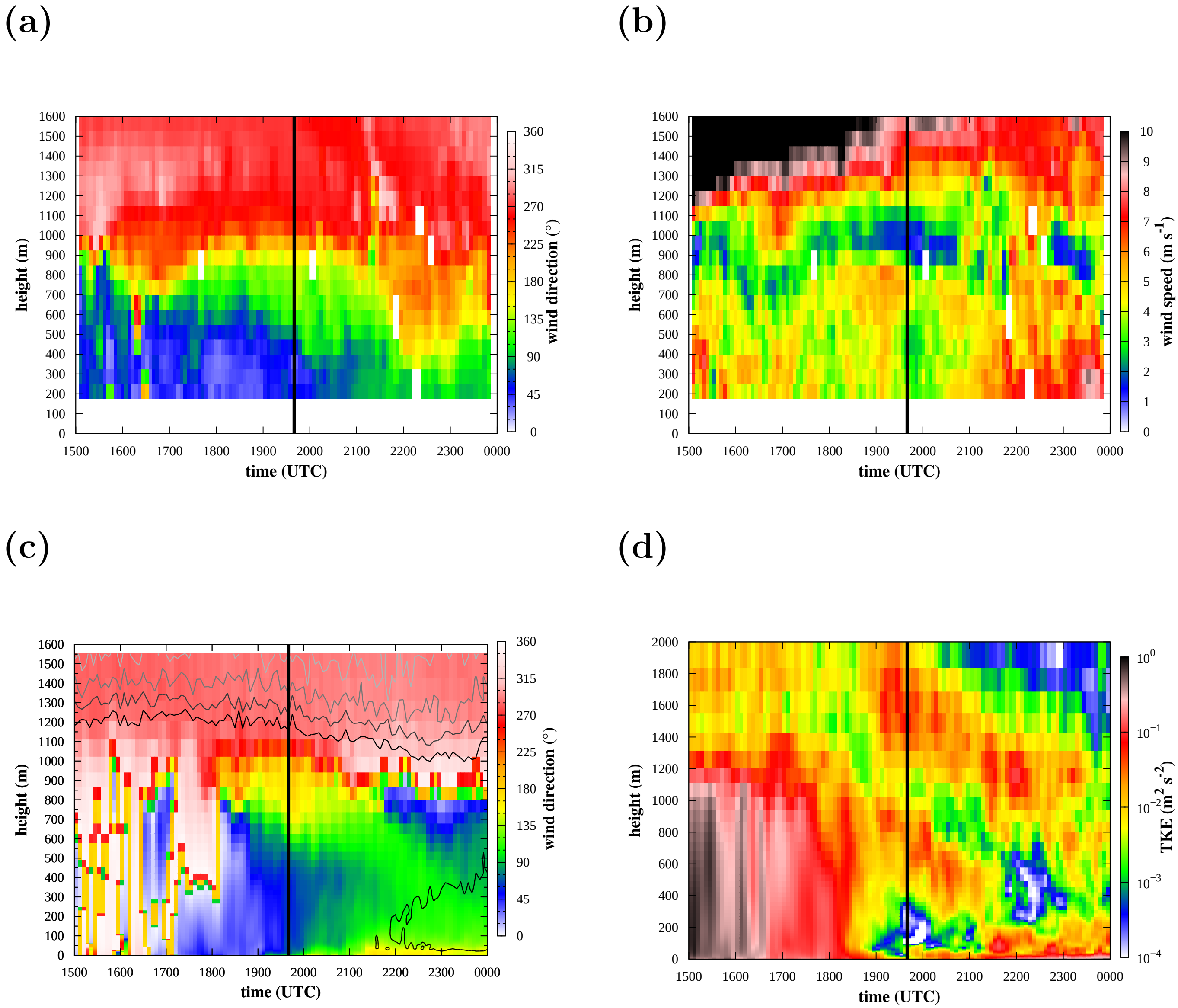

Figure 4. Temporal evolution of the vertical profiles for (a) UHF wind direction (in °), (b) UHF wind speed (in $\mathrm{m\,s^{-1}}$), (c) MesoNH wind direction (in colours) and wind speed (in lines, for values $\geq 4\,\mathrm{m\,s^{-1}}$, contour interval = $2\,\mathrm{m\,s^{-1}}$) and (d) MesoNH TKE (in $\mathrm{m^2\,s^{-2}}$). The time of sunset is represented with a black vertical line.

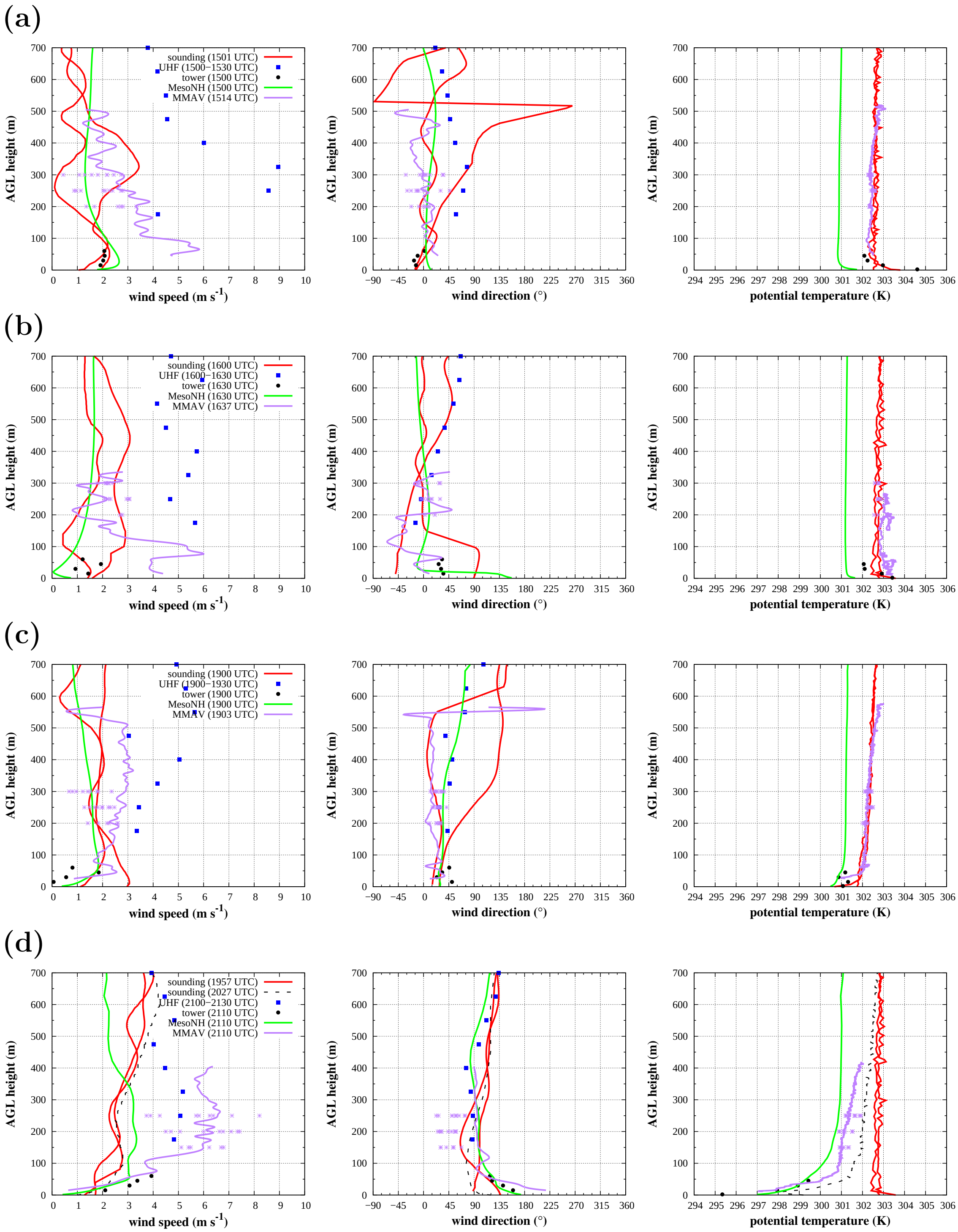

Figure 5. Vertical profiles of the wind speed (in $\mathrm{m\,s^{-1}}$) on the left, wind direction (in $^{\circ}$) in the center and potential temperature (in K) on the right, obtained from $\mathrm{M^2AV}$ (in violet) for the four flights of 2 July 2011: (a) 1500, (b) 1630, (c) 1900 and (d) 2110 UTC. Purple dots correspond to mean values for each horizontal leg. $\mathrm{M^2AV}$ data are compared against instantaneous observations from UHF (blue squares), 60-m tower (black dots), and frequent (red) and standard soundings (black) together with mesoscale simulation results (green). The legend indicates the corresponding times to each data source.

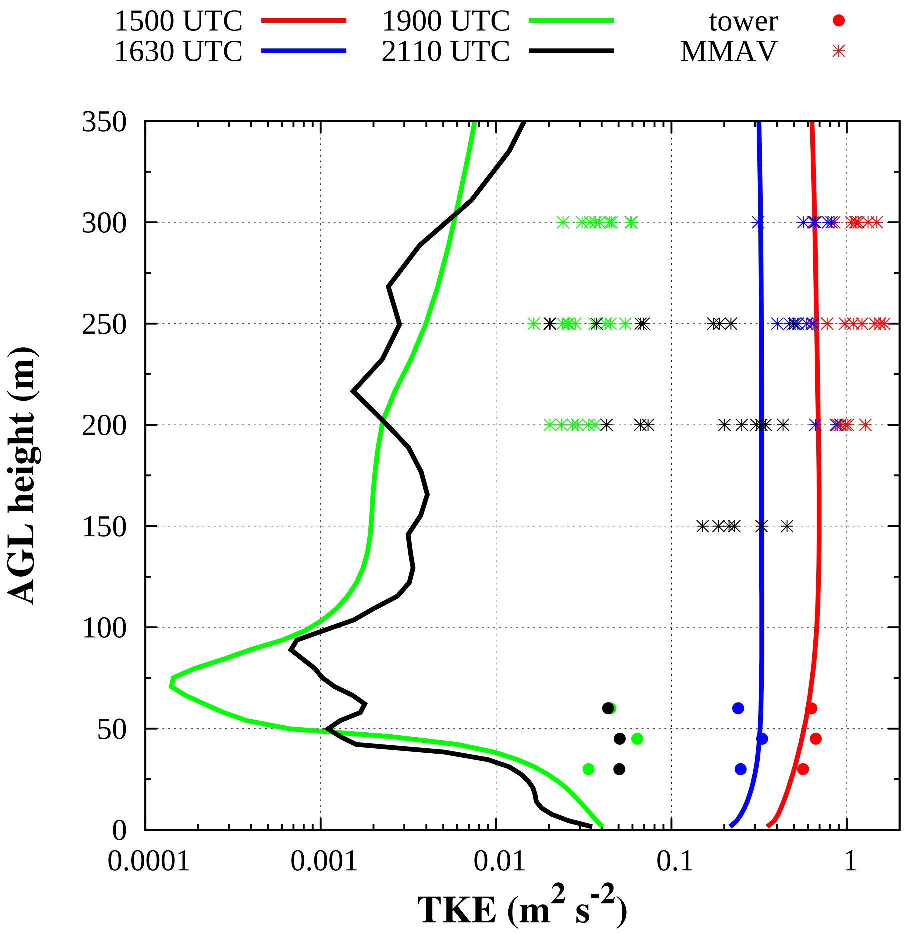

Figure 6. Vertical profiles of the simulated TKE (in lines) at different instants during the M^{2}AV flights (see legend). 60-m tower (in dots) and M^{2}AV (in asterisk) observations are also included. Note the logarithmic scale on the x-axis. For M^{2}AV, $\sigma_u^2 = \sigma_v^2$ is assumed.

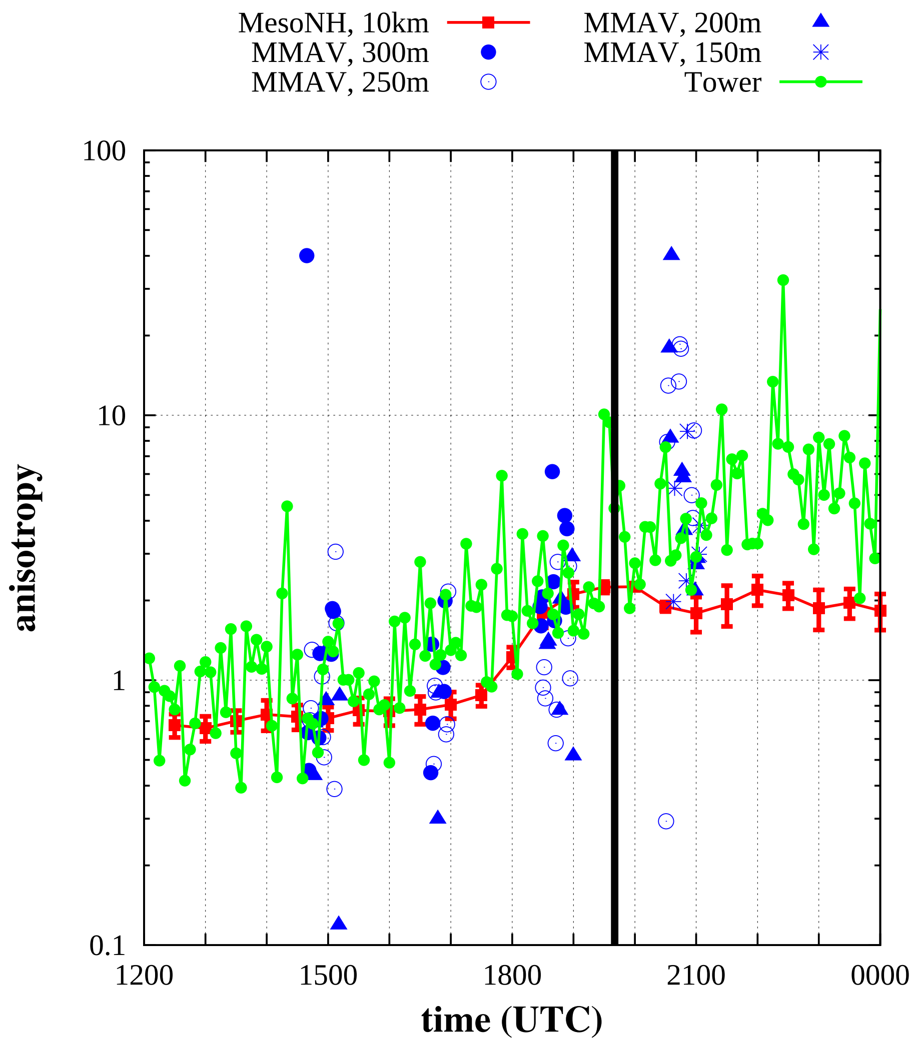

Figure 7. Time series of the anisotropy computed from different sources: (1) M^2AV flight observations at 150 m, 200 m, 250 m and 300 m AGL during the four flights, each symbol representing a particular height (in blue); (2) tower measurements at 60 m AGL every 5 min covering the afternoon-evening transition (in green); (3) model results averaged between 150 m and 300 m AGL to be close to the altitudes of the M^2AV observations considering a spatial area of 10 km x 10 km centered at Lannemezan (in red). The time of sunset is represented with a black vertical line. Note the logarithmic scale on the y-axis. For M^2AV, $\sigma_u^2 = \sigma_v^2$ is assumed.

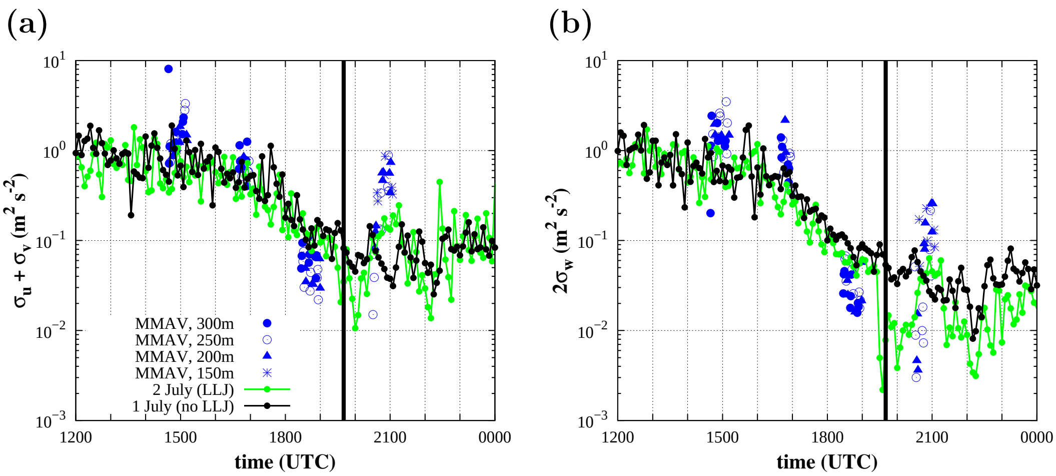

Figure 8. The same as Fig.7 but for the (a) horizontal $\sigma_u + \sigma_v$ and (b) vertical $2\sigma_w$ variances computed from the tower observations at 60 m AGL during 1 July 2011 (IOP 9, without an LLJ, black line) and 2 July 2011 (IOP10, with an LLJ, green line); together with those derived from M^{2}AV observations. For M^{2}AV data, $\sigma_u^2 = \sigma_v^2$ is assumed.