Poster 25

Turbulence kinetic energy decay in the late afternoon over heterogeneous surface: BLLAST experiment

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1. Introduction

In the context of the BLLAST project (Boundary Layer Late Afternoon and Sunset Turbulence) (Lothon et al., 2012), which studies the turbulent processes of the decaying convective boundary layer, we investigate the turbulence kinetic energy (TKE) decay that is associated with the progressive shut down of the buoyancy energy from the mid-afternoon to sunset.

The TKE decay has been studied in a fairy large extent, especially with numerical studies (e. g. Monin and Yaglom (1975); Stillinger et al. (2010); Nieuwstadt and Brost (1986); Sorbjan (1997); Goulart et al. (2003)) or observations of the surface layer (Grant (1997); Fernando et al. (2004); Fitzjarrald et al. (2004); Brazel et al. (2005); Edwards et al. (2006)).

Nieuwstadt and Brost (1986) studied the TKE decay in a mixed-layer with idealized numerical simulation. This decay was the consequence of an abrupt cut of surface heat flux. The effect of a more progressive decrease of surface flux was analyzed by Sorbjan (1997) with large eddy simulation (LES).

Nadeau et al. (2011) fitted surface layer measurements with an analytical model based on convective boundary layer (CBL) parameterization, with predominance of buoyancy and dissipation in the TKE budget. Most of the studies find a power law of TKE decay whose coefficient is a function of τ_f/t_*, where τ_f is the forcing (or 'external') time scale and t_* is the convective time scale (z_i/w_*, where z_i is the CBL depth and w_* is the convective velocity). τ_f is usually taken as the time delay between the maximum and the zero value of the forcing flux (either surface heat flux or net radiation).

Fig. 1 (after Nadeau et al. (2011))) gathers some of those results, with different values of the ratio τ_f/t_*. The larger the ratio, the later but more abrupt the TKE decay. In this figure, t_* and w_* are taken at the initial time when the forcing flux is maximum. Also note that this graph gathers two different estimates: TKE integrated over the entire CBL depth (numerical studies) and TKE observed at one level within the surface layer (observations), and adjusted to the initial level of the former, for decay comparison.

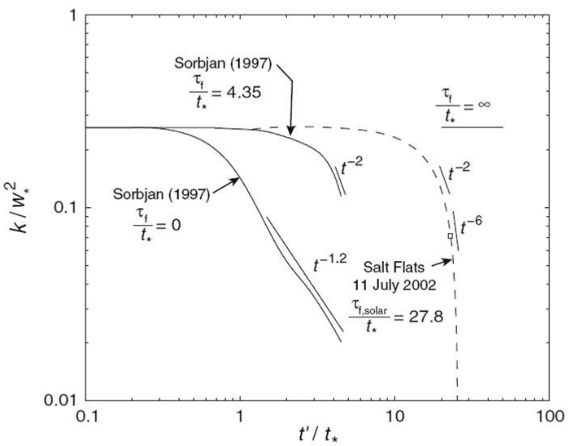

Figure 1: *Normalized TKE as a function of non-dimensional time. The two first curves are large eddy simulation results from (Sorbjan, 1997). The third curve is an analytical model that fits surface measurements over a desert in July 2001 and from LITFASS experiment in Germany (Nadeau et al., 2011).*

The decay of turbulence up to the top of the mixed or residual layer remains poorly documented by observations, and still not well understood. Especially, the role of other CBL processes coming into play (like wind shear, radiation, clouds) and of surface heterogeneity need to be further addressed. The differences in surface energy balance (SEB) as a function of the vegetation cover may imply phase shifts of the transition from one surface to the other, as they turn from positively buoyant to negatively buoyant. This could play a significant role in the atmospheric dynamics close to surface and above.

The recently collected BLLAST dataset enables us to

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address some of those issues. In this study, we start to address two aspects: (1) the surface energy budget heterogeneity, and (2) the TKE decay process over heterogeneous surface and above.

2. Experimental data

BLLAST experiment, which took place in South of France in June and July 2011 (Lothon et al. (2012), BLT 14.B1) was dedicated to the decaying CBL. 12 fair weather days, so called intensive observing periods (IOP), were extensively documented, with measurements densification during the afternoon, from midday to after sunset.

Eleven surface stations measuring surface energy balance were implemented over different vegetation covers. Six of them, settled in a 5 km radius circle, are used in this study to characterize the TKE decay during the late afternoon transition over grass, wheat, corn, moor, pine forest and bare soil with few little bushes. Turbulent moments have been computed with an eddy-covariance uniform-process using EC-pack (Wageningen University, Van Dijk et al. (2004)).

To complement surface measurements, airborn measurements allow to study the TKE decay at different heights in the CBL. The French Piper Aztec (SAFIRE/Météo-France) and the Italian Sky Arrow (CNR-IBIMET/Italy) flew stacked legs in and above the CBL, in the vicinity of the surface stations, from early afternoon to sunset.

3. Surface heterogeneity

During BLLAST, an instrumented site was dedicated to the study of surface heterogeneity and its role on the dynamics during the late afternoon transition. Three adjacent surfaces of about 1-2 km scale, covered with pine forest, corn and moor respectively, were equipped with instrumented masts. Here we discuss composite SEB made over the 12 IOP days, on each of those three surfaces (Fig. 2).

The composite day over the 12 IOPs shows differences up to 100 W m^{-2} on net radiation between the three vegetation covers (Fig. 2a). These differences are due to the albedo differences (0.1, 0.15 and 0.2 for the forest, the corn and the moor respectively). These differences in albedo imply different outgoing short and long wave radiation. The former is entirely in phase with the solar irradiance, whereas the latter displays a time shift from one type of surface to the other (Fig. 2b), which is likely linked to differences in the heat storage within their canopy. The outgoing infrared radiation over corn is slightly larger than those over moor, but after 1500 UTC it becomes smaller. This phenomenon is even more noticeable over the forest because of the thicker canopy.

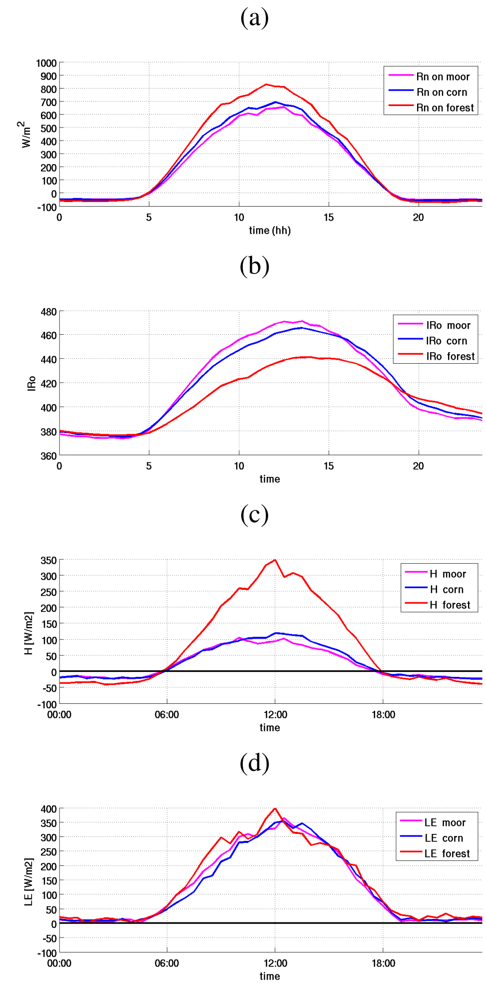


Figure 2: *Composite daily evolution of (a) net radiation, (b) outgoing long wave, (c) sensible heat flux and (d) latent heat flux over three different vegetation covers: moor, corn and forest.*

These albedo and canopy structure differences affect the surface buoyancy via the sensible (H) and latent (LE) heat flux. H over forest (about 350 W m^{-2} at midday) can be up to three times the flux over moor and corn (about 100 W m^{-2}) (Fig. 2c). Furthermore, a time shift between the times of maximum flux can be noticed : until 1000 UTC, H over corn is slightly smaller than H over moor, then it becomes larger. At night, H over forest becomes smaller than H over corn and moor.

On the contrary the latent heat flux (LE) is very similar from one vegetation cover to the other (Fig. 2d). During the morning, LE over the forest is larger than LE over corn, which is larger than LE over moor, but in the afternoon the latent heat fluxes are approximately the same above the three surfaces.

The TKE is governed by dynamical conditions through

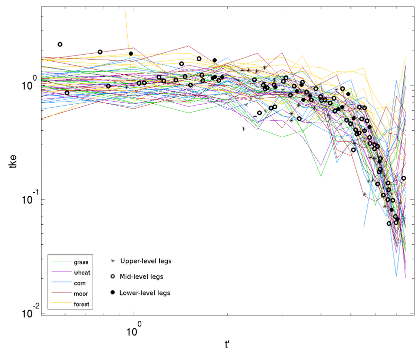


Figure 3: *Temporal evolution of TKE (from noon to sunset) measured during the 12 IOPs over the 5 vegetation covers at surface (color scale) and by the aircraft at different levels in the CBL (markers).*

the wind shear (Goulart et al., 2010) and by buoyant conditions through the sensible heat flux. Are the vegetation cover behaviour differences noted previously able to imply some significant TKE decay differences in the late afternoon?

4. Turbulence Kinetic Energy decay within the CBL

The TKE has been estimated in the surface layer and at different levels in the CBL thanks to the surface stations and airborne measurements during BLLAST campaign. Fig. 3 puts together the evolution of TKE with time for all IOP, at surface over the different surface vegetation covers, and at different heights in the ABL. A similar evolution is observed no matter the surface vegetation cover and the height measurements even without normalization. This is somehow consistent with the results of Nadeau et al. (2011) who were able to model the decay observed in the surface layer with a model based on a mixed-layer based parameterization, rather than with a surface-based parameterization. The increase of TKE at the end of late afternoon is generally due to the set up of the katabatic nocturnal flow typical of the location which implies in that case an increase of turbulence.

However logarithmic representation is misleading and discrepancies exist. This scattering may be due to the effect of large scale forcing, wind shear, pressure terms, entrainment and surface heterogeneity. Using experimental data, one can easily notice that the TKE decay rate is difficult to estimate since it varies with time along the afternoon.

In the following, we investigate the buoyancy effect on the TKE decay close to the surface, comparing the timing of TKE decay to the sensible heat flux decay.

5. TKE decay

The eleven IOPs are used to estimate a composite IOP over each vegetation cover in order to link the TKE decay with the sensible heat flux decay. Fig. 4 and 5 give the method used for one of the vegetation cover (wheat). For each IOP, the forcing time scaling is defined as τ_{IOP_f} which is the duration between the time (t_{IOP_M}) of maximum surface sensible heat flux (H_{IOP_M}) and the time when sensible heat flux is zero. Therefore in this study τ_f is IOP and vegetation dependent (Fig. 4a). Fig. 4b and c present normalized sensible heat flux (H_{IOP} / H_{IOP_M}) and TKE evolution against normalized time ($t - t_{IOP_M}$) / τ_{IOP_f}) for the surface site over wheat.

From these normalized temporal evolution, TKE and H decay rates (R_{TKE} and R_H) against time are computed as follow:

$$R_{TKE}(t) = \frac{\delta log(TKE(t))}{\delta log(t)},\ R_H(t) = \frac{\delta H(t)}{\delta t} \qquad (1)$$

TKE decay rate is plotted against H decay rate for a composite IOP in Fig. 5a. Decay rates evolve from near zero values, which correspond to midday when H and TKE are both maximum, to negative values when both H and TKE decrease, the last point corresponding to zero surface flux. This curve points out three stages: 1) H is at its maximum and starts to decrease (decay rate sligthly negative). TKE remains constant (decay rate near zero), 2) H continues to decrease and TKE starts decreasing with a small decay rate until H rate reaches a minimum (H inflection point), 3) H decay rate increases (but is still negative) whereas TKE decay accelerates with a strongly decreasing rate.

Then, the timing of these three stages is rescaled in time using the averaged value of τ_{IOP_f} over the IOPs (Fig. 5b).

The method previously explained was applied to the 6 different vegetation covers. Very similar results are obtained (Fig. 6a) and all show the three stages already pointed out. The timings of stages 2 and 3 are converted in UTC and compared to the evolution of the composite H over IOP (Fig. 6b). Stage 2 begins between 1230 and 1400 UTC whereas stage 3 begins at the H rate inflection point whose timing ranges from 1530 to 1630 UTC according to the vegetation cover.

6. Conclusions

BLLAST experiment provides a very good data set to study the TKE decay close to the surface but also at different heights in the CBL. In addition to surface and airborne measurements, Remotely Piloted Aircrafts and turbulent measurement below tethered balloon have been performed and will enrich the analysis.

The analysis of the TKE decay in relation with the buoyancy conditions at the surface shows that the TKE does not decay with a constant time rate. This rate evolves in three stages: 1/ close to zero whereas H is already decreasing, 2/ low until H inflection point (between 1330 and 1600 UTC in average), 3/ high until sunset. The similar pattern obtained over the different vegetation covers shows that the TKE decay near the surface is strongly governed by buoyancy effects during BLLAST IOP days. The close timing pointed out between TKE decay and H decay remains to be explained, but this result shows that different surfaces and vegetation covers are able to imply TKE decay differences. However, disparity of each IOP curve to the composite could be quantified and related to the wind shear to study the impact of dynamical effect.

Acknowledgements

BLLAST field experiment was made possible thanks to the contribution of several institutions and supports : INSU-CNRS (Institut National des Sciences de l'Univers, Centre national de la Recherche Scientifique, LEFE-IDAO program), Météo-France, Observatoire Midi-Pyrénées (University of Toulouse), EUFAR (EUropean Facility for Airborne Research) and COST ES0802 (European Cooperation in the field of Scientific and Technical). The field experiment would not have occurred without the contribution of all participating European and American research groups, which all have contributed in a significant amount. BLLAST field experiment was hosted by the instrumented site of Centre de Recherches Atmosphériques, Lannemezan, France (Observatoire Midi-Pyrénées, Laboratoire dA érologie).The 60m tower is partly supported by the POCTEFA/FLUXPYR European program. BLLAST data are managed by SEDOO, from Observatoire Midi-Pyrénées.

REFERENCES

Brazel, A. J., H. J. S. Fernando, J. C. R. Hunt, N. Selover, B. C. Hedquist, and E. R. Pardyjak, 2005: Evening transition observations in Phoenix, Arizona, *J. Appl. Meteorol.*, **44**, 99–112.

Edwards, J. M., R. J. Beare, and A. J. Lapworth, 2006: Simulation of the observed evening transition and nocturnal boundary layers: single column modelling, *Quart. J. Roy. Meteorol. Soc.*, **132**, 61–80.

Fernando, H. J. S., M. Princevac, and E. R. Pardyjak, 2004: The decay of convective turbulence during evening transition period, *In: Proc: 11th Conference on Mountain Meteorology and MAP Meeting, Bartlett (NH), USA*.

Fitzjarrald, D. R., J. M. Freedman, M. J. Czikowsky, R. K. Sakai, O. C. Acevedo, and O. L. L. Moraes, 2004: Momentum and scalar transport during the decay of cbl turbulence, *In: Proc: 16th AMS Symposium on boundary layers and turbulence, 9-13 August 2004, Portland (ME), USA*.

Goulart, A., G. Degrazia, U. Rizza, and D. Anfossi, 2003: A theoretical model for the study of convective turbulence decay and comparison with Large-Eddy Simulation data, *Boundary-Layer Meteorol.*, **107**, 143–155.

Goulart A., B. Bodmann, M. de Vilhena, P. Soares, D. Moreira, 2010: On the time evolution of the turbulent kinetic energy spectrum for decaying turbulence in the convective boundary layer, *Boundary-Layer Meteorol.*, **138**, 61–75.

Grant, A. L. M., 1997: An observational study of the evening transition boundary-layer, *Quart. J. Roy. Meteorol. Soc.*, **123**, 657–677.

Lothon M. et al, 2012: The Boundary-Layer Late Afternoon and Sunset Turbulence field experiment, *In: Proc: 20th Conference on Boundary-Layers and Turbulence, Boston (MA), USA*.

Monin, A. S. and A. M. Yaglom, 1975: *Statistical fluid mechanics, Vol. 2*, John L. Lumley, Ed., The MIT Press, Massachusetts, 874 pp pp.

Nadeau, D. F., E. R. Pardyjak, C. W. Higgins, H. J. S. Fernando, and M. B. Parlange, 2011: A simple model for the afternoon and early evening decay of convective turbulence over different land surfaces, *Boundary-Layer Meteorol.*, **141**, 301–324.

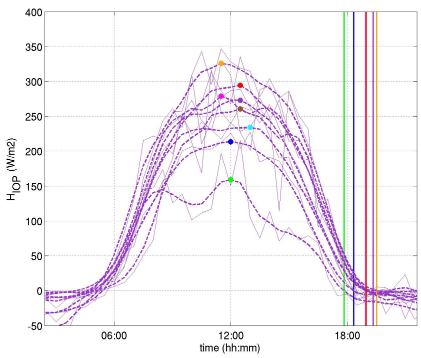
Nieuwstadt, F. T. M. and R. A. Brost, 1986: The decay of convective turbulence, *J. Atmos. Sci.*, **43**, 532–546.

Sorbjan, Z., 1997: Decay of convective turbulence revisited, *Boundary-Layer Meteorol.*, **82**, 501–515.

Stillinger, D. C., K. N. Helland, and C. W. Van Atta, 2010: Experiments on the transition of homogeneous turbulence to internal waves in a stratified fluid, *J. Fluid Mech.*, **131**, 91–122.

van Dijk, A., A. Moene, and H. A. R. De Bruin, 2004: *The principles of surface flux physics: theory, practice and description of the* ECPACK *library*, Internal Report 2004/1, Meteorology and Air Quality Group, Wageningen University, Wageningen, the Netherlands, 99pp pp.

(a)



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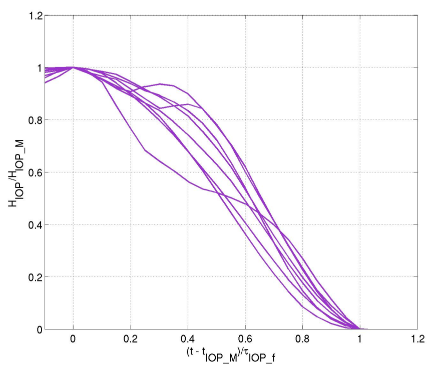

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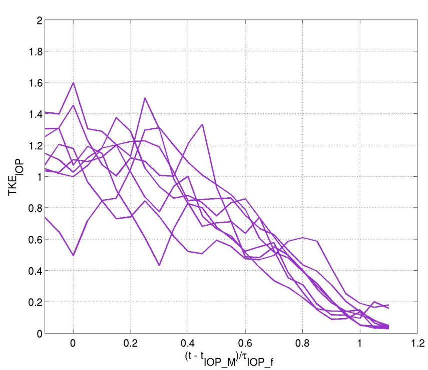
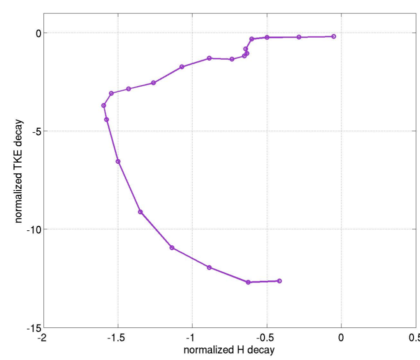


Figure 4: *(a) Temporal evolution of the sensible heat flux over wheat vegetation cover for 8 IOP of BLLAST campaign. Colored dots indicate t_{IOP_M} and colored vertical lines are for the time when sensible heat flux is zero. (b) Normalized sensible heat flux and (c) TKE against adimentional time.*

(a)



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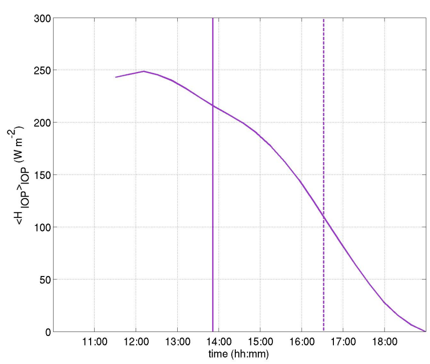
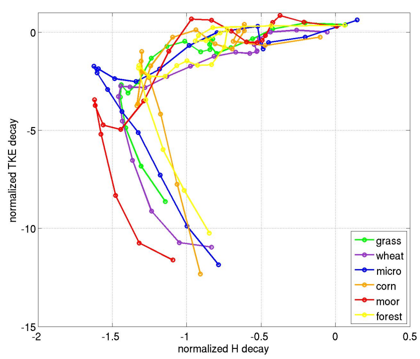


Figure 5: *(a) Composite evolution over IOPs of TKE decay against surface sensible heat flux decay. (b) Composite evolution over IOPs of surface sensible heat flux for wheat surface. Vertical dashed lines indicate the start of the second and third stages of the TKE decay.*

(a)



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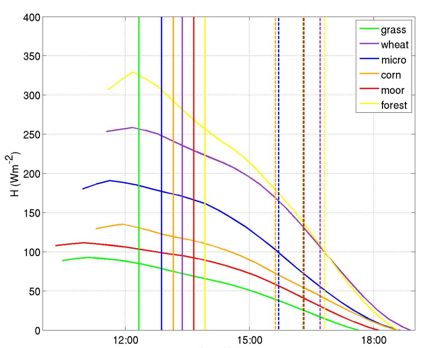

Figure 6: *Same as Fig. 5 but for all the vegetation covers.*