CHARACTERIZATION OF TURBULENCE AND THERMODYNAMIC STABILITY IN THE ATMOSPHERIC BOUNDARY-LAYER FOR AIR QUALITY NETWORK APPLICATIONS

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INTRODUCTION

Characterizing the structure and evolution of the atmospheric boundary layer (ABL) is crucial for better parametrizing this lowest part of the troposphere in models, as well as for air quality research and for understanding the water and energy cycle of the Earth system (Fersch, 2020). Highly resolved observations in space and time are key for a better knowledge about associated processes. Ground-based remote sensing instruments have proven to be capable of continuously monitoring vertical structures and the temporal variability of quantities like temperature, water vapor, and wind in the ABL (Wulfmeyer, 2015). Routine and long-term operation of active and passive sensors in ground-based networks and their synergistic application are vital for data assimilation and improvements of weather forecast models (Illingworth, 2007). In this study, we utilize a combination of microwave radiometer observations for temperature and humidity profiling and a Doppler wind lidar based classification algorithm to identify turbulent mixing and thermal stratification during different atmospheric conditions and showcase the ability for network application of these robust tools. Within ACTRIS, this work will serve as a valuable tool for studying the dispersal of pollutants at facilities where both in-situ and remote sensing observations are available.

Turbulence is a key process in the ABL dynamics and characterization. Its identification and classification is possible thanks to highly resolved and continuous measurements of the 3D wind vector by a Doppler lidar at the JOYCE observatory in Jülich, Germany (Manninen *et al.* 2018). Moreover, the turbulent processes in the boundary layer take place in a variably stratified medium, where the stratification acts as a moderator of turbulence. At this super-site, co-located temporally highly resolved temperature measurements from a microwave radiometer (MWR) allow characterizing the stability in the boundary layer and its evolution as well. The present investigation focuses on the synergy of Doppler lidar and MWR observations to characterize the boundary layer and quantitatively investigate the interactions between stratification and turbulence generated by different sources. In this manner, we show an example of the potential that simultaneous observations provide for characterizing the boundary-layer dynamics and evolution.

While weak stratification in the boundary layer is usually well described by similarity theory and numerical models, strong stratification is more difficult to resolve (Mahrt, 2014). Because of this, we investigate days with a stably stratified nocturnal boundary layer and the transition to the daytime boundary layer. Additionally, in order to consider the difference depending on the season, we provide two showcases: one in winter and one in late spring. The diurnal growth of the convective boundary layer is investigated by characterizing the stably-stratified conditions in which it develops and its evolution in the course of the day. A more rapid erosion in the stratification is identified during May than in winter-case.

METHODS

Simultaneous highly-resolved measurements of wind and thermodynamic profiles (temperature and humidity) at the Jülich Observatory for Cloud Evolution (JOYCE) in Western Germany (Loehnert, 2015) are employed in order to characterize the evolution of the boundary-layer processes during two highly stable-stratified episodes. The first episode took place during winter 2015 (14-16 February) and the second one in late spring of the same year (1-3 May). In both cases, a highly stably stratified nocturnal configuration was identified and its erosion in the diurnal cycle was investigated by identifying and characterizing the turbulence in the boundary-layer. In order to quantitatively perform this investigation two procedures were utilised and are described in the following subsections.

Turbulence classification via Doppler lidar measurements

An objective classification of turbulence in the atmospheric boundary-layer is shown in panels (a) and (b) of Figs. 1 and 2. The method used is based on Doppler wind lidar quantities to detect turbulent regions and identify different mechanisms of mixing (Manninen, 2018). Sources of turbulence include surface-driven convection during daytime, wind shear derived from horizontal wind information, and top-down mixing from cloud topped layers. The classification gives insights into diurnal and seasonal cycles of the cloudy boundary-layer in various climate regimes operationally and for long-term data sets, which makes it suitable for network applications In future, this classification shall be available for all ACTRIS national facilities with Doppler lidar observations.

Stability characterization via microwave radiometer temperature profiles

Temperature profiles from a microwave radiometer HATPRO are employed in order to identify thermally stable layers that act like a moderator for turbulent movements. Two episodes with very stable nocturnal stratification are analyzed and thermal inversions are identified in the nocturnal boundary-layer. The employment of high temporal resolution thermal profiles obtained from the HATPRO, allow us to quantify the nocturnal stability that is later dissolved through diurnal convection, as well as elucidate its evolution. In order to do so, the most thermally stable layer and its height are identified every hour during two stably stratified episodes, as it can be seen in panels (c) and (d) of Figs. 1 and 2. Additionally, on panels (e) we show the temperature profiles for these days retrieved from HATPRO up to 5000 m. The vertical resolution of the HATPRO is best in the lowest 500 m above ground (100-200 m), however rapidly declines as a function of height to values greater than 500 m at 1000 m height above ground.

RESULTS

The evolution of two highly stably-stratified cases is investigated. The synergy of wind Doppler lidar (providing turbulence variables) and a microwave radiometer (providing thermal stability) is shown to be significantly revealing for the investigation of boundary-layer evolution. This evolution involves convectively-driven turbulence in a stratified media, which will be further elucidated via the estimation of parameters that consider both thermal stability and velocity mixing, such as the Richardson bulk number. Thanks to the fact that at JOYCE all of these variables are continuously measured, it is possible to closely investigate the diurnal evolution of these parameters, as well as their variability in height.

Two episodes with highly stable stratification are investigated. Firstly, 14-16 February 2015 is shown in Figure 1. Before sunrise on 14th February, stably stratified conditions are observed, in

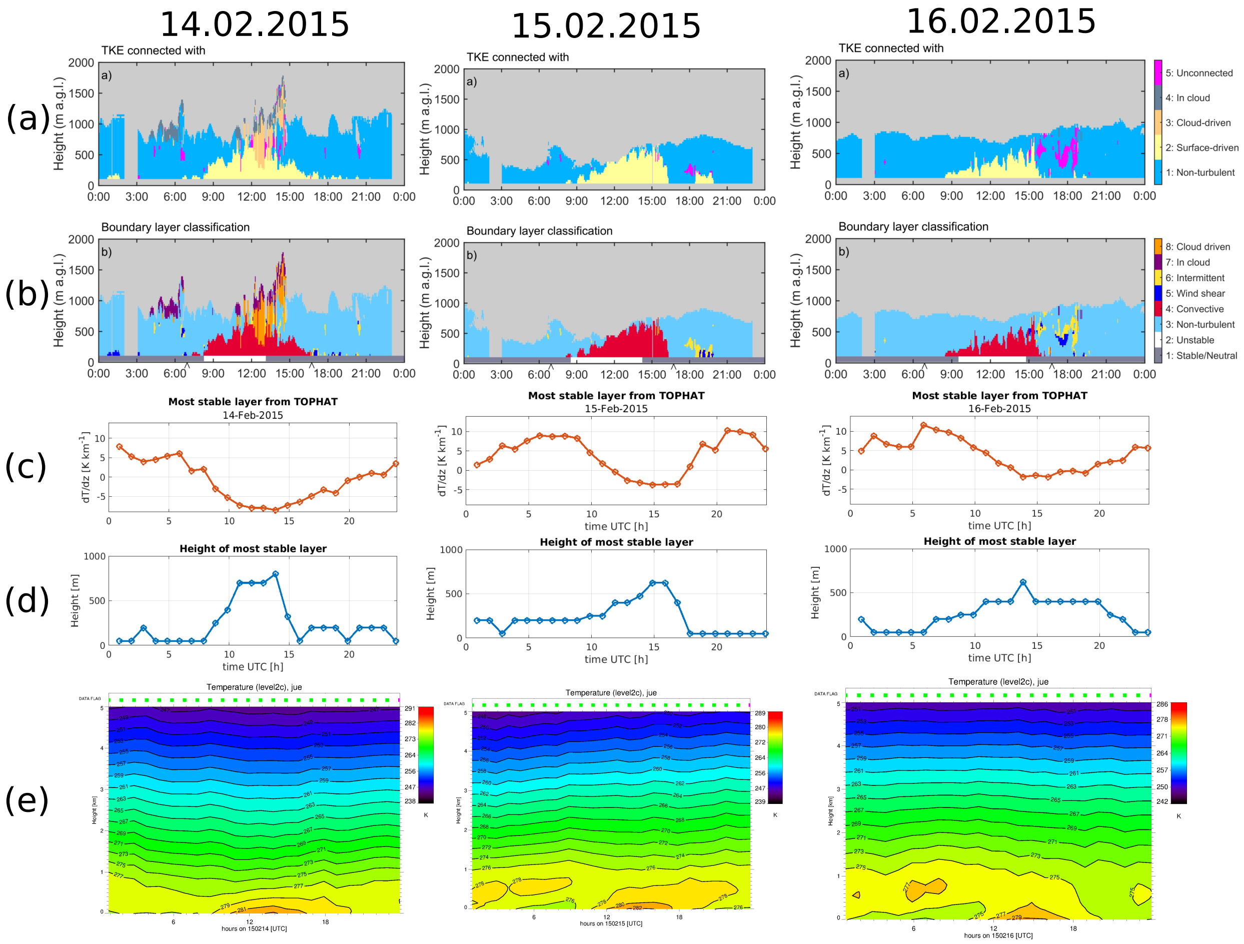

Figure 1: Winter day-cases in February 14th (left), 15th (middle) and 16th (right panels) in which the atmospheric boundary layer classification is shown (a and b). A differentiation is made between the cases when there is a connection with the surface and when the turbulent mixing source is not in the surface (i.e., surface driven versus cloud driven). In (c) and (d), the diurnal evolution of the maximum gradient of temperature with height (red), which corresponds to the most stable layer from ground to 1000 m a.g.l. and its height (blue) are shown. Finally, the diurnal evolution of the vertical temperature profiles up to 5000 m, obtained from HATPRO, is shown in (e).

which inversions dT/dz peak above $5Kkm^{-1}$. During the following day-time conditions, dT/dz reaches values close $-10Kkm^{-1}$ for a short period between 12 an 14 UTC, indicating a well mixed boundary layer up to 750 m a.g.l. This surface-driven mixing is enhanced by a cloud-layer around 1000 m height, itself initializing a cloud-top driven mixing. In the nocturnal boundary layer of 15 and 16 February (Fig. 1 (c) and (d) panels) even higher $dT/dz > 5Kkm^{-1}$ values are observed and these are more persistent than on the day before. On these two days, the following surface-driven convective turbulence is shown to only weakly grow in height during the day, hardly reaching higher altitudes than 600 m. In this case, the strong nocturnal inversion, paired with the weak convective motions due to the low winter solar irradiation are not strong enough to effectively dissolve the stable boundary layer.

Secondly, an episode with nocturnal highly stable conditions during spring is investigated. From 1-3 May 2015, it is shown that strong thermal inversions develop, reaching $dT/dz > 10Kkm^{-1}$ on May 2nd before sunrise. However, the persistence of these thermal inversions is much weaker than in the winter case. The strong solar insolation increase during May brings forth enough

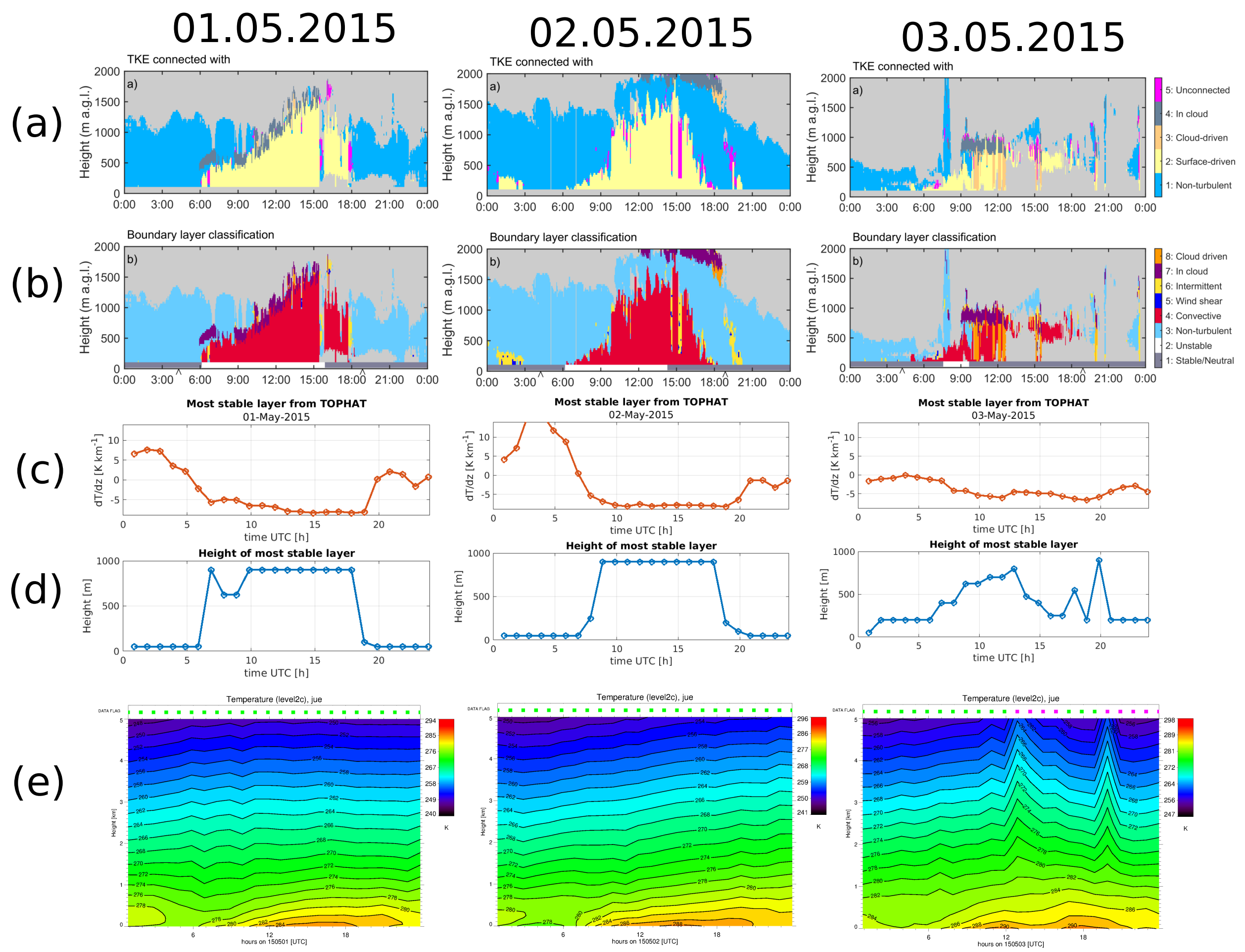

Figure 2: Spring day-cases in May 1st (left), 2nd (middle) and 3rd (right panels) in which the atmospheric boundary layer classification is shown (a and b). In (b) and (c), the diurnal evolution of the maximum gradient of temperature with height (red), which correspond to the most stable layer from ground to 1000 m a.g.l. and its height (blue). The diurnal evolution of the temperature structure up to 5000 m, obtained from HATPRO, is shown in (e).

convectively-driven turbulence to rapidly dissolve the inversion, as it can be seen in Figure 2 ((a) and (b) panels). During these spring days at daytime, dissolving thermal inversions are clearly mirrored in the turbulence classification, which shows that the height of daytime convective layers reaches 1000 m and higher. Additionally, the thermodynamic stability that can be elucidated with HATPRO data shows that, although strong inversions can develop during nighttime, well-mixed conditions are reached in daytime hours of May 1 and May 2 ($dT/dz \ -10K/km$), while the height of the well-mixed conditions grows during daytime. On May 1 the early formation of clouds around 6 UTC hinders a rapid increase of the convective mixing layer depth; both the mixing layer depth grows and the stability decreases continuously, but rather slowly until around 13-14 UTC. On May 2 (cloud free before noon), a much more rapid growth of convective mixing layer depth and a well as decrease of stability is observed. It is interesting to note, that, especially on May 2, there is a rather rapid break-down of turbulent mixing between 16 and 17 UTC, whereas the temperature profile still shows a dry-neutral state up to 19 UTC. May 3 differs from the other days due to the fact, that after a rapid increase of the convective mixed layer depth, a closed cloud deck forms at 9 UTC, leading to a mixture of surface-driven and cloud-driven turbulent mixing. After the cloud disappears around 14 UTC, solar radiation is not able to heat the surface enough in order to initiate a further surface-driven convective boundary layer. During this day, the static stability in the boundary layer remains around the moist-neutral gradient.

The present synergy employs Doppler lidar measurements for turbulence classification in transitions of highly-stratified boundary to convective boundary layer characterized by thermodynamic profiles derived from a microwave radiometer. The analysis that can be made thanks to these simultaneous highly-resolved measurements are capable of elucidating the processes in the boundary layer as it evolves in the diurnal cycle. Furthermore, given that there is a continuous monitoring of these relevant dynamical variables at JOYCE and other ACTRIS Cloudnet sites, the next step of this research will analyse averaged diurnal and seasonal statistics as a function of climatological region. Such analyses are crucial for a better characterization of the lower troposphere and can be used for improving the boundary layer parametrization schemes of numerical models as well as for air quality applications, especially in combination with ACTRIS in-situ observations.

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