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Short communication

On the factors governing water vapor turbulence mixing in the convective boundary layer over land: Concept and data analysis technique using ground-based lidar measurements

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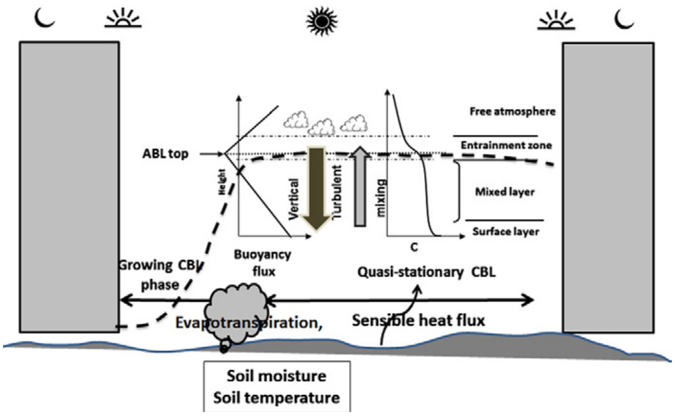
HIGHLIGHTS

- Lidar based study for CBL turbulence features
- Water vapor and aerosol turbulence profiles
- Processes governing boundary layer turbulence profiles using lidars

GRAPHICAL ABSTRACT



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ABSTRACT

The convective boundary layer (CBL) turbulence is the key process for exchanging heat, momentum, moisture and trace gases between the earth's surface and the lower part of the troposphere. The turbulence parameterization of the CBL is a challenging but important component in numerical models. In particular, correct estimation of CBL turbulence features, parameterization, and the determination of the contribution of eddy diffusivity are important for simulating convection initiation, and the dispersion of health hazardous air pollutants and Greenhouse gases. In general, measurements of higher-order moments of water vapor mixing ratio (q) variability yield unique estimates of turbulence in the CBL. Using the high-resolution lidar-derived profiles of q variance, third-order moment, and skewness and analyzing concurrent profiles of vertical velocity, potential temperature, horizontal wind and time series of near-surface measurements of surface flux and meteorological parameters, a conceptual framework based on bottom up approach is proposed here for the first time for a robust characterization of the turbulent structure of CBL over land so that our understanding on the processes governing CBL q turbulence could be improved. Finally, principal component analyses will be applied on the lidar-derived long-term data sets of q turbulence statistics to identify the meteorological factors and the dominant physical mechanisms governing the CBL turbulence features.

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1. Introduction

Measurements of near-surface thermodynamic variables and characterization of turbulence features using eddy covariance method are common, routinely achieved around the world, and have been well documented (e.g., Aubinet et al., 2012). We do not often reach to observational "truth" of the variables we are mainly interested in. For example, we may want to investigate the structures of eddies in the convective boundary layer (CBL), but we only get profiles of state variables or relevant parameters that include both the mean state as well as the turbulent component embedded in them. On the other hand, we can use models (e.g., large eddy simulations) that are detailed, limited only by computational resources and our understanding on the turbulence processes, but these models may not represent turbulence profiles appropriately due to inherent model configuration problems or parameterization issues. How can we best reconcile the gaps in our model knowledge using observations that may be erroneous and not directly related to the quantities we are truly interested in? Therefore, the investigation of the vertical variability of the turbulence features in the quasi-stationary CBL (often deep with CBL height, z_i, of more than 1.0 km above ground over land surface) is not straightforward which calls for high spatiotemporally resolved measurements of the state variables within and above the CBL using new methodologies and validation of models at a later stage.

The development of the boundary layer in convective conditions, and the depth of the layer must be well understood to relate fluxes and concentrations. A large scientific community interested in air pollution and greenhouse gas budgets are interested in precisely tracing the mixing depth to improve predictions of atmospheric tracers (Hu et al., 2014; Paris et al., 2014; Pal et al., 2012, 2015a). In general, the CBL height (z_i, also called CBL depth) is a key parameter to understand and quantify mixing of atmospheric constituents and tracers like water vapor, aerosols, and trace gases (e.g., Srivastava et al., 2014) since it defines the volume of the CBL where turbulence mixing takes place. Within the CBL, aerosols are accumulated and clouds are also formed and the key sources of heat, water, moisture generally lie here. Therefore, almost any measurement or prediction inherently involves the spatiotemporal variability of z_i. Consequently, an unambiguous monitoring of z_i during different dynamical, thermal and stability regimes prevailing throughout the entire diurnal cycle is of paramount importance for turbulence profiling of CBL.

Different geophysical processes and feedback mechanisms contribute to the land-atmosphere interactions which play an intricate role in determining z_i variability and turbulence features on a diel timescale. For instance, heat fluxes, energy transfers between land and atmosphere, as well as CBL dynamics contribute to the shaping of local and regional climate characteristics (e.g., Stull, 1988; Kara et al., 2002). Pal and Haeffelin (2015b) illustrated that even slight changes in the soil moisture affect the z_i variability on diurnal time scale. While analyzing the variability in the both latent and sensible heat fluxes for the same period, they found that the sensible (latent) heat fluxes are higher (lower) for the regimes with lower (higher) soil moisture concentration governing the z_i variability. In most of the large eddy simulation studies and lidar-based studies, z_i is used as scaling parameter so that the vertical profiles of aerosol, temperature, water vapor turbulence, and heat flux are investigated with respect to z/z_i where z is altitude (e.g., Mahrt, 1991; Couvreux et al., 2007; Behrendt et al., 2015). Key advantage of such scaling as has been considered in this study is that the results obtained from various sources (e.g., tower-based in-situ, ground-based lidar, aircraft measurements) can be directly compared as well as used for the purposes of model validation and parameterizations (e.g., Turner et al., 2014).

Aerosol vertical and temporal variability is used to trace mixing (e.g. from lidar backscatter); however, it should be noted that aerosol distributions are also influenced by other physical and chemical processes (e.g., Behrendt et al., 2011b; Lac et al., 2013; Zhang et al., 2015; Pal, 2014; Pal and Haeffelin, 2015b). Fig. 1 depicts a simplified diagram explaining major components of the CBL development and cloud formation during daytime where the z_i variability is clearly marked on a typical diel cycle. Shortly after sunrise, thermals begin to form near the surface, which transport warm air upward and cause entrainment of warm air from above the nocturnal inversion into the nocturnal boundary layer, NBL (e.g., Stull, 1988; Pal et al., 2013). Once the near surface inversion is eroded, surface heating and upward turbulent heat fluxes increase, a rapid growth of the CBL is observed until the time when the z_i reaches the capping inversion near the residual layer (RL) top, typically towards solar noon. At that point, the z_i variability becomes quasi-stationary without any significant growth rates (Stull, 1988). The nature of the transition (direct transition from stable to very unstable or through neutral stable) defines the delay in the onset (from sunrise) of the CBL growth in the morning. Followed by the sunrise and crossover, the convective eddies mixes the air so that the stable boundary layer characteristics are dissipated. In the evening, after sunset, the CBL decouples from the surface as mixing is inhibited between the surface and the RL. In general, once the turbulent kinetic energy starts to drop, the turbulent mixing near the surface also starts to be limited within a shallow layer.

Additionally, routine investigation of the turbulence features even for CBL in diverse meteorological conditions remained highly challenging. However, recent advances in lidar remote sensing technology yielded a step forward for this research (e.g., Pal and Devara, 2012; Pal et al., 2014). The differential absorption lidar (DIAL) and Raman lidar (RLID) have unique capability for profiling q within the CBL with high temporal and spatial resolutions. For instance, water vapor and temperature lidars systems can provide measurements to heights of ~4 km in daytime and ~10 km at night (e.g., Wulfmeyer et al., 2010).

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program's RLID at the Southern Great Plains site in north central Oklahoma is one of the few (<5) truly operational water vapor RLs in the world and currently no operational water vapor DIALs exists. Only recently, ground-based RLIDs have been found useful to define higher-order moments of q turbulence statistics in the CBL within case studies (Wulfmeyer et al., 2010) as well as for a long-term data set (Turner et al., 2014).

However, our knowledge about the physical mechanisms and the factors governing q turbulence features in the well-mixed CBL regimes remained limited. The understanding of the role of near-surface thermodynamics, boundary layer dynamics, entrainment processes at z_i, CBL forcing mechanisms, clouds, and in particular of their interaction under well-mixed regimes is one of the challenging tasks to better understand the mechanisms governing the CBL turbulence processes. Precisely, some gaps are still present in our knowledge in identifying and describing physical processes that can explain CBL q turbulence.

In the past, water vapor measurements obtained from both ground-based and airborne DIALs were used to determine turbulence moments up to fourth order (e.g., Wulfmeyer et al., 2010). Lenschow et al. (2000) determined turbulence moments for both q and vertical velocity (w) for well mixed CBL regimes while Pal et al. (2010, 2013) applied for aerosol turbulence features. Recently, Turner et al. (2014) confirmed the ability of the ARM RLID system to measure the q variance and skewness in the CBL using comparisons with aircraft measurements using few case studies. Most of the studies based on DIAL or RLID observations were limited to case studies except the recent study by Turner et al. (2014) where they illustrated the potential of the RLID for long-term measurements of turbulence features in the well-mixed CBL. Additionally, they also found that q variance profiles at z_i vary seasonally and are strongly related to the gradient of q across the entrainment zone (EZ). However, a more comprehensive detail on the forcing mechanisms driving the vertical variability of q turbulence moments is still required so that a conceptual framework for the CBL moisture regimes could be developed. The goal of this paper is to discuss an observational approach for investigating aerosol and water vapor turbulence profiles in the daytime CBL