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Title: Ground-based observations for assessing sensitive and latent heat fluxes in the Atmospheric Boundary Layer over western Germany

Abstract:

The land-atmosphere interactions that take place in the Atmospheric Boundary layer (ABL) involve energy and water fluxes that have a significant impact on different processes, such as cloud formation and extreme events. While the quantification of energy budgets in the daytime ABL is a challenging task, it is highly relevant, given that it is necessary to better parametrize the involved processes in weather and climate models. The present research offers an observational perspective of energy and water fluxes, which is relevant in order to be compared with model assessments that have been performed in previous investigations (Santanello et al. 2018, Milovac et al 2016). Moreover, the growing coverage of high-quality ground-based measurements (performed in networks such as the Aerosol, Clouds and Trace Gas Research Infrastructure, ACTRIS) provide a suitable starting point to perform observational studies of sensitive and latent heat fluxes in the ABL. Furthermore, the capabilities and limitations of the measurements and their resulting variables need to be assessed, and the present research provides an evaluation of such products.

We utilize measurements at the Jülich Observatory for Cloud Evolution (JOYCE), in particular, temperature and humidity profiles from an azimuth-scanning MicroWave Radiometer (MWR) and 3D wind vector from a Doppler Wind Lidar (DWL). Synergistic variables are obtained: Richardson bulk number (Rib) for ABL height determination, as well as local temperature and humidity advections. Rib is a measure of instability in the ABL that considers both thermal and dynamical characteristics; moreover it can be relatively easily estimated. Nevertheless, advection is a more challenging variable to be estimated utilizing only measurements from DWL and MWR. While previous authors have estimated advection from temperature and humidity profiles measured with ground-based remote sensing at different locations (Wagner et al. 2021), the present investigation utilizes a single scanning instrument to asses thermal and humidity horizontal inhomogeneities. In order to achieve that, horizontal differences of temperature and humidity are computed from the MWR azimuth-scans at 30° elevation and also horizontal velocities from DWL are employed. Appropriate vertical restrictions and averaging are applied to derive rough local values of temperature and humidity advection within the ABL. In turn, the synergistically-obtained variables, i.e., Rib, and advections, are utilized to then quantify energy budgets with the mixing diagram approach.

In a mixing diagram we can investigate the temporal co-evolution of the vertically-averaged ABL sensible and latent heat over a defined time interval. Over this time interval, the overall sensitive and latent energy budgets in the ABL are explained as a sum of surface fluxes, advection, and entrainment. Therefore, a quantification of these processes is done considering the closing of the energy budgets in the ABL. We build mixing diagrams as follows:

1. $C_p\theta \; vs \; Lq$ Evolution: obtained from MWR from surface up to ABL height (from Ri_B).
2. Surface sensitive and latent heat fluxes: obtained from a close-by Eddy-Covariance station from the Integrated Carbon Observation System (ICOS) in Selhausen.
3. Advection: estimated from MWR horizontal inhomogeneities and velocities from DWL.

4. Entrainment: estimated as a residual vector as in Santanello et al. (2009).

The resulting product from the mixing diagrams is the entrainment. Although this variable is estimated as a residual vector to close the energy budget, the magnitude of entrainment can be related to the land-atmosphere coupling. Furthermore the quantification of entrainment regulates the exchange of momentum and scalars (such as water vapor and pollutants) between the ABL and the free troposphere. Nevertheless, quantification of entrainment at the top of the ABL is notoriously difficult both in observations and models (Santanello et al. 2018). In this context, the present research provides a completely observational entrainment estimation. Although uncertainties are currently found to be high and an automatization of the present entrainment quantification is still not possible, the current research does elucidate the capabilities of remote-sensing synergies to quantify this crucial variable in a particular study-case of a very warm period over western Germany. In particular, three summer days in June 2022 are investigated. These days were perceived as a heat wave, as it was pointed out by the German Weather Service; therefore they constitute a particularly interesting period to be addressed.

Although we emphasize that careful assessment of uncertainties in the synergistically-obtained variables is crucial and still a challenging task, our results are physically realistic for the study case (16-18th of June 2022). This research suggests that the entrainment has a high contribution in warming the ABL in days when very high surface temperature are reached. This is likely to be induced by a very significant contribution of potentially warmer air subsiding and enhancing high temperatures in the ground, which are perceived as a heat wave. Such a situation is in accordance with the subsiding potentially warmer air from the middle-troposphere has a significant role in the development of heat waves. The interaction of these larger-scale processes with the ABL dynamics is a crucial matter in order to better understand the development of heat waves (De Villiers et al. 2020). The present investigation aims to contribute to this interaction between the ABL and the free troposphere; illustrating the capabilities of ground-based remote sensing synergies.

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Session selection:

Select the area of research to which you wish to submit your abstract *(Required)*

- ◉ Determination of the extent to which Earth's water cycle can be observed and predicted
- ○ Quantification of the inter-relationships between Earth's energy, water and carbon cycles to advance our understanding of the system and our ability to predict it across scales
- ○ Quantification of the anthropogenic influences on the water cycle and our ability to understand and predict changes to Earth's water cycle
- ○ Extremes in the water cycle and risks to society
- ○ Open Session

Select the topic *(Required)*

- ◉ Observing the energy, water, and carbon cycles
- ○ Energy, water, and carbon cycle balance studies
- ○ Regional and catchment scale perspective on the water and energy cycles
- ○ Emergent issues

Select your prefered session *(Required)*

- ○ Observing the Water Cycle from Space
- ○ Global Precipitation Experiment (GPEX)
- ◉ Novel observation methods from ground-based, airborne, and space platforms for closing observational gaps in the water, energy, and carbon cycles
- ○ Reconstruction of Historical Global and Regional Hydroclimate Systems
- ○ Sustainability of groundwater resources

Alternative session:

Select the area of research to which you wish to submit your abstract *(Required)*

- ○ Determination of the extent to which Earth's water cycle can be observed and predicted
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- ○ Extremes in the water cycle and risks to society
- ○ Open Session

Select Topic *(Required)*

- ○ Atmospheric processes (Centennial celebration of atmospheric science education and research in China)
- ○ Land surface processes
- ◉ Land-atmosphere coupling
- ○ Modelling the Earth system

Select your prefered session *(Required)*

- ○ Land-Atmosphere Interactions and Climate Predictability, Including Subseasonal to Seasonal (S2S)
- ○ Land-Atmosphere Interactions and Water Cycle over the Third Pole Region
- ○ Grand Challenges in Land-atmosphere Interaction in Asia
- ◉ Land-Atmosphere System – synergetic observations, modeling for improved process understanding (incl. Atmospheric boundary layer/GLAFO)