The vertical structure of the Saharan boundary layer: Observations and modelling

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1. Introduction

Aircraft and ground observations from the FENNEC observational campaign over the data-sparse central Saharan region, combined with a cloud-resolving model, are used to investigate the turbulence and mixing structure of the Saharan boundary layer (SABL).

The Saharan atmosphere is a key component of the climate system, as a major dust source and an important driver of the West African monsoon. The SABL is one of the deepest on Earth, commonly reaching 5-6km, and is crucial in controlling the vertical redistribution and transport of dust, moisture, heat and momentum fluxes in the Sahara. Its unusual depth, and particular structure, with only a very small temperature inversion separating the convective boundary layer (CBL) from the residual layer (RL), suggests there may be significant differences in the mixing within and between these layers compared to a typical boundary layer .

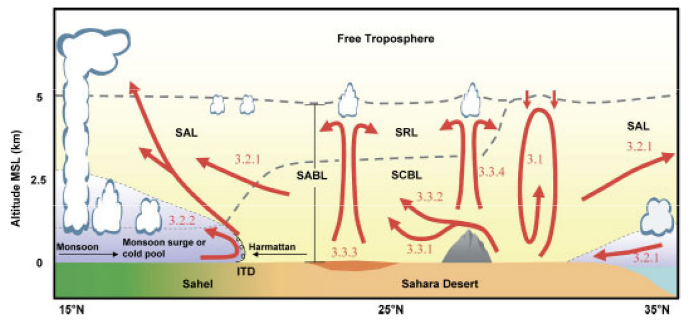


Figure 1: Schematic of the mechanisms (red arrows) which control the SABL structure and dust vertical redistribution (Cuesta *et al.*, 2009).

2. Modelling approach and validation

The Met Office Large Eddy Model (LEM) was used at 200m horizontal and variable vertical resolution to set up an idealized SABL simulation. Data from the Fennec supersite at Bordj-Badji Mokhtar (BBM) on 20/06/11 were used to initialize the model at 06Z and provide the prescribed surface fluxes for the 12 hour simulation.

Figure 2 compares the LEM results to the BBM radiosondes at 12 and 18Z.
• The three main layers of the SABL appear well represented in the simulation at 12Z. By 18Z the CBL has grown into all of the RL and reached its maximum extent in both the simulation and observations.
• The temperatures are 1-2K too warm in the model at 12Z, but slightly too cool at 18Z.
• The SABL height is lower in the model.

The above two discrepancies do not have a significant impact on the boundary layer processes of interest. They can be attributed to processes that are missing in the LEM, such as:
• *Large scale advection*: Can change the location of the residual layer/free troposphere boundary.
• *Dust radiative impacts*: Dust can either warm or stabilize the SABL depending on its location. The impact of dust is poorly understood and beyond the scope of this study.
• *Large-scale subsidence*.

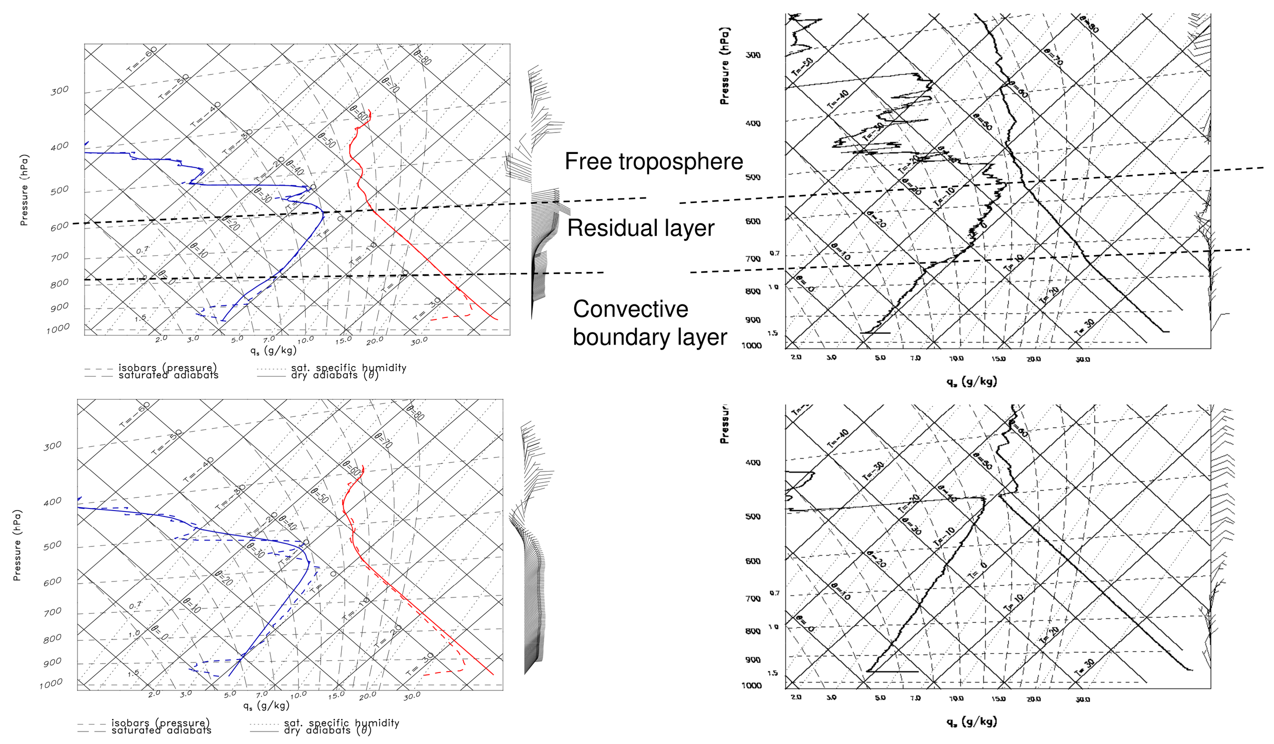


Figure 2: Domain-mean tephigram from the LEM (left) and BBM (right) at 12Z (top) and 18Z (bottom).

3. SABL vertical structure in the model

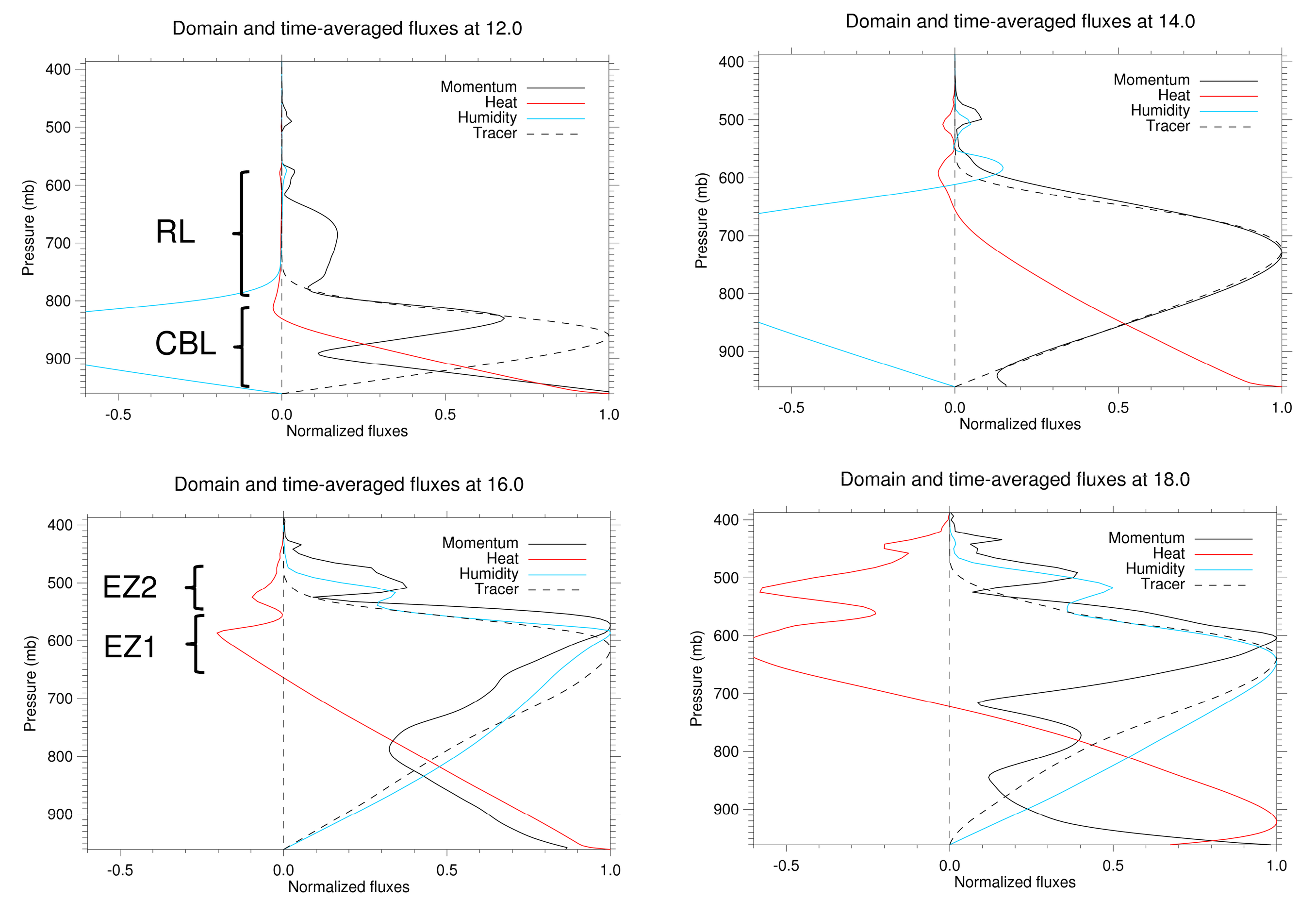


Figure 3: Normalised fluxes in model at 12Z (top left), 14Z (top right), 16Z (bottom left) and 18Z (bottom right). CBL: convective boundary layer, RL: residual layer, EZ: entrainment zone.

- **PBL height varies between ~570-700mb at 18Z.**
- **Eddie length-scales are of 5-10km**, increasing with time, consistent with the CBL height. Updraughts peak at over 3m s^{-1}.
- **Main entrainment zone (EZ1) is particularly deep (~100mb).** This could be due to either the very deep CBL (longer acceleration of parcels) or very small inversion (reduced return force for overshooting parcels). Large variability in CBL depth may also contribute to this.
- **EZ1 is assymetrical**, about twice as deep below the minimum compared to above.
- **There is a second entrainment zone (EZ2) between the residual layer and free troposphere.** Fluxes are about 50% compared to EZ1. Could either be shear-induced from above, or thermals escaping the CBL from the bottom.
- **There is transport of tracer (initialized at the surface) from the CBL into the residual layer.** Seen in the tracer concentrations (amounts of ~50% compared to CBL), and also the slightly positive tracer fluxes in the RL. Cause could be clouds (at least partially responsible) but also turbulent transport. No tracer escapes the RL into the free troposphere.
- **Cloud formation occurs at local peaks in the CBL height** as also observed on the onboard aircraft lidar (not shown)**.**

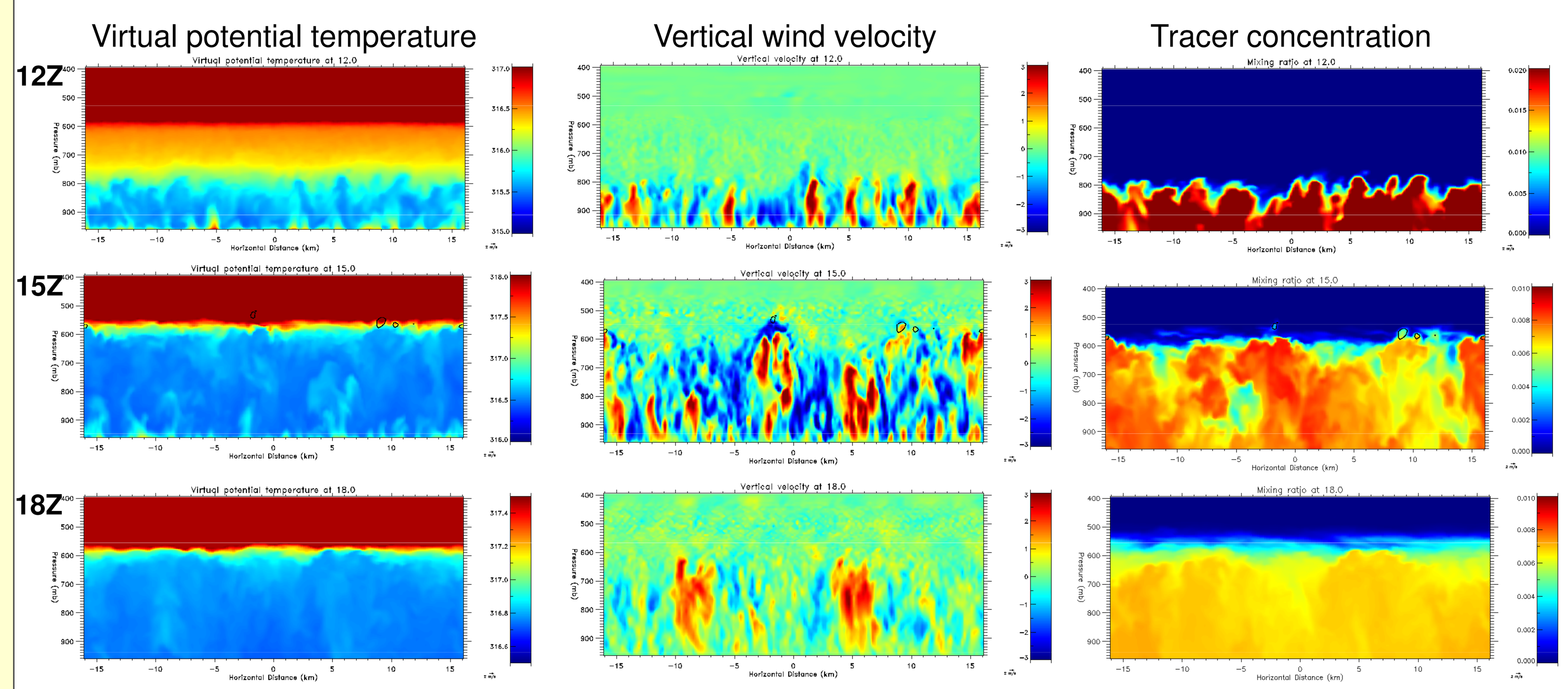
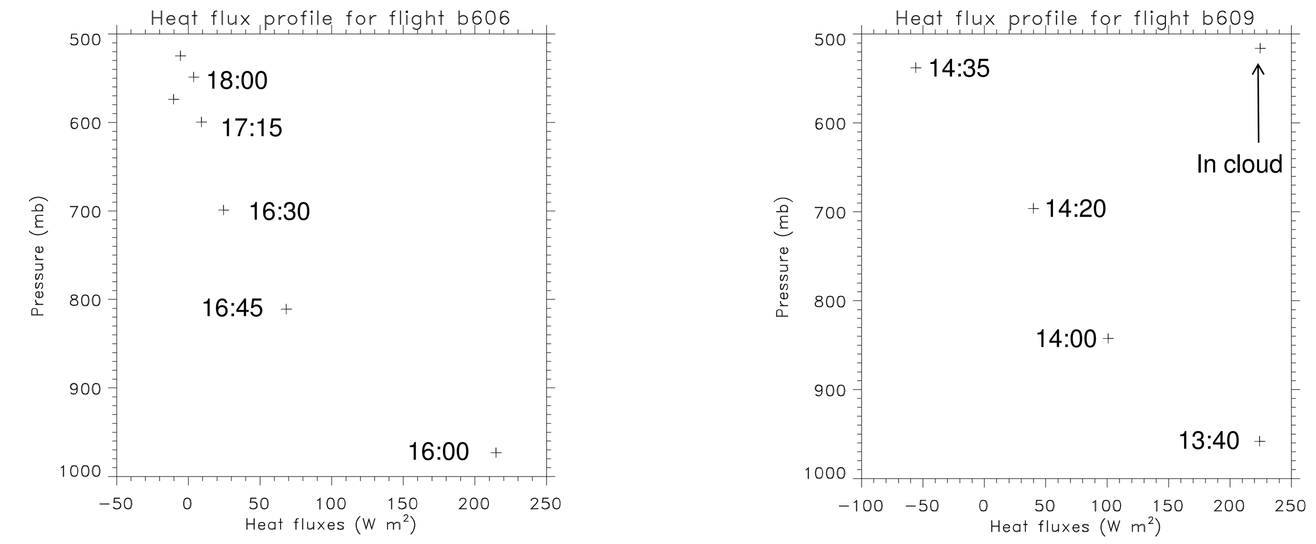


Figure 4: Virtual potential temperature (left) vertical wind velocity (middle) and tracer concentration initialized at the surface (right) at 12Z, 15Z and 18Z (top to bottom). Black contours are clouds.

4. SABL vertical structure in aircraft observations



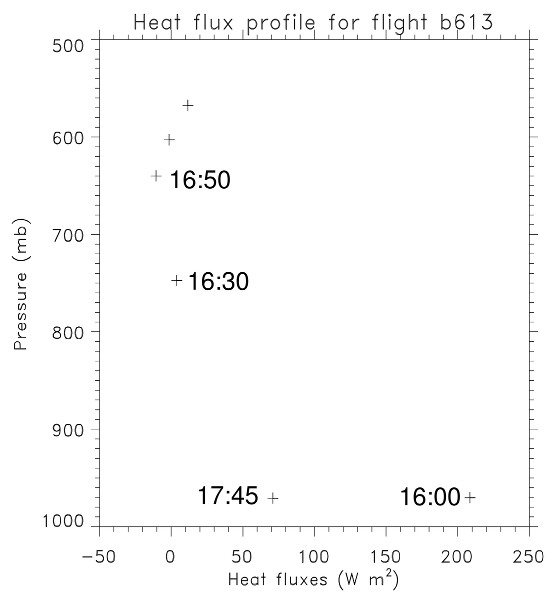


Figure 5: Sensible heat flux profiles from three FENNEC flights. Times of legs shown next to each data point (UTC).

- First aircraft-derived heat flux profiles over the remote Sahara.
- Flux magnitudes and heights consistent with model, as is the CBL top variability as observed in dropsonde data.
- The (straight line) CBL fluxes are well sampled, but the entrainment zone fluxes were very weak due to time evolution during the flight.
- B613 highlights the significant time-evolution of low-level fluxes between 16:00 and 17:45 UTC.
- Entrainment zone fluxes are weak on two of the flights due to time evolution, but are still consistent with the low-level fluxes at that time as observed on B613 (~20-25%).

6. Conclusions

The vertical structure of the SABL, with its three distinct layers (convective, residual and free troposphere) are well reproduced by the LEM model. Some differences with observations remain, particularly with a different maximum extent of the SABL, probably due to missing large-scale and dust processes.

Certain features observed particular to the SABL are:
- A particularly deep boundary layer, with large variability in its height and a deep entrainment zone (up to 100mb).
- A second entrainment zone between the residual layer and the free troposphere, related to shear at the RL top, but potentially also thermals entering the RL from the CBL.
- Transport of tracer from the CBL to the RL – particularly important for dust transport.

The first *in situ* observations of the boundary layer in the central Sahara provide a first insight in the vertical structure of heat fluxes from observations. Future work will use these observations to gain a better understanding of the turbulence structure at each level.

Acknowledgements

The Fennec project was funded by the UK Natural Environment Research Council grant NE/G017166/1. The authors would also like to thank all those involved in the deployment of the FAAM aircraft.

References

Cuesta, J., Marsham, J. H., Parker, D. J. and Flamant, C. (2009), Dynamical mechanisms controlling the vertical redistribution of dust and the thermodynamic structure of the West Saharan atmospheric boundary layer during summer. Atmosph. Sci. Lett., 10: 34–42. doi: 10.1002/asl.207