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A Lagrangian View to the Evolution of Convective Updrafts

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1. Introduction

Modelling convection is a known source of uncertainty within current operational weather and climate models. Convection is largely represented as a sub-grid process. Small-scale features of convection, such as entrainment and detrainment, require parameterisation. However, parameterisations can have simplistic assumptions, introducing sources of error. These processes are modelled more accurately by Large Eddy Simulation (LES), though the higher resolution is computationally expensive. This work develops a stochastic-Lagrangian parcel model to represent convective updrafts. The Lagrangian element of the model allows the tracking of how parcel characteristics change over time. The changes caused by certain processes can be diagnosed and analysed. We aim to further our understanding of convective processes and inform improvements to how convection can be parameterised in large-scale models.

2. Model Description

Initial conditions and forcings of the model are based on the BOMEX campaign[1]. The single column model contains a large ensemble of air parcels, each carrying values of velocity and conservative variables for heat and moisture.

- The stochastic term in (1) represents turbulent motions. Relaxation terms simulate the dissipation of turbulence towards the ensemble mean, governed by a turbulent time-scale.

$$w_p^{n+1} = w_p^n + \left(-\frac{w_p^{n+1}}{\tau} - \frac{w_p^{n+1}|w_p^n|}{L} + \frac{g\left(\theta_{v_p} - \overline{\theta_v}\right)}{\overline{\theta_{v_0}}} + C_w dW_w\right)dt \quad (1)$$

- Ensemble mean is calculated as a weighted kernel average of nearby parcels.

$$\theta_{l_p}^{n+1} = \theta_{l_p}^n + \left(\frac{\theta_{l_p}^{n+1} - \overline{\theta_l}}{\tau}\right)dt \quad (2)$$

- For the buoyancy term in (1), parcels are buoyant relative to θ_v, requiring that q_{tot} be split into q_v and q_l components. This is done using a Newton iterator and a reference pressure profile to find the q_{sat} of the parcels, and the value of θ_l is adjusted accordingly. This allows latent heat release to be captured by the model.

$$q_{tot_p}^{n+1} = q_{tot_p}^n + \left(\frac{q_{tot_p}^{n+1} - \overline{q_{tot}}}{\tau}\right)dt \quad (3)$$

- If a parcel passes within the lowest 1% of the boundary layer (BL), a surface flux term is applied. Here, the surface forcings are distributed amongst the parcels at each time-step, generating surface instability and rising motions. The same method is used for both θ_l and q_{tot}.
- A method of ensuring that parcels remain in uniform density has also been devised, utilising the kernel density estimation (KDE). Parcels are displaced from regions of high KDE to regions of lower KDE in incremental amounts in each time-step. This process is a proxy of dynamic pressure and allows the well-mixed criterion to be satisfied[2].
- The model utilises an algorithm to ensure conservation of the key variables θ_l and q_{tot}. This introduces a correction to the relaxation terms in (2) and (3) to ensure that the ensemble retains the original values of heat and moisture, plus that introduced via the surface terms. As such, the relaxation terms will not generate or lose excesses in heat or moisture.
- The time-scale τ varies dependent upon the parcels' position. Within the BL, it is based upon the ensemble average TKE and the dissipation rate of TKE. Above the BL, this is based upon the parcel's individual energy, as the influence of turbulence reduces. As such, a fast moving parcel above the BL relaxes towards the ensemble mean faster. A similar approach is taken with C_w, where stochastic contributions are larger for faster moving parcels outside of the BL.
- For the dry convective boundary layer case, moisture variables can be set to zero and θ_l reduces to θ.

3. Preliminary Results: Dry Case

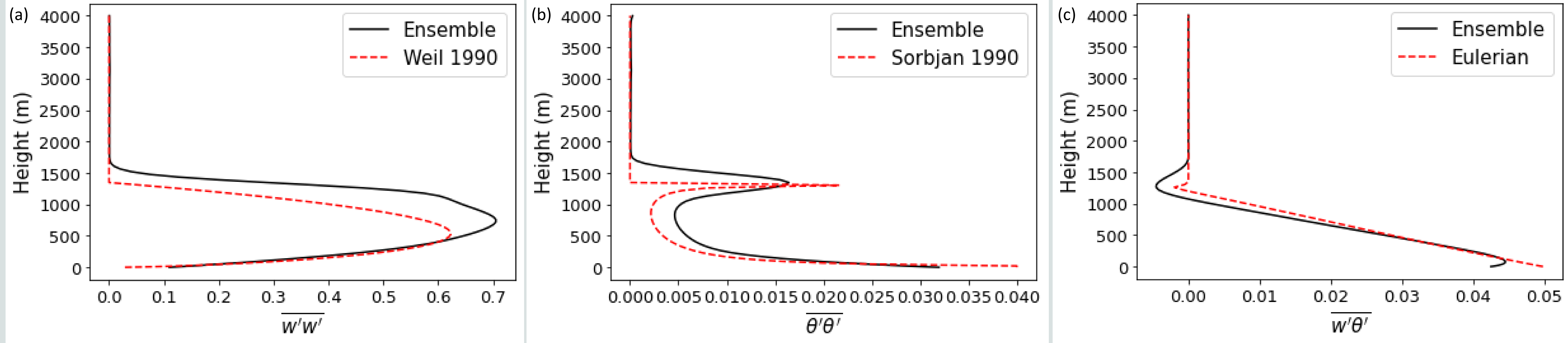
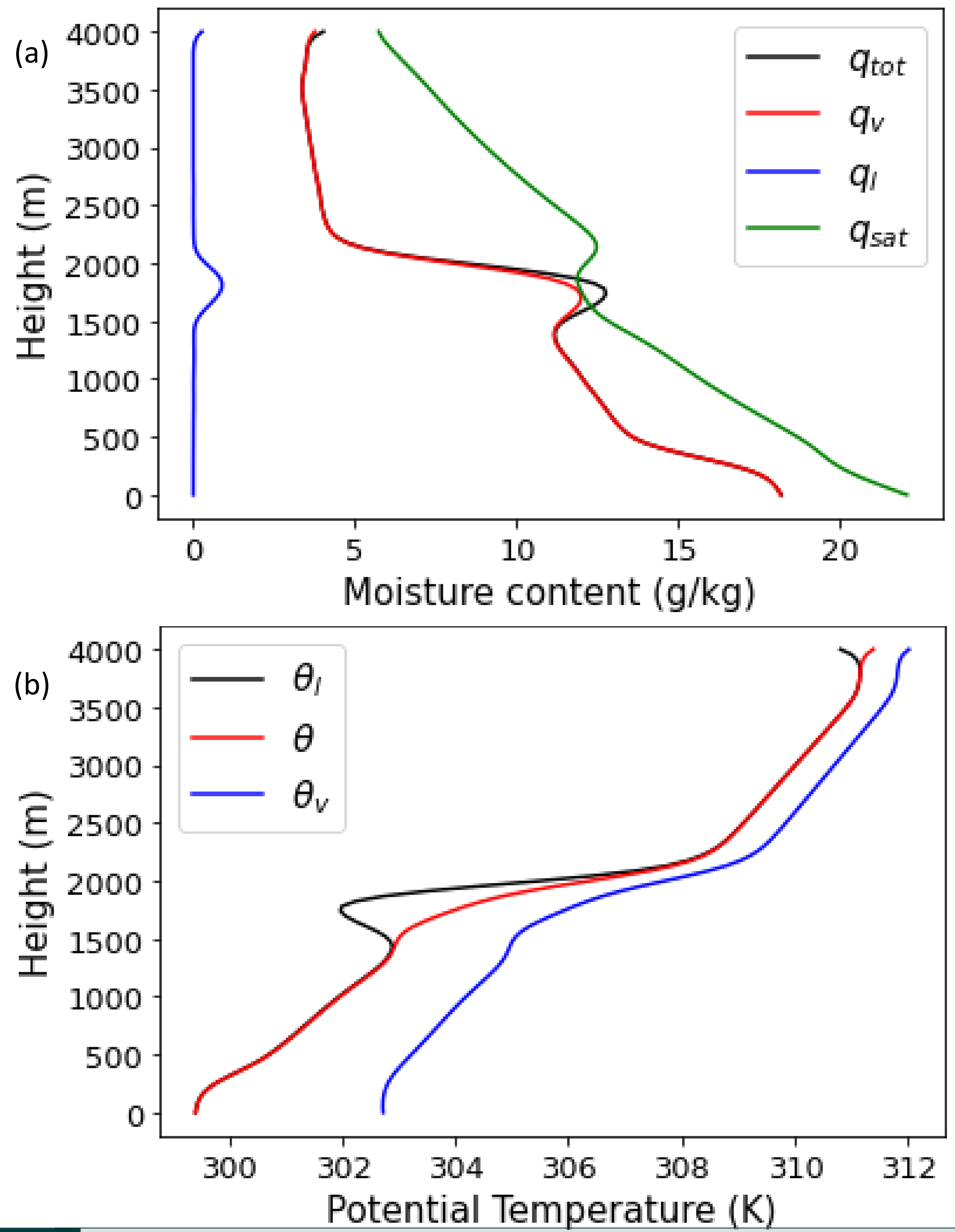


Figure 1: Vertical profiles of (a) $\overline{w'w'}$, from the parcel ensemble and similarity theory profiles found within literature[3], (b) $\overline{\theta'\theta'}$, likewise[4], and (c) $\overline{w'\theta'}$ from the parcel ensemble and a background Eulerian model with the same initial conditions and forcings. All profiles are the 1-hr average of the final hour of a 7-hr dry model simulation.

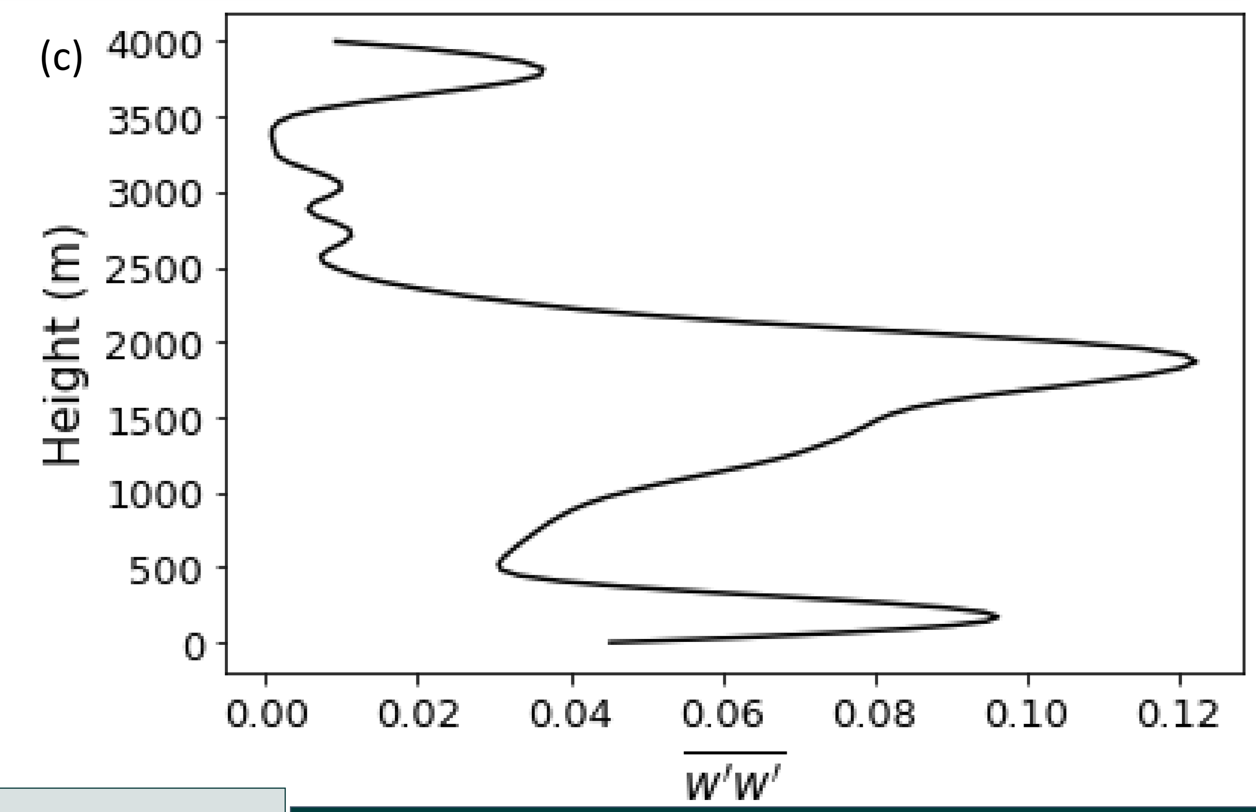
- The model captures large scale features expected of dry convective boundary layers, agreeing with profiles from literature and other modelling methods.
- BL warming rate in agreeance with the warming rate theory of the mixed layer model.

4. Preliminary Results: Moist Case



- Cloud top is estimated to be 2000 metres. Surface values of variables θ_l and q_{tot} are as expected. The $\overline{w'w'}$ profile captures the double peaks in the BL and the cloud layer.
- Latent heat releases during vapour phase change allow for the shallow convection to occur above the BL top.
- Cloud base is higher than anticipated. Entrainment and detrainment are not being modelled. Dry air that is displaced by the rising moist air inhibits cloud formation in the lower parts of the expected cloud layer.
- Unphysical contributions from the stochastic term above the BL contribute to the non-smooth nature of the $\overline{w'w'}$ profile.
- Several parcels are trapped at the top of the domain, causing irregularities in the moisture and temperature profiles.

Figure 2: Vertical profiles of (a) moisture variables from the parcel ensemble, (b) potential temperature variables from the parcel ensemble, (c) $\overline{w'w'}$ from the parcel ensemble. All profiles are the 1-hr average of the final hour of a 7-hr moist model simulation.



5. Future Work

- Improve representation of the stochastic term above the BL such that unrealistic parcel motions are not observed.
- Implement a method of modelling the entrainment and detrainment within the expected cloud layer.
- Compare results to LES using a series of diagnostics.

6. References

[1] Siebesma et al. 2003, Journal of the Atmospheric Sciences
[2] Thomson 1987, Journal of Fluid Mechanics
[3] Weil 1990, Journal of the Atmospheric Sciences
[4] Sorbjan 1990, Journal of Applied Meteorology

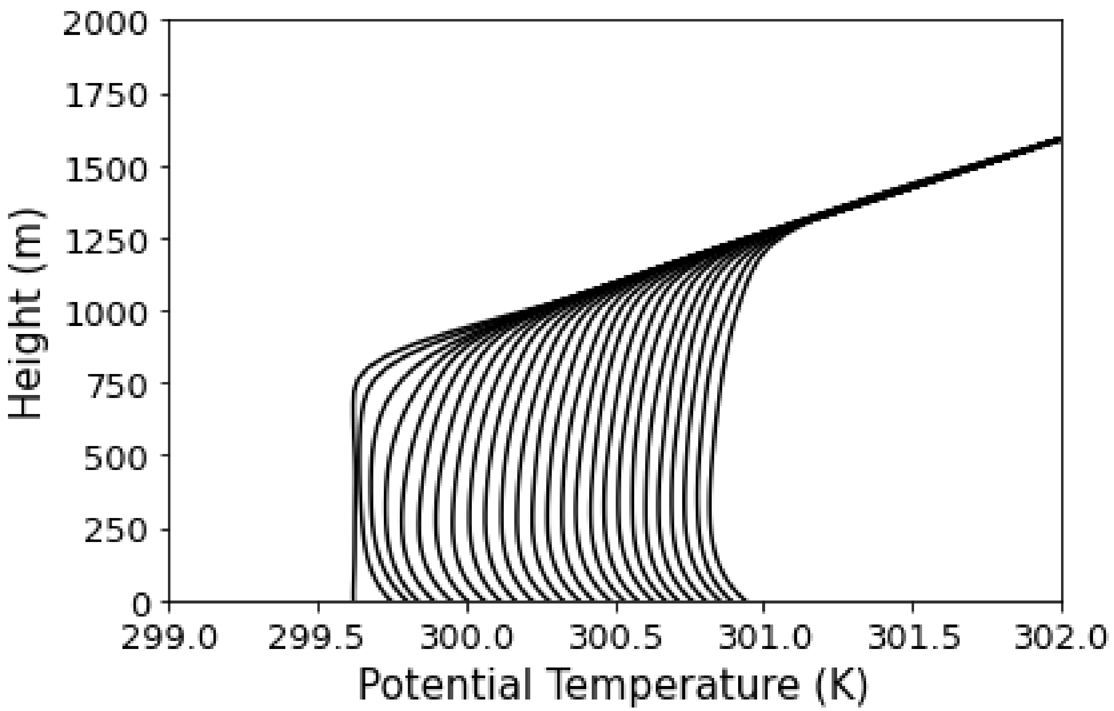


Figure 1: Profile of potential temperature plotted every 1000 seconds using the dry convective boundary layer case. The warming rate on display closely matches the expected warming rate predicted by the mixed layer model.

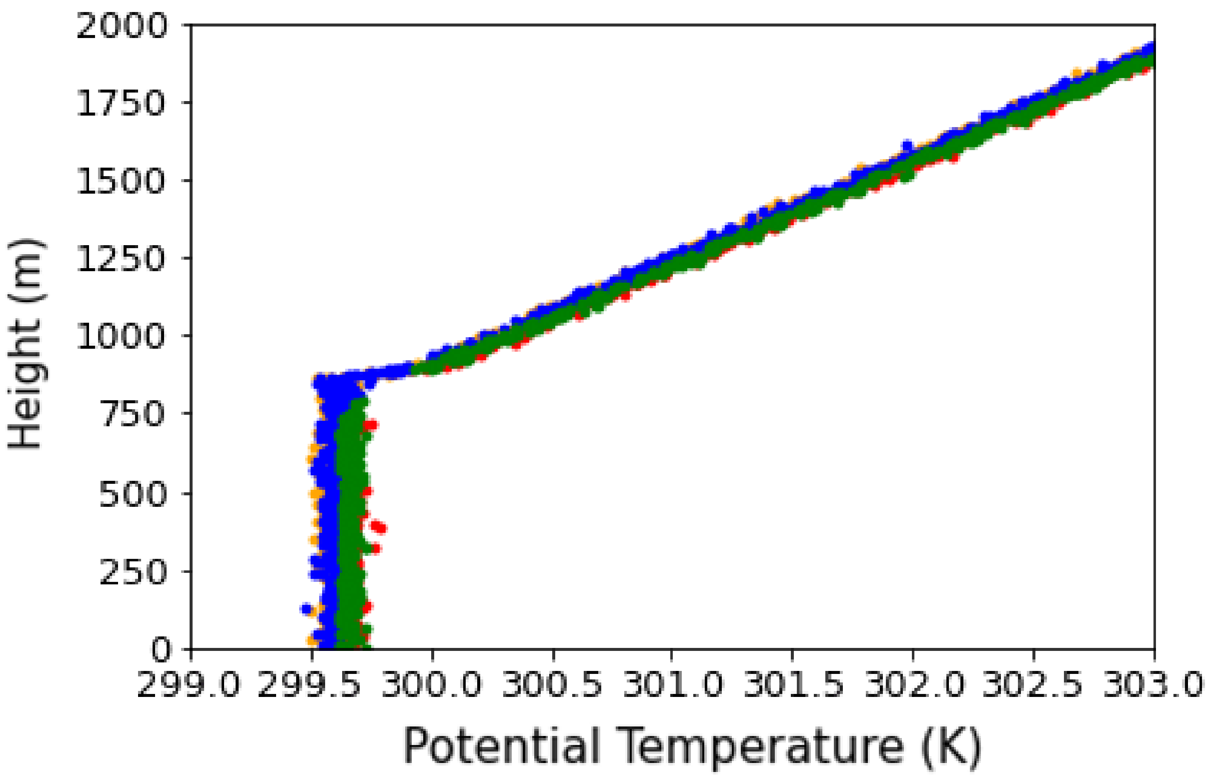


Figure 2: Animation of every parcel in the ensemble, with one frame every 100s for a 7-hour run for a dry convective boundary layer. Red parcels are rising and warmer than the ensemble mean, orange are rising and cooler. Blue parcels are falling and cooler than the ensemble mean, while green parcels are falling and warmer.

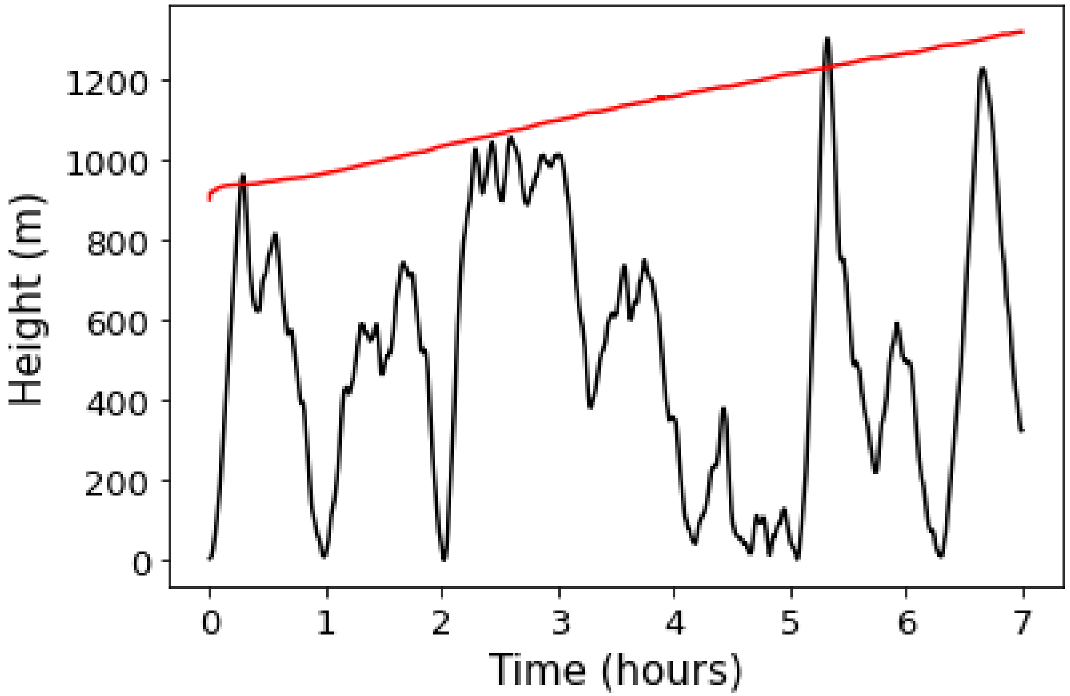


Figure 3: Trace of an individual parcel's position throughout a model run using dry convective boundary layer conditions (black) with the diagnosed boundary layer depth (red).

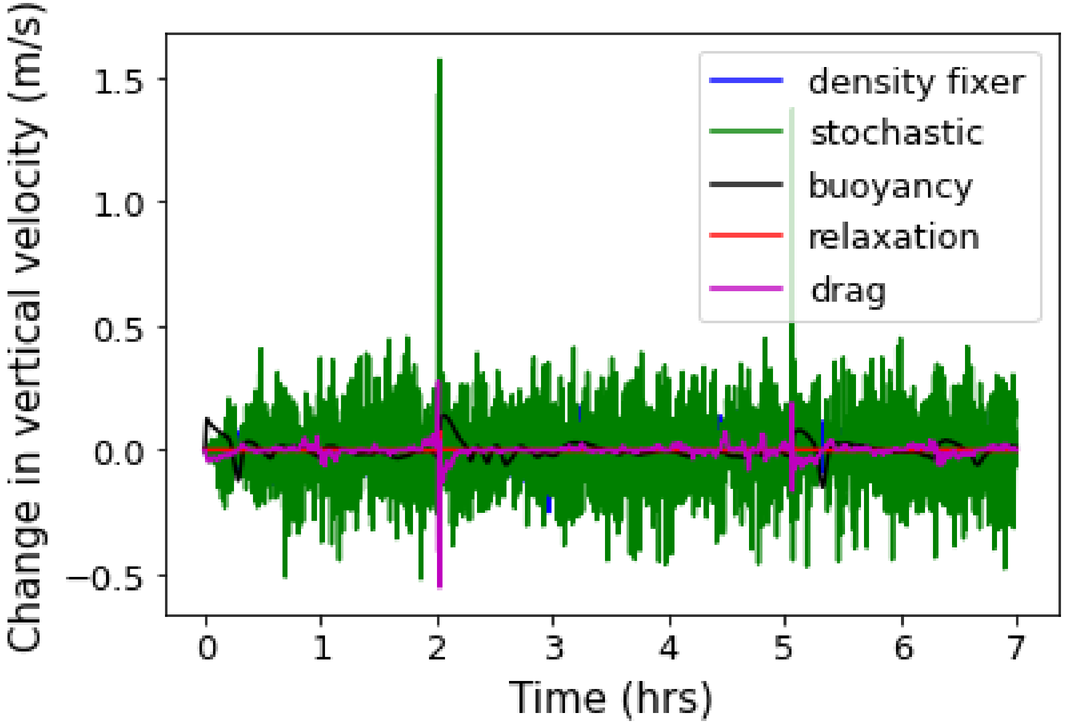


Figure 4: Magnitude of each term in the dw equation during a run for a dry convective boundary layer for the parcel shown in Fig. 3.

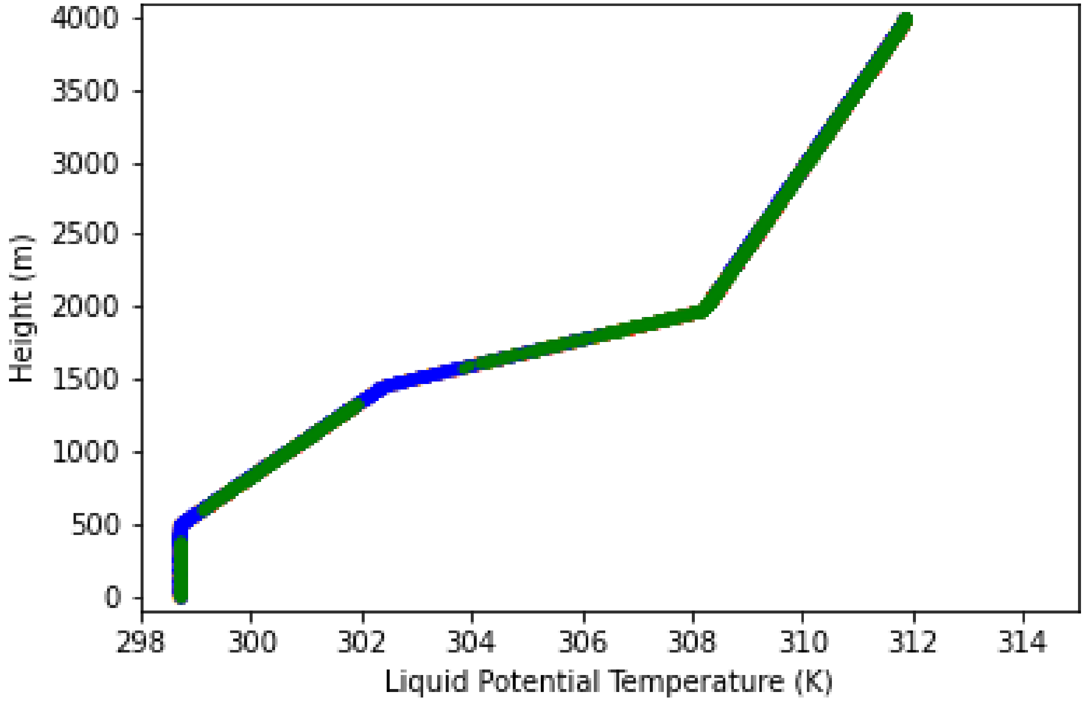


Figure 5: Animation showing θ_l of every parcel in the ensemble, with one frame every 100s for a 7-hour run for the BOMEX case. Red parcels are rising and warmer than the ensemble mean, orange are rising and cooler. Blue parcels are falling and cooler than the ensemble mean, while green parcels are falling and warmer.

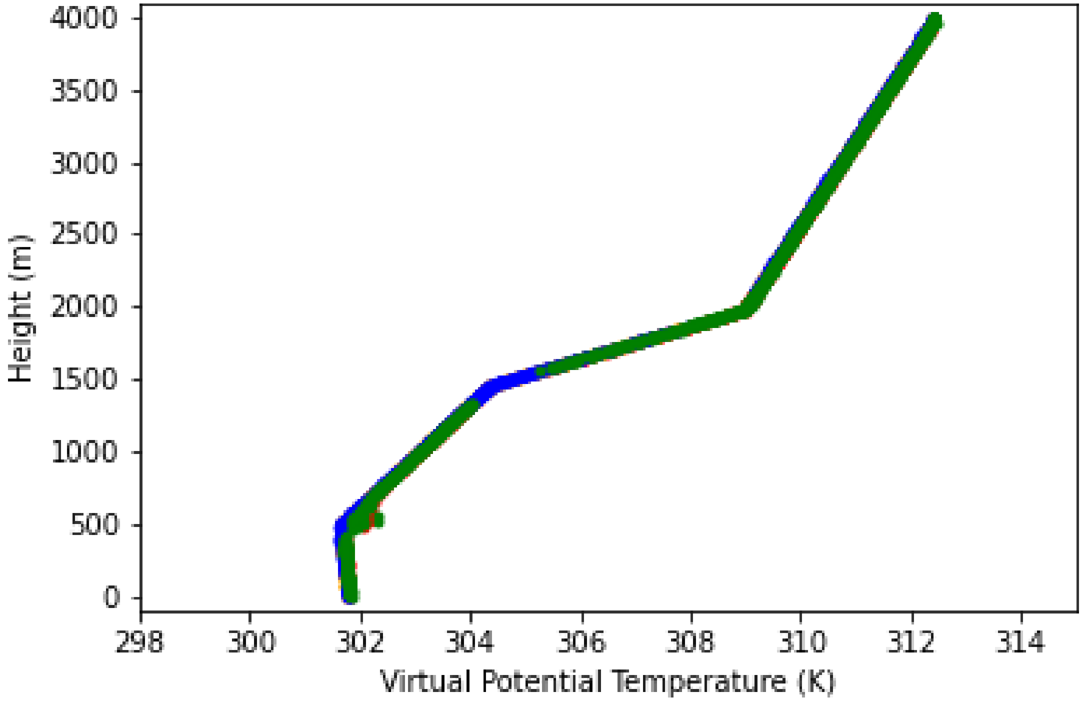


Figure 6: Animation showing θ_v of every parcel in the ensemble, with one frame every 100s for a 7-hour run for the BOMEX case. Red parcels are rising and warmer than the ensemble mean, orange are rising and cooler. Blue parcels are falling and cooler than the ensemble mean, while green parcels are falling and warmer.

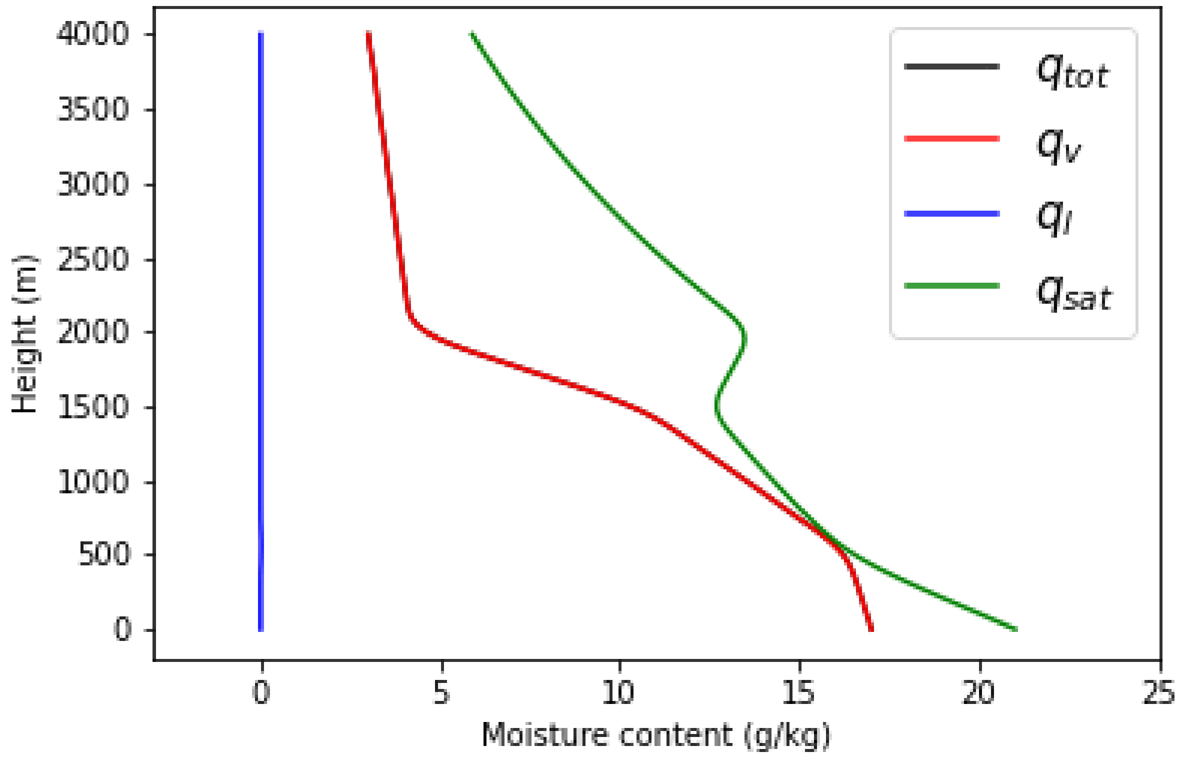


Figure 7 : Animation showing the ensemble mean moisture profiles, with one frame every 100s for a 7-hour run for the BOMEX case.

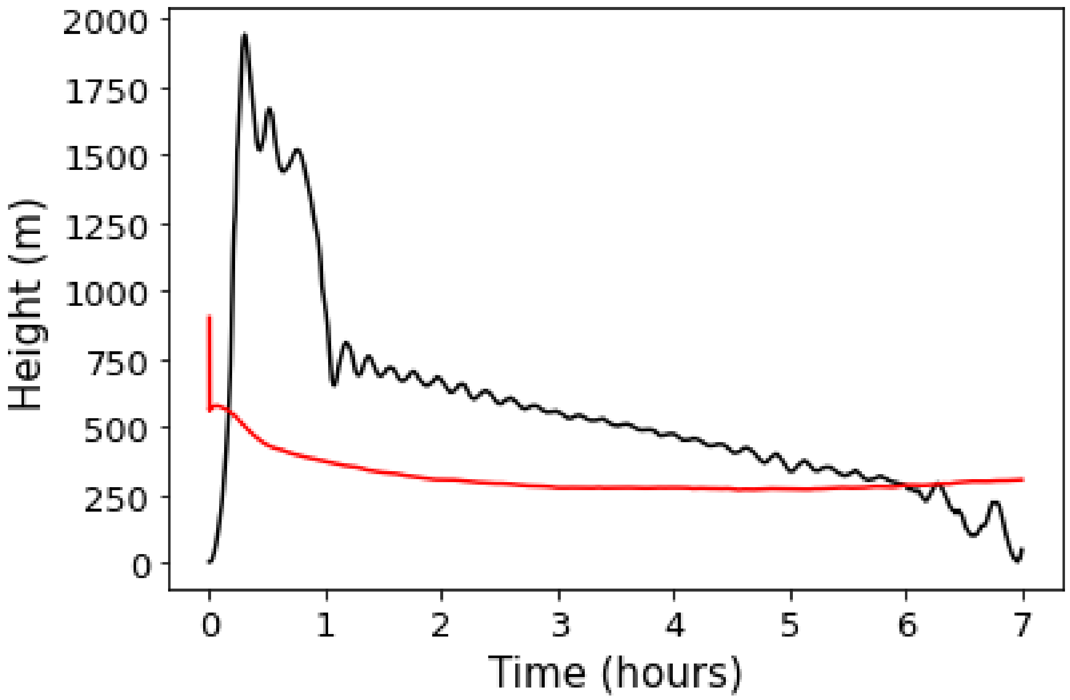


Figure 8: Trace of an individual parcel's position throughout a model run using BOMEX conditions (black) with the diagnosed boundary layer depth (red).

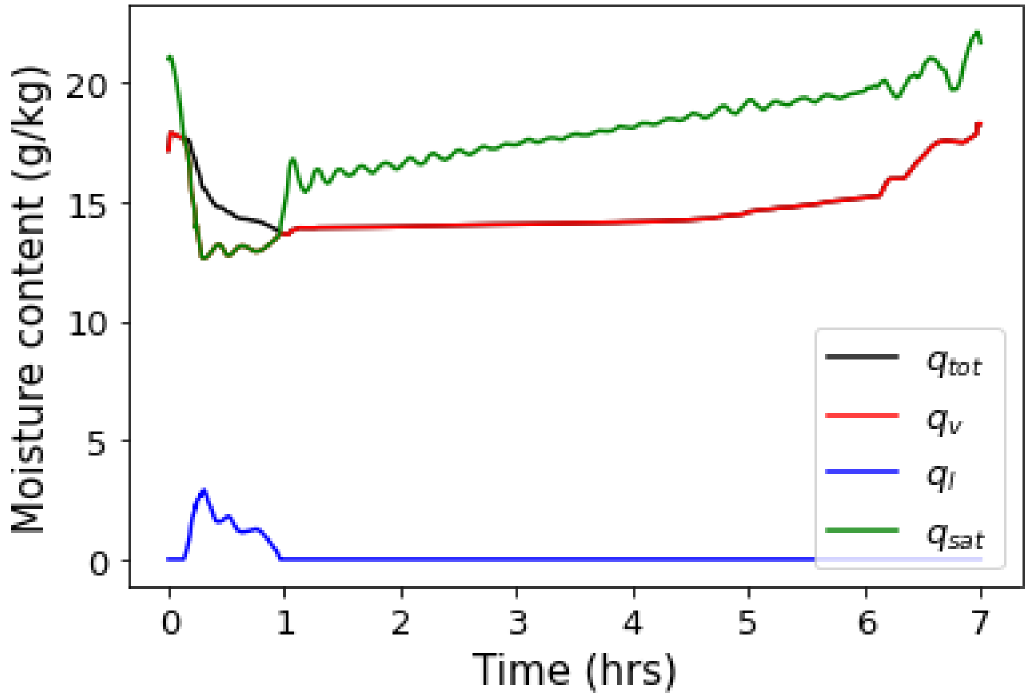
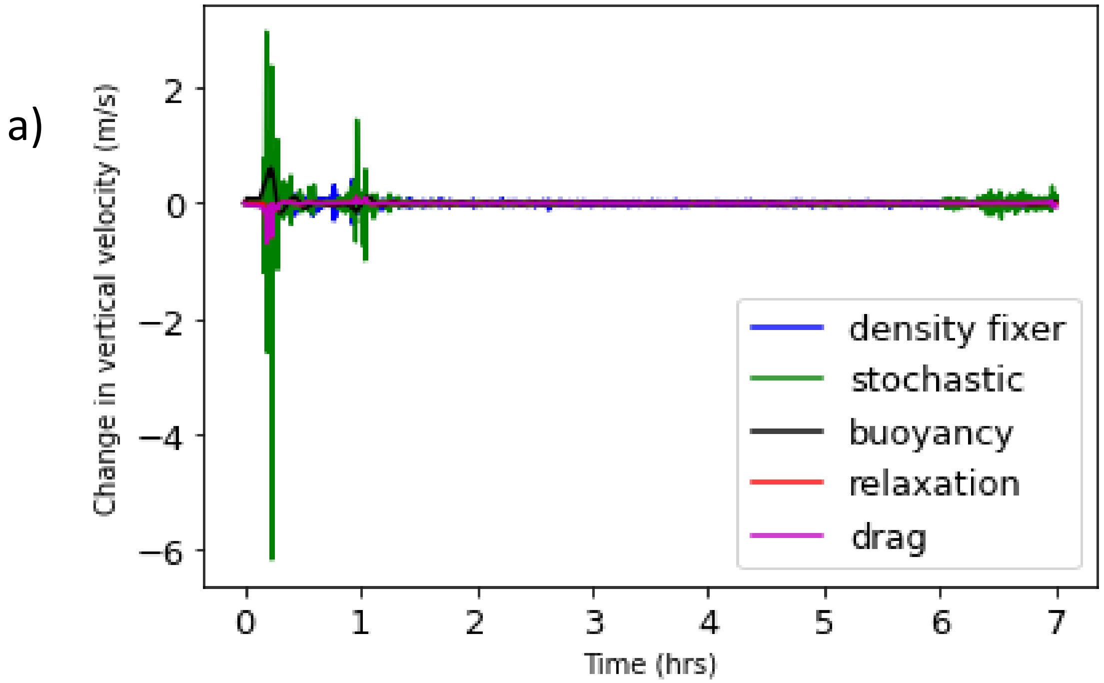


Figure 9: Traces of moisture variables for the parcel shown in Fig. 8.



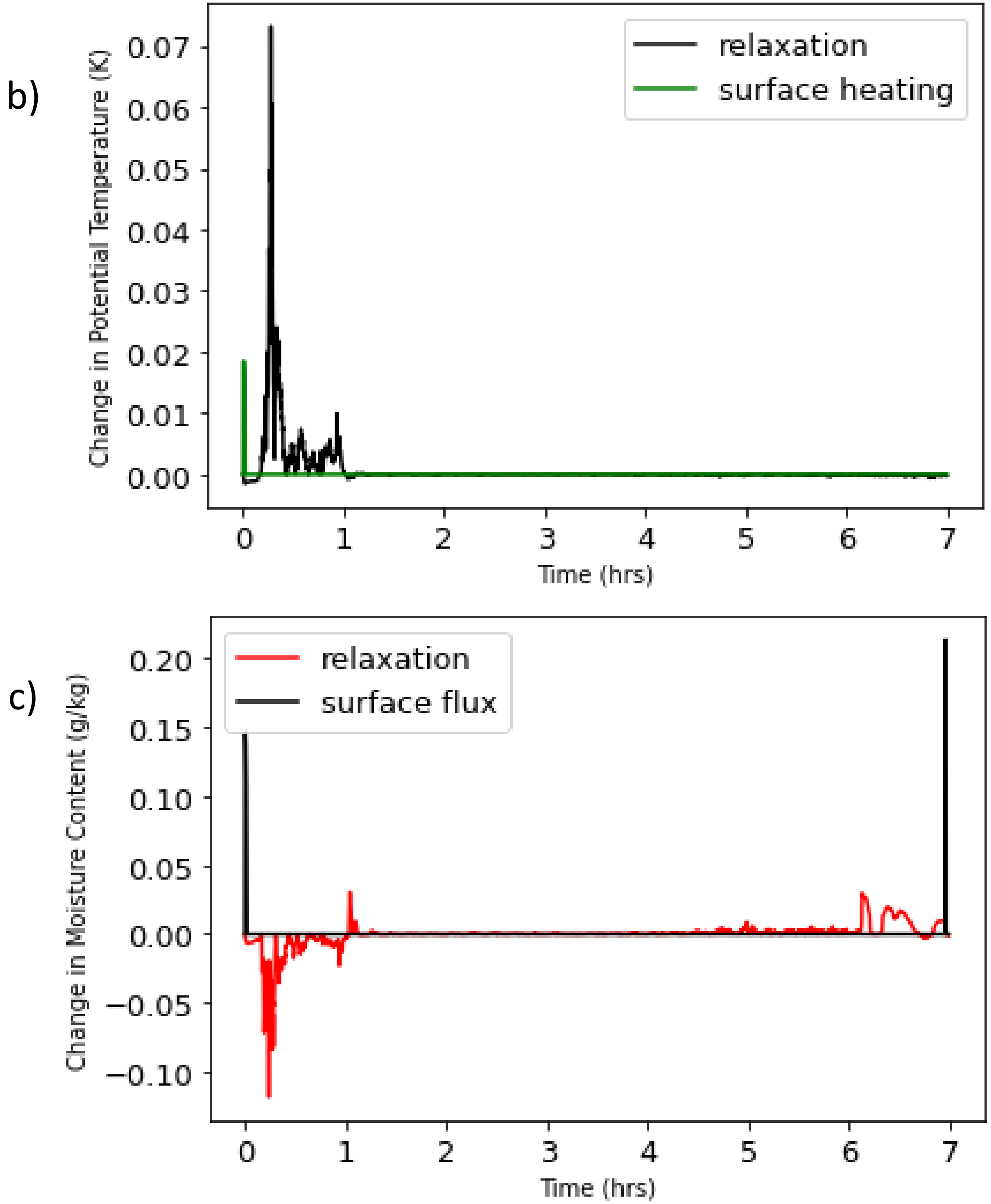


Figure 10: For the parcel shown in Fig. 8, the magnitudes of each term in the a) dw equation, b) $d\theta_l$ equation, and c) dq_{tot} equation during a run for the BOMEX case.