Properties of shallow convection from Large-Eddy simulations

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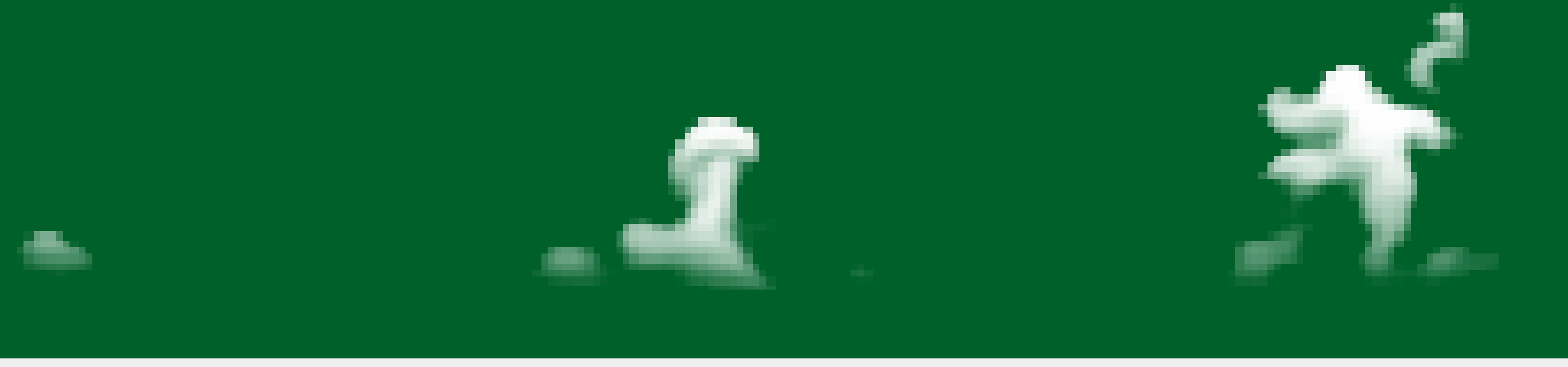

Aim

Primary aim:

- Use **high-resolution simulation** ($\Delta x \leq 25m$) to study **dynamics of convective updrafts**
- focus on **entrainment** (mixing of cloudy air with environment)
- improve 1D entraining parcel model of CCFM (Wagner and Graf 2010) convection scheme

Secondary aims:

- Investigate assumptions of CCFM
- Quantify perturbations causing formation of convective updrafts
- Compare CCFM spectrum calculation with spectrum diagnosed from LES

Background

- Convective clouds are not as tall as predicted purely based on thermodynamics, this due to dilution through mixing, *entrainment* of, environment air
- **Parameterisation of entrainment is significant tunable parameter in GCMs** (Global Circulation Models) **and in NWP** (Numerical Weather Prediction), Knight et al. 2007 found **30% of variation in climate sensitivity predictions** between models accounted for by variations in entrainment parameterisation.
- Entrainment rate typically taken to be inversely proportional to radius (Morton-Turner model, Morton et al. 1956), $\mu = \beta/r$, difficulty becomes defining β
- CCFM predicts the ensemble of interacting convective clouds given large-scale forcing, environment profile and vertical cloud profiles predicted with 1D entraining parcel model

Research questions

- **Skill of 1D entraining parcel model** in predicting vertical profiles (vertical velocity, radius, temperature, hydrometeors) of convective clouds?
- **Characteristic properties of the convective cloud-base** (in terms of e.g. vertical velocity, temperature and moisture perturbation)? How do these **relate to properties of the boundary layer** below cloud-base?
- Do all clouds develop from the same cloud-base height?
- Do all clouds of same cloud-base radius have the same cloud-top height? *Assumption used to define cloud-type in CCFM.*
- **Does the Morton-Turner model apply to moist convective plumes** or should a different entrainment rate parameterisation be developed?

Simulation setup & analysis methods

Two sets of simulations:

1. **Individual clouds triggered with localised perturbation** to temperature and/or moisture in LES ($\Delta x = 5m$)
   - Idealised profile with layer of conditional instability leading to formation of shallow convection
   - Using ATHAM (Active Tracer High Resolution Atmospheric Model) Herzog et al. 1998
2. **Multiple ($O(10^4)$) interacting clouds triggered through surface-fluxes and large-scale forcing** in large domain ($50km \times 50km$) LES ($\Delta x = 25m$)
   - Radiative-Convective Equilibrium precipitating marine shallow cumulus based on RICO measuring campaign
   - Using UCLA-LES Stevens et al. 2005
   - Individual clouds identified with cloud-tracking algorithm, Heus and Seifert 2013

Results (simulation of individual clouds)

- **3D simulation necessary to capture full dynamical structure**: in 2D axisymmetric simulations entrainment decreased, causing higher cloud-top height
- **Agreement with 1D entraining parcel model only with diagnosed entrainment** (and not $\mu \propto 1/r$), **and only for 2D axisymmetric clouds** (Fig. 1), not for 3D cloud simulations (Fig. 2) - *as of yet, more work needed.*
- **Diagnosed entrainment rate (passive tracer) largely insensitive to cut-off value when using cloud liquid water**. Likely because entrainment rate is function of vertical gradients, i.e. shape of cloud envelope (which are concentric contours)
- Forcing required for shallow convection very small and may force water vapour instead of temperature ($\Delta q_v = 0.2g/kg$). Forcing vertical velocity undesirable due to acoustic waves produced and divergent flow.
- Convergence (in terms of cloud-top height) appears reached with $\Delta x = 5m$ isotropic grid resolution - *need to investigate impact of turbulence initiation in future work.*

Vertical profiles below were extracted over life-time of cloud. Show differences between 2D and 3D simulations, note agreement with 1D cloud-model for 2D axisymmetric simulations with diagnosed entrainment.

2D LES compared to 1D cloud-model

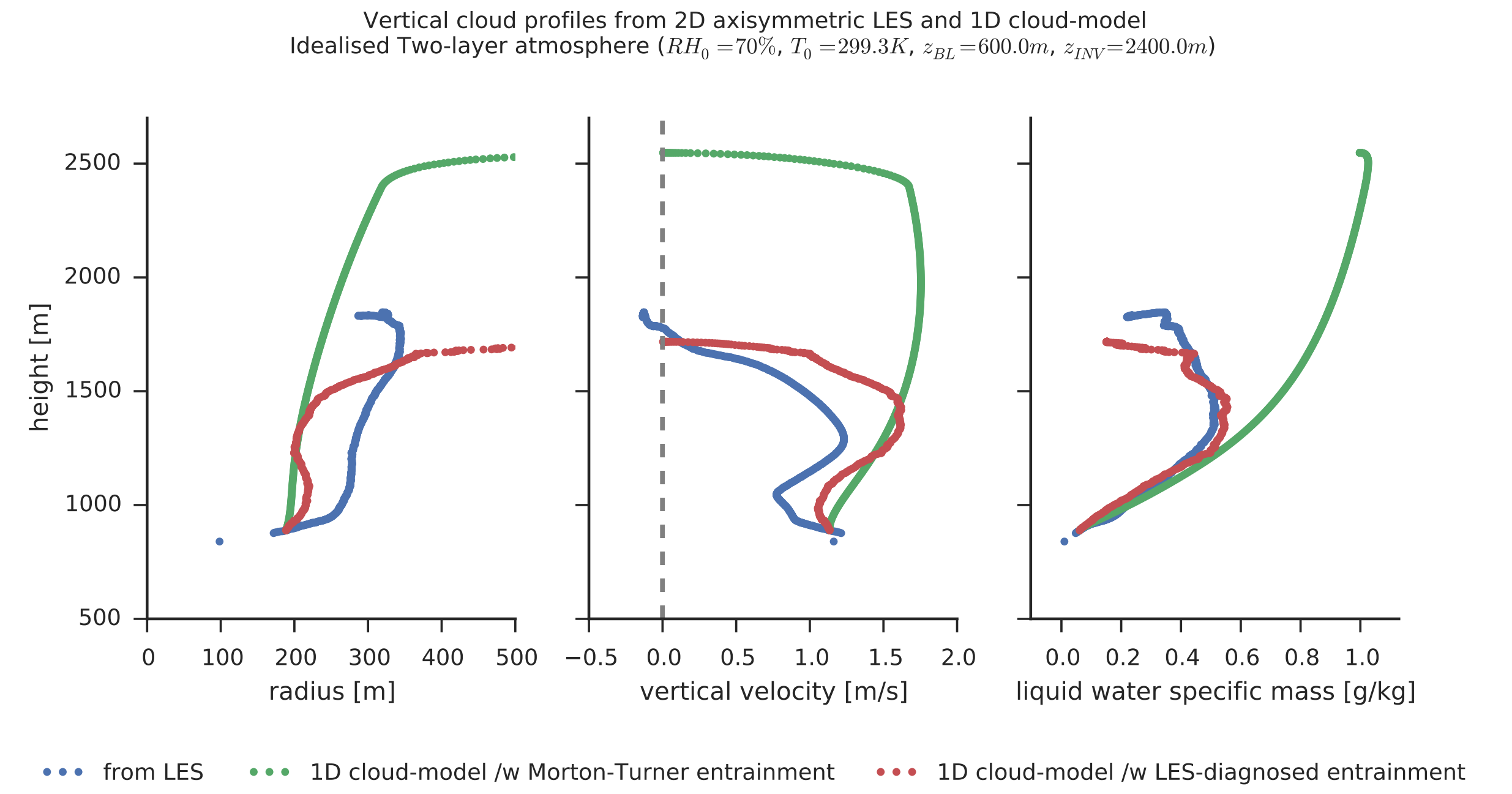

Figure 1: Cloud-profiles extracted from 2D axisymmetric simulation compared to predictions with entraining parcel model, with and without diagnosed entrainment rate. With Morton-Turner model of entrainment cloud-model produces much higher cloud-top height and in-cloud liquid water is inadequately diluted, whereas when LES-diagnosed entrainment is used both radius, vertical velocity and cloud liquid water is much closer to profile extracted from LES.

3D LES compared to 1D cloud-model

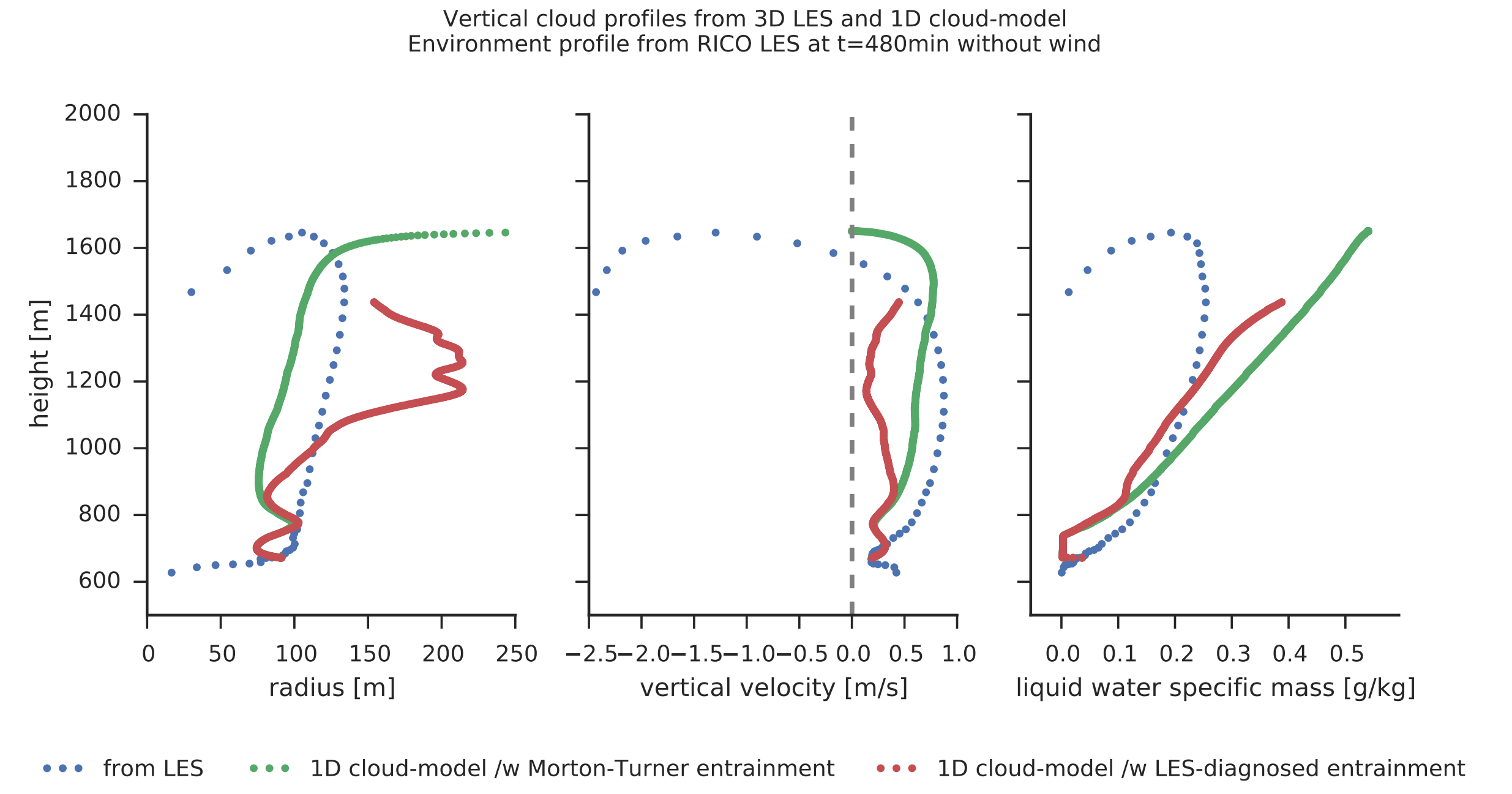

Figure 2: Cloud-profiles extracted from 3D simulation compared to predictions with entraining parcel model, with and without diagnosed entrainment rate. With Morton-Turner entrainment rate cloud-model produces better cloud-top height estimate than with diagnosed entrainment rate, but the high cloud-liquid water indicates that neither cloud-model integrations capture the thermodynamic changes from entrainment correctly. Cloud-model integration also shows stretching from acceleration not observed in 3D LES.

Results (large-domain cloud-field simulations)

- **All clouds rise from same cloud-base height** (within grid resolution $\Delta x = 25m$), direct agreement with lifting condensation level using near-cloud temperature and water vapour specific mass.
- **Cloud have well-defined cloud-base** during initial growth, however generally disappears before maximum cloud-top height is reached; behave like **transient thermals not steady-state plumes**
- **No correlation between instantaneous cloud-base radius and cloud-top height. Maximum cloud-base radius poor predictor of cloud-top height**, spread likely from increased entrainment from non axisymmetric cloud morphology (Fig. 3)
- **Variation in cloud-top height seen in LES only reproduced with 1D entraining parcel model when variations in immediate environment of cloud are taken into account**. Importance is not *rate* of entrainment as much as *what* is entrained (Fig. 4).
- **Characteristic values of cloud-base perturbations** (compared to boundary layer characteristic): water vapour $\Delta q_v = 0.3g/kg$, $\Delta\theta = 0.02K$. Vertical velocity $w \approx 0.5m/s$. RICO clouds appear forced by boundary layer thermals buoyant from loading with water vapour, could be characteristic of marine shallow cumulus (Fig. 5)
- **CCFM cloud spectrum** (number of clouds for a given radius) **prediction qualitatively agrees with LES diagnosed spectrum** (Fig. 6)

Examining correlation of r_{base} and z_{top}

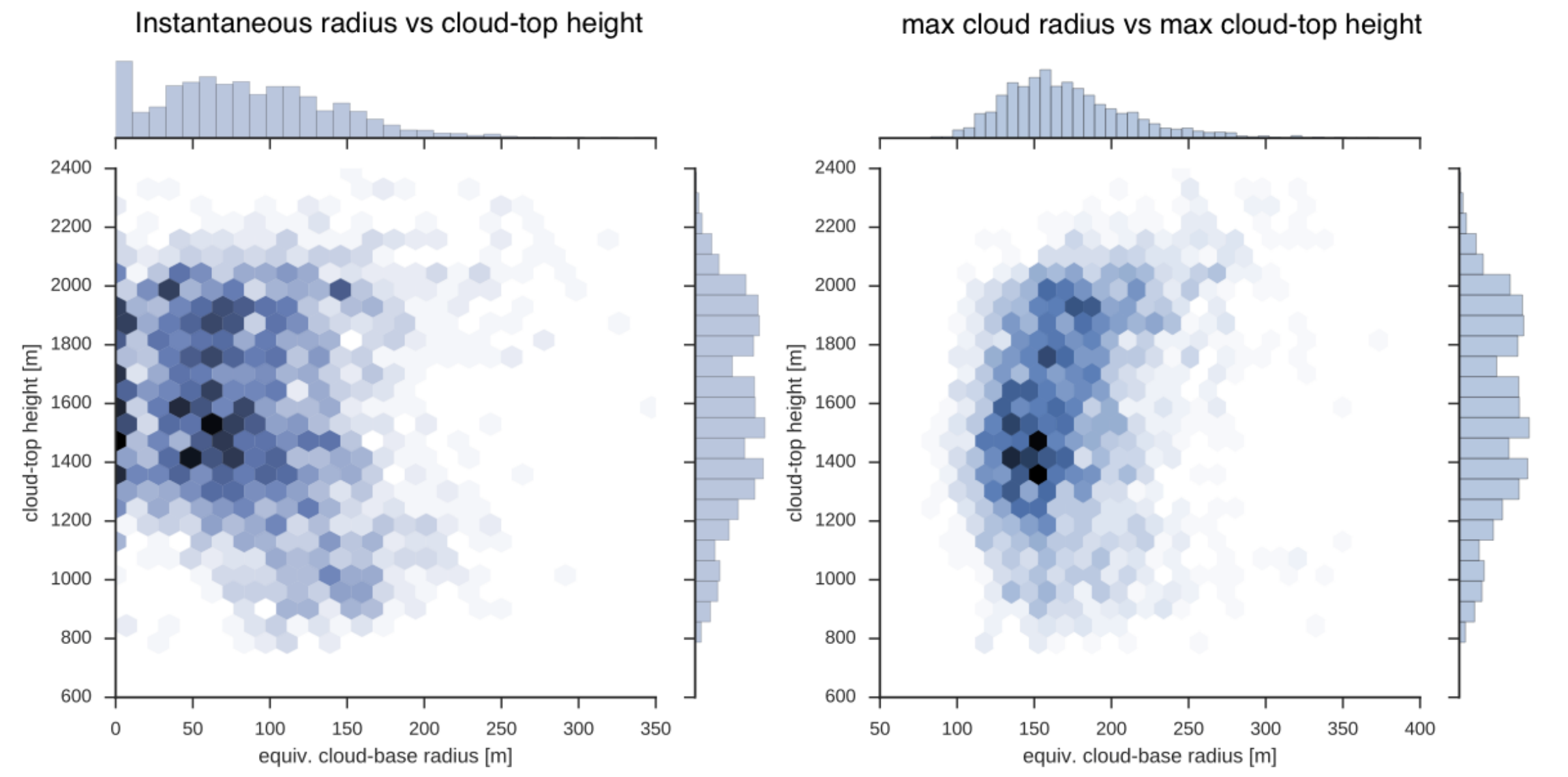

Figure 3: Instantenous (left) and maximum over lifetime (right) of cloud-base radius vs cloud-top height shows no correlation for the instaneous values and maximum values only weak correlation. Suggests that cloud-base radius is not itself adequate to define a cloud-type as all clouds of same type (cloud-base radius) should go through same evolution.

Examining z_{top} variation with 1D cloud-model

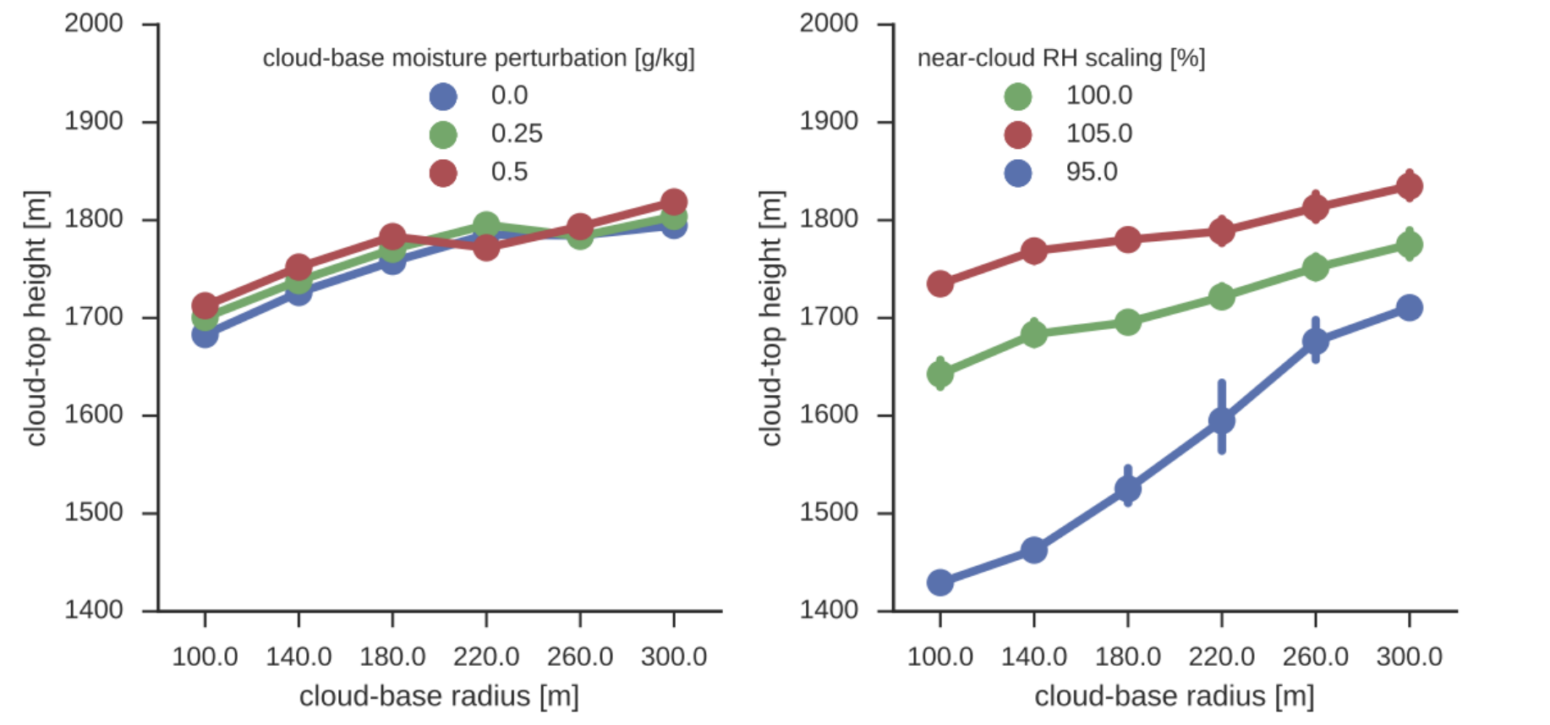

Figure 4: 1D entraining parcel model integrated with ambient profile including near-cloud variations in cloud-base water-vapour (left) and near-cloud relative humidity (right) from horizontal mean. Only by varying relative humidity of environment (which is entrained) can variation in cloud-top which is observed in LES be reproduced with 1D cloud-model, indicating that variations in near-cloud environment must be taken into account.

Results (large-domain cloud-field simulations), continued

Below-cloud perturbations from LES

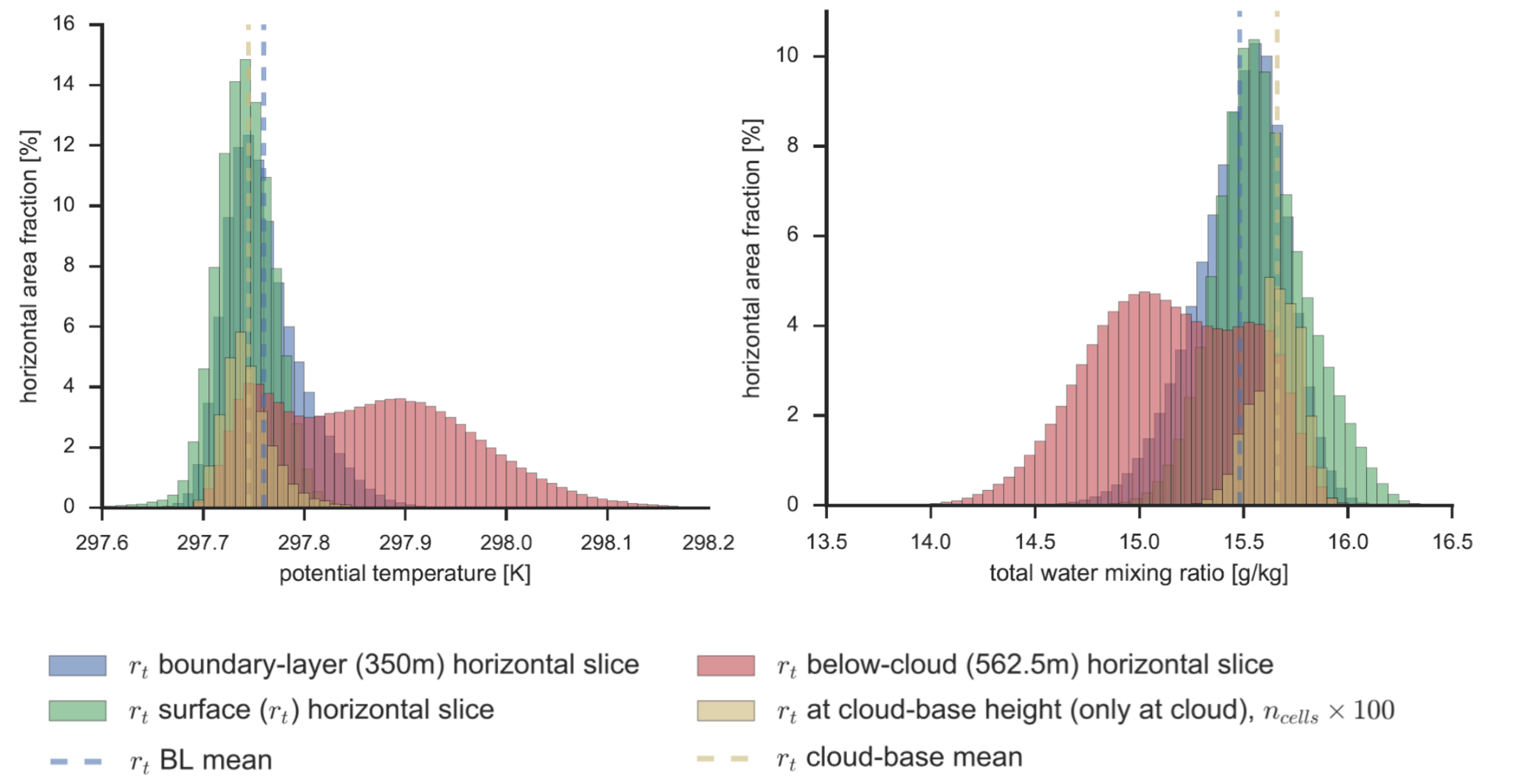

Figure 5: Distributions of total water and potential temperature in characteristic heights in boundary layer and at cloud-base extracted from 3D LES. Bimodal distribution at cloud-base made of cold and moist updrafts likely originating from surface, mean value at cloud-base colder than boundary-layer mean.

LES and CCFM cloud-spectrum

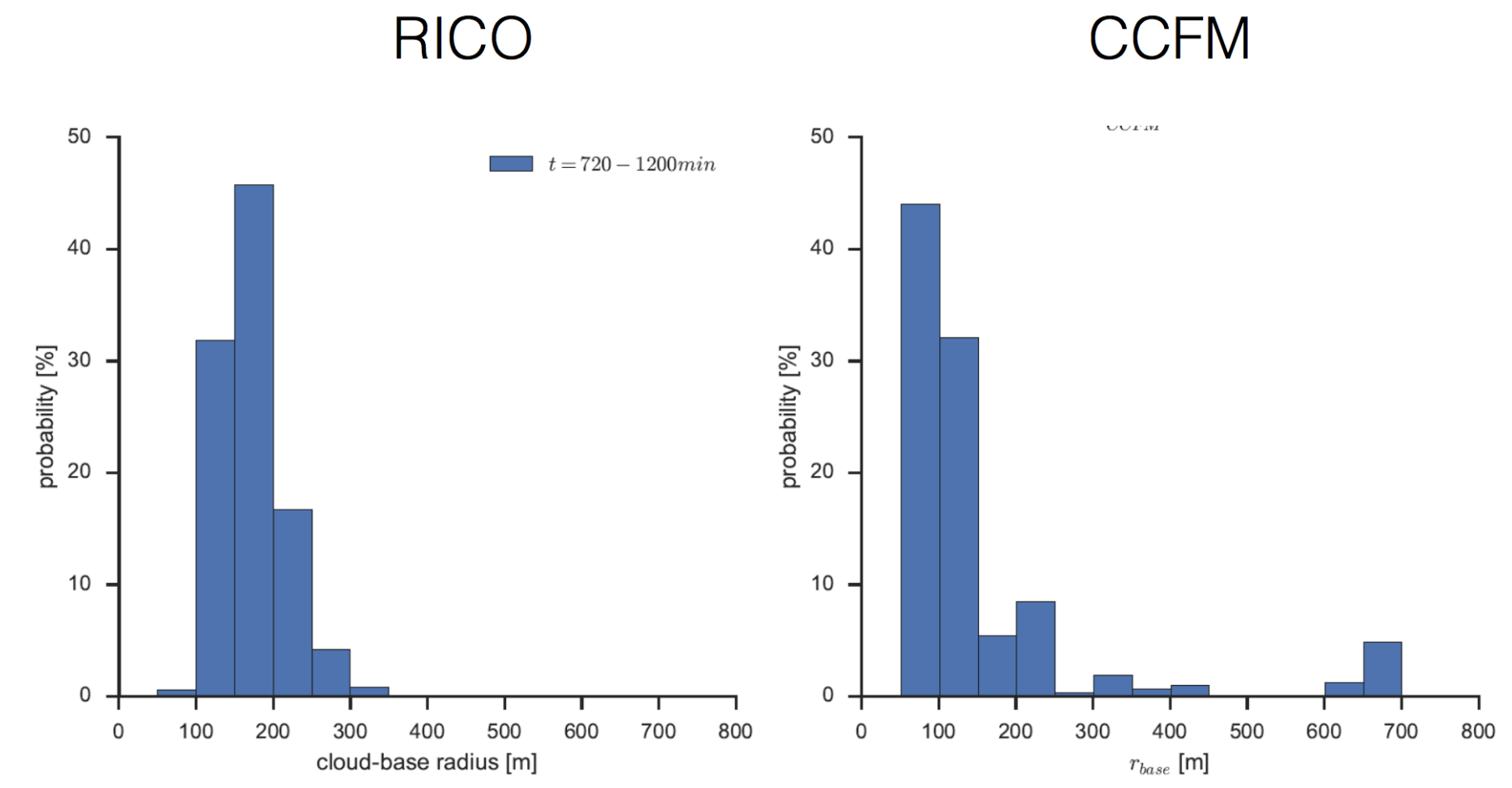

Figure 6: Cloud-spectrum (in terms of number of clouds with a given maximum cloud-base radius) as extracted from LES and predicted by CCFM spectrum calculation. The two spectra show similar features however CCFM predicts a number of clouds at $r \approx 600m$, could be due to multi-core thermals being excluded in analysis. Also note that minimum cloud-size is restricted by $\Delta x = 25m$ resolution in RICO LES.

Future work

- Extracting characteristic scales of thermals in convective boundary layer using LES to study the formation of convective updraft (convective genesis)
- Further study dynamic of convective updraft using LES, to better understand entrainment process and quantify differences between 2D axisymmetric and 3D simulations
- Study effect of wind-shear on entrainment and maximum cloud-top height
- Further investigate (not mentioned here) effects of microphysics on development of convective updrafts

References

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