Using high-resolution modelling to study convective updrafts

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Outline

1. Summary of PhD work
2. Plans for updraft work in GENESIS

1. Summary of PhD work

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), C. G. 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 B. Stevens et al. (2005)
   - Individual clouds identified with cloud-tracking algorithm, Heus and Seifert (2013)

Single-cloud analysis

- **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**, not for 3D cloud simulations - *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)

Single-cloud analysis (2D LES and 1D cloud-model)

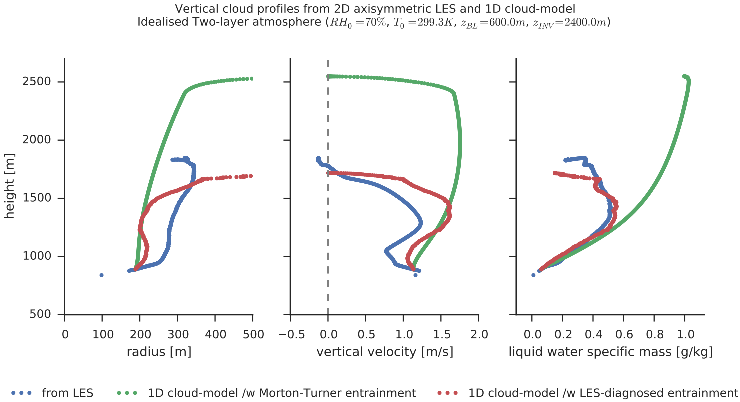

Figure: Cloud-profiles from 2D axisymmetric and 1-D entraining parcel mode with and without diagnosed entrainment rate. With Morton-Turner model of entrainment cloud-model produces much higher cloud-top height and in-cloud liquid water is inadequately diluted.

Single-cloud analysis (3D LES and 1D cloud-model)

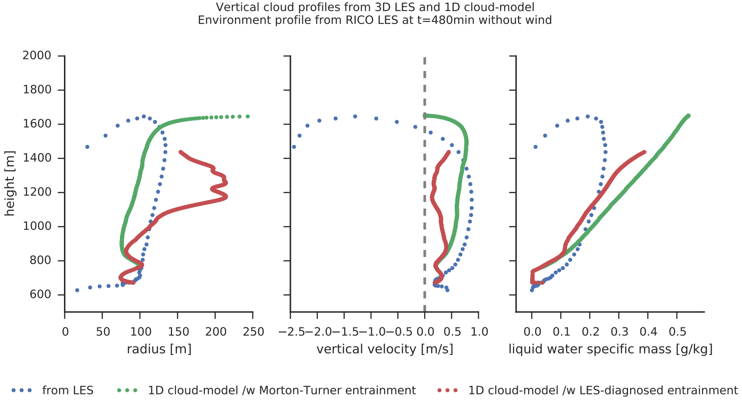

Figure: Cloud-profiles from 3D simulation compared to with entraining parcel model with and without diagnosed entrainment rate. Cloud-model agrees poorly both with and without diagnosed entrainment.

Multi-cloud analysis

- **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**

Multi-cloud analysis (correlation of r_{base} and z_{top})

No correlation between instantaneous cloud-base radius and cloud-top height $\Rightarrow$ Maximum cloud-base radius poor predictor of cloud-top height.

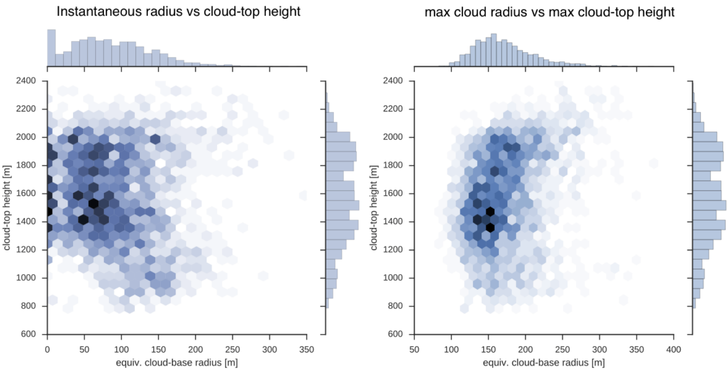

Figure: Instantenous (left) and maximum over lifetime (right) of cloud-base radius vs cloud-top height.

Multi-cloud analysis (z_{top} variation, 1D cloud-model)

Variation in cloud-top height seen in LES only reproduced with 1D entraining parcel model when variations near-cloud are included ⇒ Importance is not *rate* of entrainment as much as *what* is entrained.

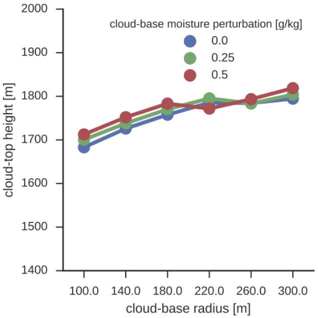

Figure: 1D entraining parcel model integrated with ambient profile including near-cloud variations in cloud-base water-vapour (left) and near-cloud relative humidity (right) from horizontal mean

Multi-cloud analysis (below-cloud perturbations)

Characteristic values of cloud-base perturbations:
$\Delta q_v = 0.3g/kg$, $\Delta\theta \approx 0.0K$, $w \approx 0.5m/s \Rightarrow$ RICO clouds forced by BL thermals buoyant from loading with water vapour (marine shallow cumulus).

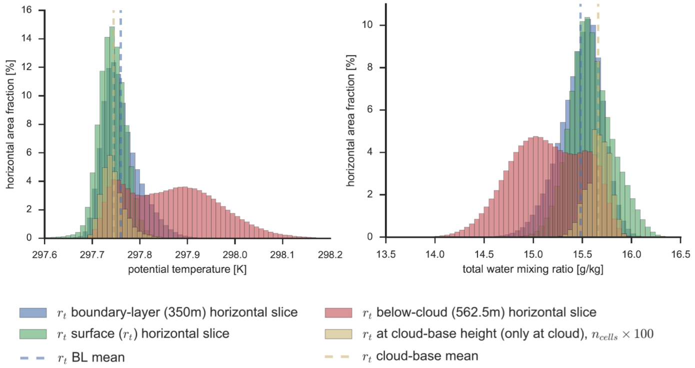

Figure: Distributions of total water and potential temperature in characteristic heights in boundary layer and at cloud-base extracted from 3D LES.

Multi-cloud analysis (LES and CCFM cloud-spectrum)

CCFM cloud spectrum (number of clouds for a given radius) **prediction qualitatively agrees with LES diagnosed spectrum**

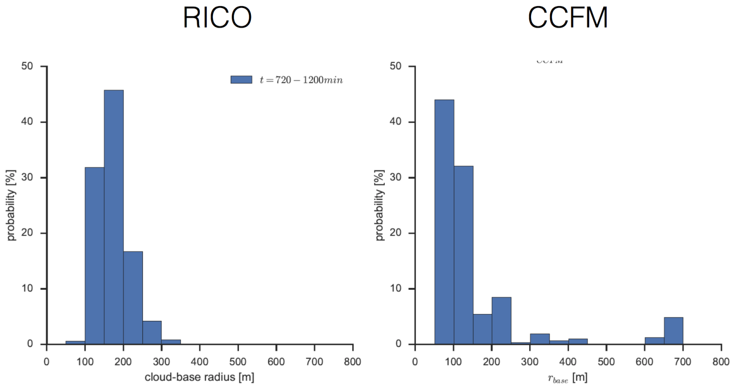

Figure: Cloud-spectrum (in terms of number of clouds with a given maximum cloud-base radius) as extracted from LES and predicted by CCFM spectrum calculation

2. Plans for updraft work in GENESIS

Aims

- Identify dynamic behaviour which causes entrainment to be different for 2D axisymmetric and 3D simulations of individual clouds
  - Further simulations of individual clouds, likely with MONC
- After quantifying characteristic scales (size and magnitude) of thermals in boundary layer (GENESIS WP 1) investigate whether these correlate with convective clouds formed
  - Re-run of shallow convective RICO with high time-resolution ($\Delta t \leq 30s$) 3D output
  - Repeat on large-domain simulations with deep convection (setup TBD)

Research questions

- To what extent can the Morton-Turner model describe entrainment in individual 2D axisymmetric/3D clouds and cloud identified in 3D RCE?
  - How important is variation of the cloud-environment from the horizontal mean?
- Are individual convective clouds in RCE forced through boundary layer thermals or are convective clouds self-sustaining?
- What parameters control whether a single convective cloud is made up of successive thermals?
  - Forcing by boundary layer thermals?
  - Self-sustaining convection through successive thermals with a characteristic time-scale? (with long time-scale forcing of individual clouds a characteristic time-scale was evident)
- Is 1D entrainment parcel model applicable to a convective cloud made of multiple thermals? Or to the thermals in these clouds?

Implications for convection schemes

- Further understanding of entrainment, leading to a more physically sound representation of entrainment in convective schemes
- Assert whether variations from horizontal mean state in convective layer must be represented
- Build understanding of clouds made of multiple thermals so that not just single-thermal clouds may be represented in convection schemes

Later in GENESIS (if time permits)

- Study effect of windshear convective updrafts (entrainment, cloud-fraction, maximum cloud-top height, etc)
- Further investigate (not mentioned here) effects of microphysics on development of convective updrafts, eg does formation of precipitation alter entrainment rate?

Thanks for listening

Questions?

References

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