Using high-resolution modelling to improve the parameterisation of convection in a climate model

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Aim

Primary aim:

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

Secondary aims:

- Investigate assumptions of CCFM
- Quantify perturbations that lead to formation of convective updrafts
- Test CCFM spectrum calculation with spectrum diagnosed from LES

Background

- Convective clouds are observed to grow to shallower heights than would be predicted purely based on thermodynamics due to *entrainment* of ambient air.
- Parameterisation of entrainment has become significant tuneable 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 in defining β
- CCFM predicts the ensemble of interacting convective clouds given large-scale forcing and profiles calculated from 1D entraining parcel model

Research questions

- What skill does the 1D entraining parcel model have in predicting vertical profiles (vertical velocity, radius, temperature, hydrometeors) of convective clouds?
- What are the characteristic properties of the convective cloudbase (in terms of e.g. vertical velocity, temperature and moisture perturbation)? How do these relate to properties of the boundary layer below cloudbase?
- Do all clouds develope from the same cloudbase height?
- Do all clouds of same cloudbase radius have the same cloudtop height?
- 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 where used:

1. Individual clouds triggered with localised perturbation to temperature and/or moisture
   - 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)
   - Indivual clouds identified with cloud-tracking algorithm, Heus and Seifert (2013)

Single-cloud analysis

- Forcing required for shallow convection very small and may force water vapour instead of temperature ($\Delta q_v = 0.2g/kg$). Forcing vertical velocity undesireable due to acoustic waves produced and divergent flow.
- Convergence (in terms of cloud-top height) appears reached with $\Delta x = 5m$ isotropic grid resolution.
- 2D axisymmetric simulations do *not* capture full behaviour of 3D simulations, entrainment appears decreased for 2D axisymmetric clouds, leading to higher altitudes
- Diagnosed entrainment rate (passive tracer) largely insensitive to envelope criterion when using cloud liquid water. Likely because entrainment rate is function of vertical gradients, i.e. shape of cloud envelope (which are concentric contours)
- Agreement with 1D entraining parcel model possible only with diagnosed entrainment, and only for 2D axisymmetric clouds, not for 3D cloud simulations (as of yet, more work needed)

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

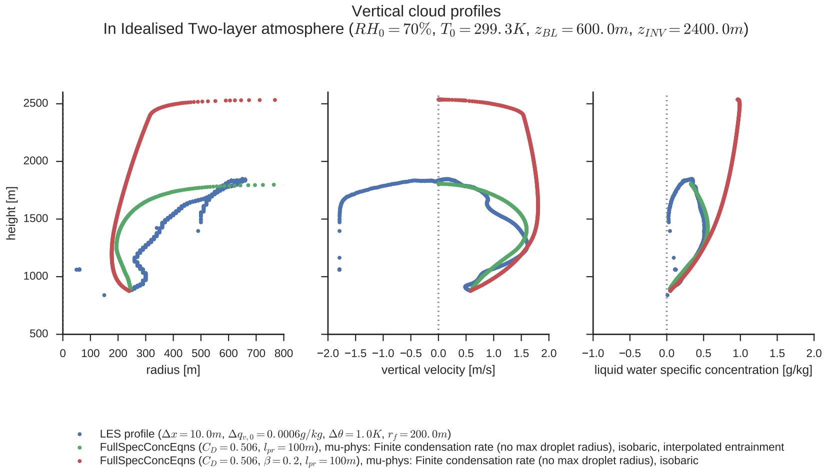

Figure: Plot of cloud-profiles extracted from 2D axisymmetric simulation compared to predictions with entraining parcel model, with and without diagnosed entrainment rate

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

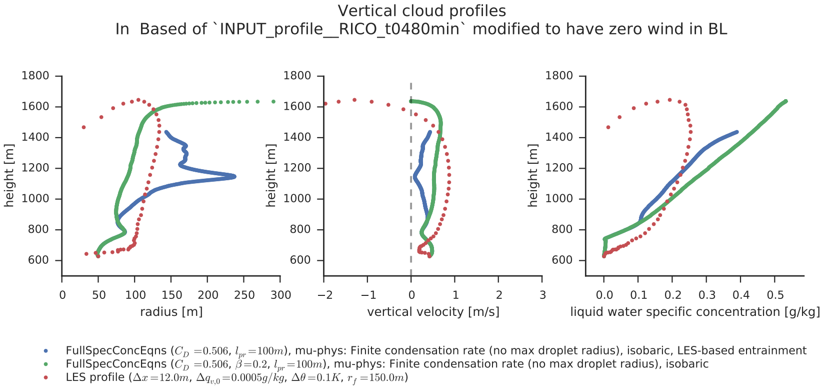

Figure: Plot of cloud-profiles extracted from 3D simulation compared to predictions with entraining parcel model, with and without diagnosed entrainment rate

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 cloud-base radius rapidly through lifetime
- As inversion is pushed up by convection distribution of maximum cloud-top heigh unchanged below $z \approx 1400m$, unclear why.
- 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

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

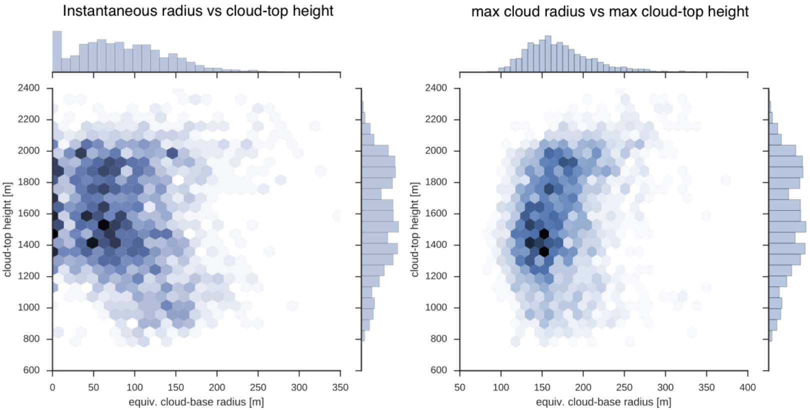

Figure: Instantenous (left) and maximum over lifetime (right) of cloud-base radius vs cloud-top height shows no correlation for the instaneous values and maximum values only weak correlation

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

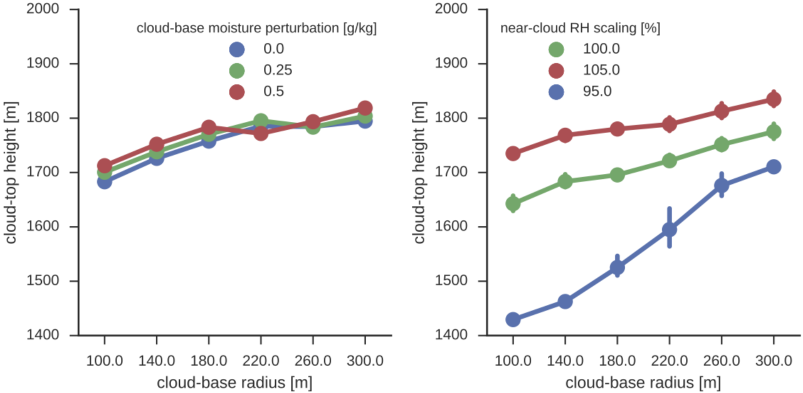

Figure: 1D entraining parcel model integrated with ambient profile including near-cloud variations in cloud-base water-vapour (left) and near-cloud relative humidity (right) from horizontal mean

Multi-cloud analysis (further results)

- Characteristic values cloud-base perturbations: 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
- Diagnosed cloud spectrum (number of clouds for a given radius) qualitatively agrees with predictions of CCFM's spectrum calculation
- To show variation in cloud-top height diagnosed from LES when integrating 1D entraining parcel model must take into account difference between immediate environment of cloud and mean ambient profile. Entrainment not ineffective unless environment dry and cold.

Multi-cloud analysis (below-cloud perturbations)

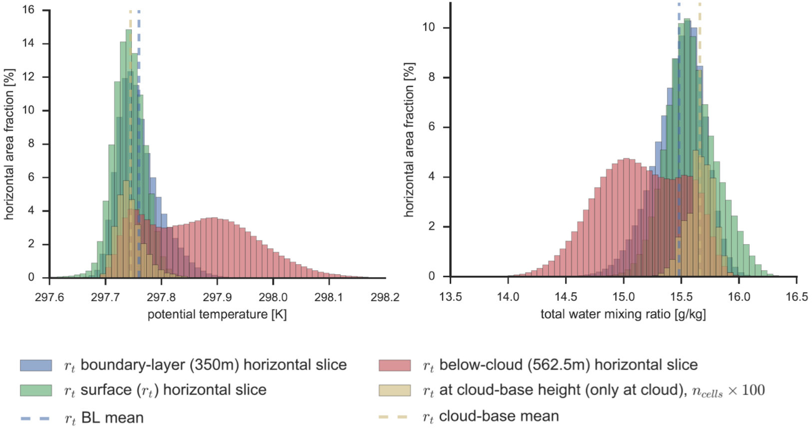

Figure: Distributions of total water and potential temperature in characteristic heights in boundary layer and at cloud-base extracted from 3D LES

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

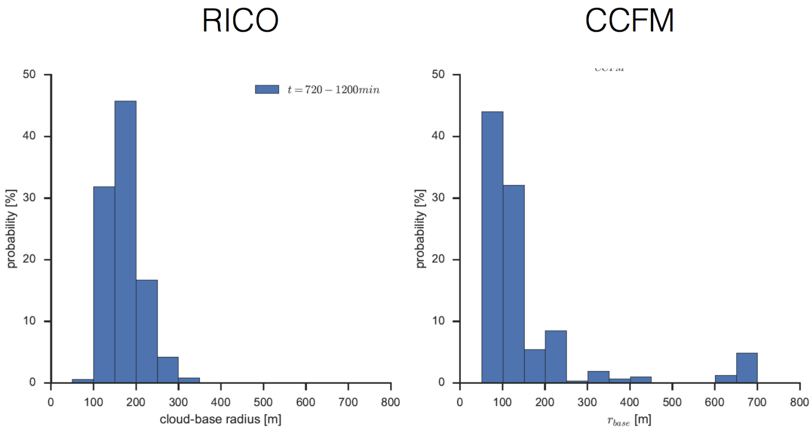

Figure: Cloud-spectrum (in terms of number of clouds with a given maximum cloud-base radius) as extracted from LES and predicted by CCFM spectrum calculation

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 windshear on entrainment and maximum cloud-top height
- Further investigate (not mentioned here) effects of microphysics on development of convective updrafts

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