How should we represent convective genesis?

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Aim

- Characterise coherent boundary-layer structures which cause the formation of moist-convective updrafts (i.e. convective clouds).
  - What are the spatial scales of boundary-layer updrafts? Horizontal/vertical aspect ratio? Spatial distribution (spatial separation)?
  - What influences these characteristics? I.e. how do these characteristics change with the boundary layer state?
  - How do specific phenomena related to moist convection (shallow/deep convection, squall lines, coldpools, etc) affect these?
  - Does the topology of these coherent structures influence their dynamical behaviour? Can the topology be used as a means of classification (instead of isosurfaces)?

So as to

- Identify which physical variables are most important to represent convective trigger, which variables carry memory.
- Provide convective scheme with joint distributions (e.g. $P(q_t, \theta_l, w)$) of cloud-base conditions.

Simulation setup

Preliminary results: **Multiple ($O(10^4)$) interacting clouds triggered through surface-fluxes and large-scale forcing** in large domain ($O(10) km^2$) LES ($\Delta x = 25m$). Original RICO case (VanZanten et al. (2011)) and RICO-like with fixed surface fluxes and with/without ambient windshear.

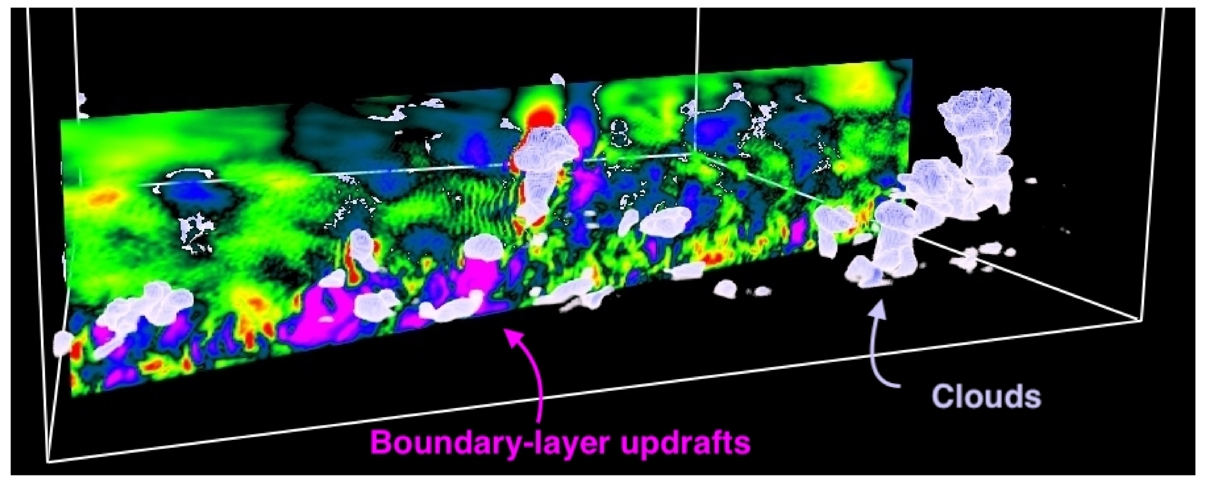


Figure 1: Radiative-Convective Equilibrium precipitating marine shallow cumulus based on RICO measuring campaign. Using UCLA-LES (Stevens et al. (2005)). Individual clouds identified with cloud-tracking algorithm (Heus and Seifert (2013))

For future simulations: **large-domain simulations capturing phenomena of interest**

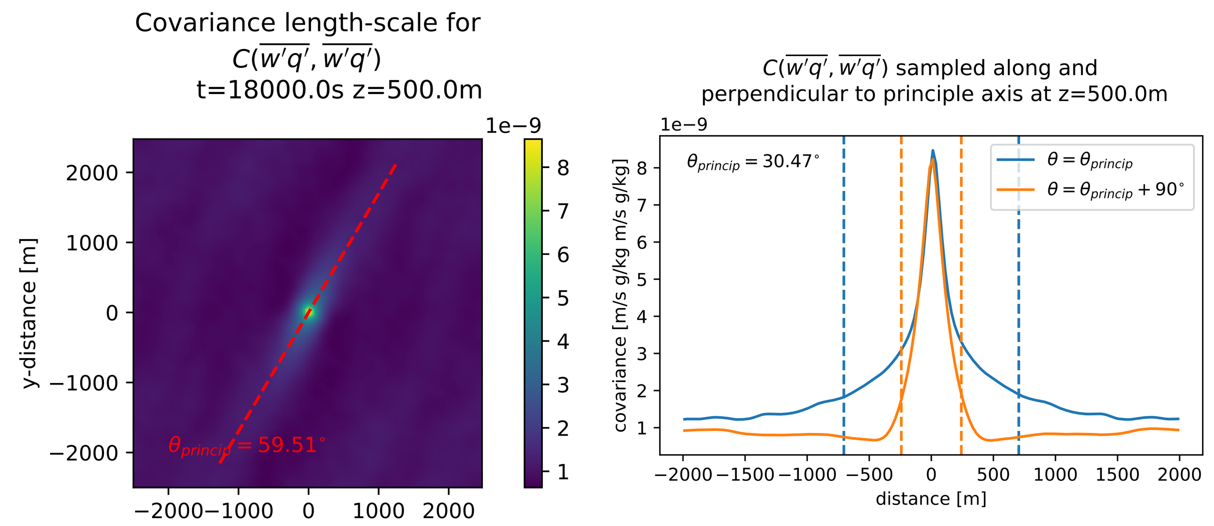
- collected literature, case descriptions, scientific motiviation, initial and boundary conditions **in one central place**: `https://github.com/leifdenby/moistconvection`. Lack of studies which focus on **surface heterogeneity** and **cold-pools**.

Analysis methods

Cumulant analysis

In Tobias and Marston (2016) cumulants (higher-order generalisation of covariance) were applied to identify the principle length-scales of coherent structures in 3D Couvette flow. For example computing the second cumulant for velocity at two different heights (z_1 and z_2) is given by

$$c_{uu}(\xi, \mu, z_1, z_2) = \frac{1}{L_x L_y} \int_0^{L_x} \int_0^{L_y} u'(x, y, z_1) u'(x + \xi, y + \nu, z_2) dx dy.$$



This method is applied in this work to identify the dominant modes in the convective boundary layer.

Topological measures

Zhdankin et al. (2014) studied energy dissipation in magnetohydrodynamic turbulence through topological measures (Minkowski functionals) of structures identified by isosurfaces of current density. Found that majority of transport done by long thin filaments. Aim to use this method to classify through their topology the coherent structures in the convective boundary layer which dominate transport of moisture and heat to trigger convective clouds.

In 3D the Minkowski functionals are

$$V_0 = V = \int dV$$
$$V_1 = \frac{A}{6} = \frac{1}{6} \int dS$$
$$V_2 = \frac{H}{3\pi} = -\frac{1}{6\pi} \int dS \nabla \cdot \hat{\mathbf{n}} = \frac{1}{6\pi} \int (\kappa_1 + \kappa_2) dS$$
$$V_3 = \frac{1}{4\pi} \int (\kappa_1 \kappa_2) dS$$

From these a characteristic *length* (L_m), *witdth* (W_m) and *thickness* (T_m) (saying whether the object more like a *sphere*, *stick* or a *pancake*) can be calculated as

$$L_m = \frac{3V_2}{4V_3}, W_m = \frac{2V_1}{\pi V_2}, T_m = \frac{V_0}{2V_1},$$

where the normalization is so that all measures correspond to the radius when applied to a sphere.

These may be further reduced as *filamentarity* (F_m) and *planarity* (P_m):

$$F_m = \frac{L_m - W_m}{L_m + W_m}, P_m = \frac{W_m - T_m}{W_m + T_m}.$$

Results

For all results cloud-base was at $z_{base} \approx 650m$.

Properties of triggering parcels

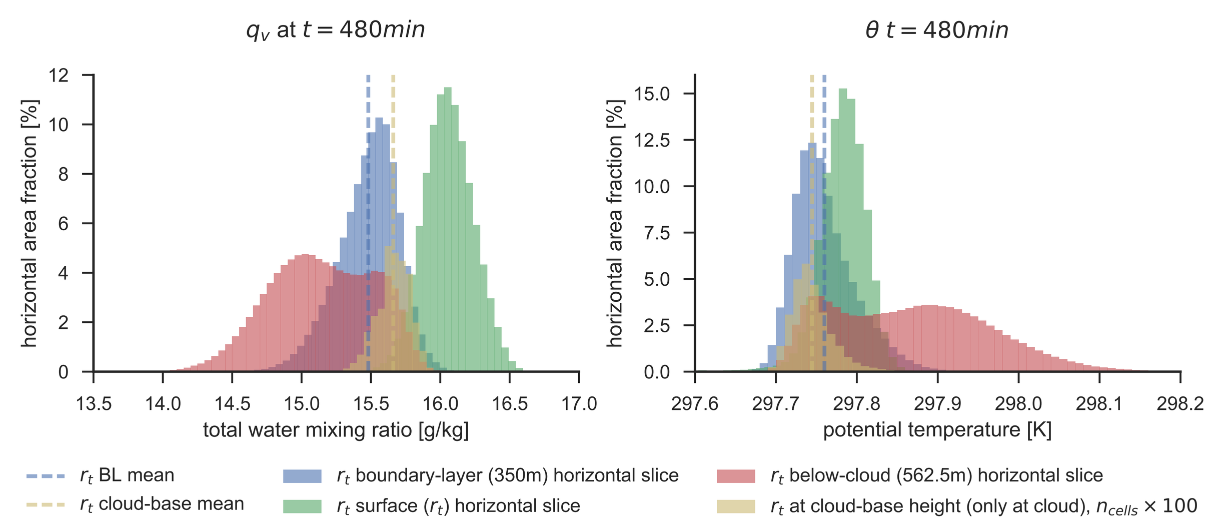


Figure 2: Distributions of water vapour (left) and potential temperature (right) in horizontal cross-sections at increasing heights through boundary-layer and extracted in cells immediately below cloud-base. Comparing distribution through boundary-layer center and cloud-base the air triggering parcels appears relatively moist and cool.

Shear vs no-shear

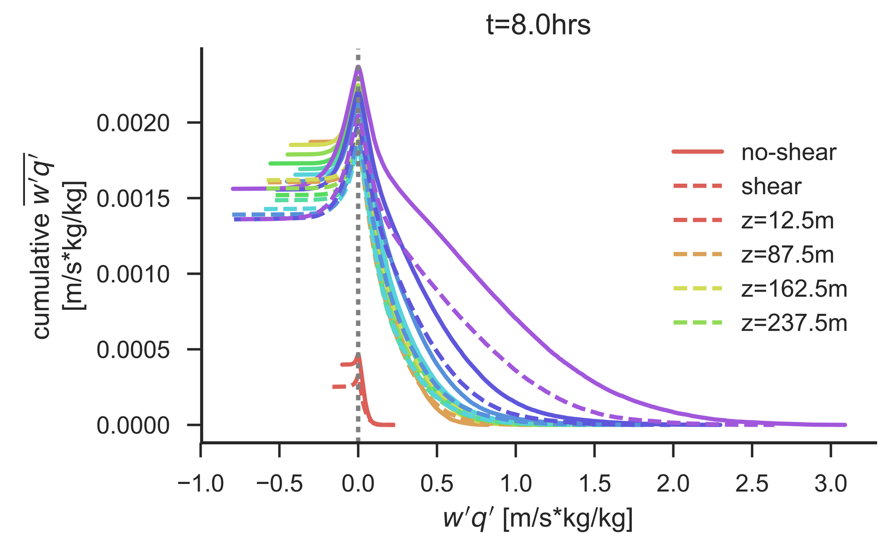


Figure 3: Cumulative vertical moisture flux at increasing height for sheared and non-sheared simulation. Both simulations show rapid change in distribution in first $100m$ of boundary layer and last $100m$ before cloud-base, with similar shape and monotonic increase in width. However regions with larger moisture flux contribute more at boundary-layer top in non-sheared simulation.

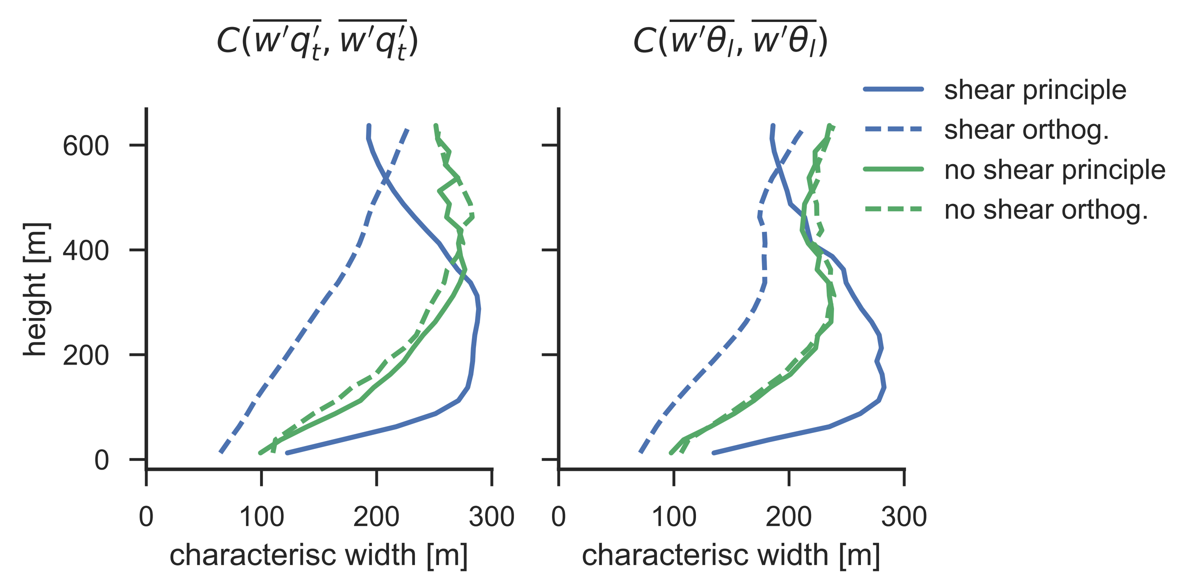


Figure 4: Change of coherence length-scale with height for vertical heat and moisture flux from pricinple direction of 2nd cumulant. Comparing sheared vs non-sheared environment the coherent boundary-layer structures are markedly elongated by wind-shear.

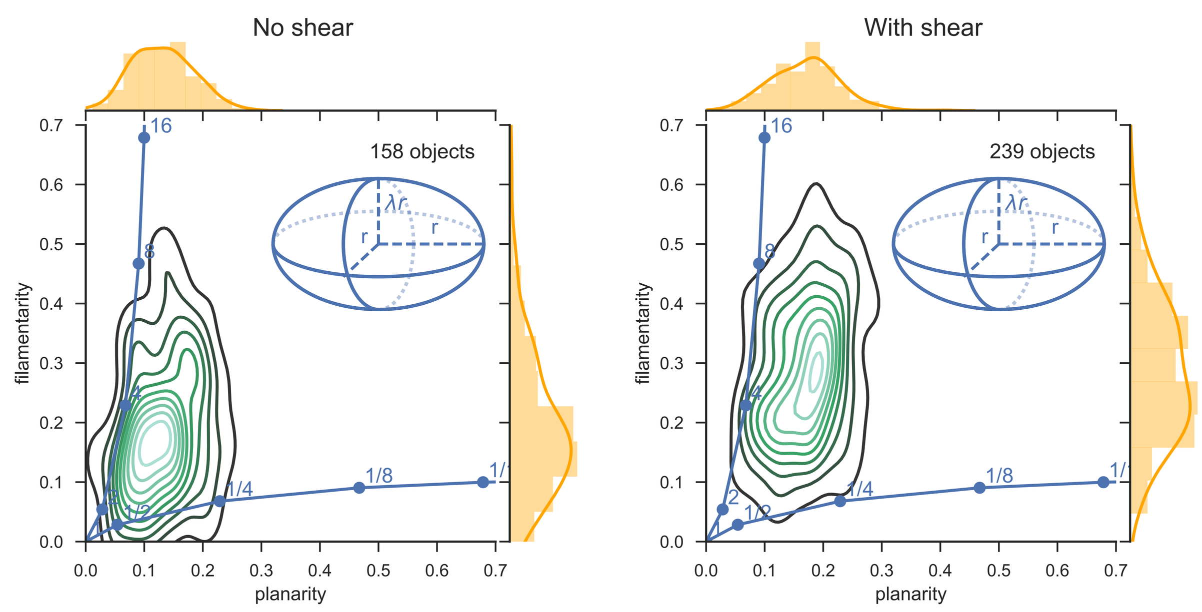


Figure 5: Planarity and filamentarity of structures defined by moisture flux ($w'q'_t = 0.3 m/s \times kg/kg$), indicating that structures of dominant moisture flux are significantly elongated in a sheared environment.

Cold-pool vs non-coldpool regions

Cold-pool regions were labelled by virtual potential temperature devition ($\theta_v < -0.1K$, from horizontal mean) once convection has aggregated ($t = 18hrs$).

References

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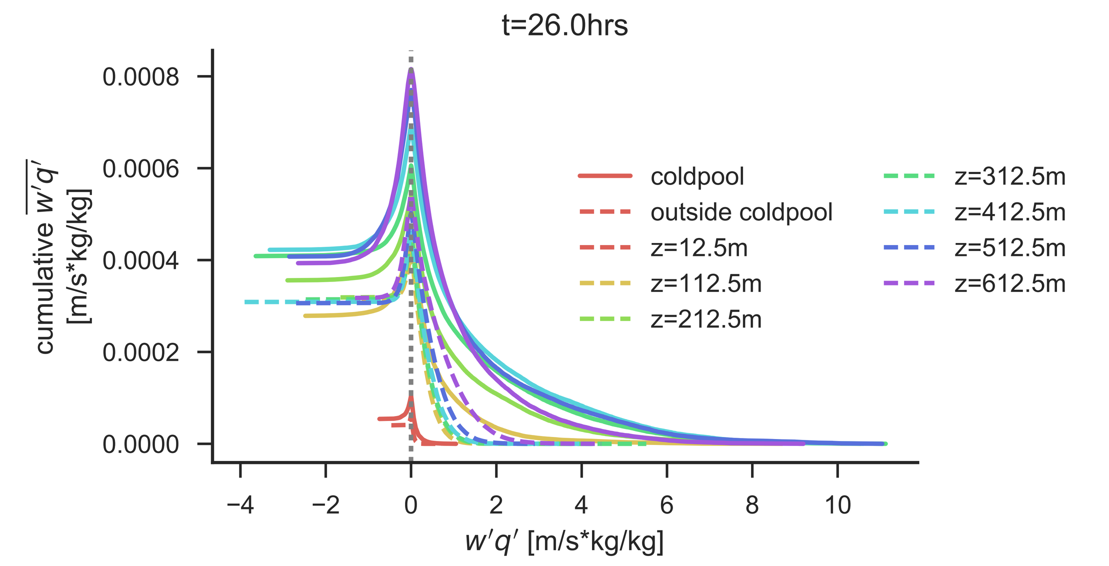

Figure 6: Cumulative moisture flux profiles in coldpool ($\theta_v < -0.1K$) and non-coldpool regions. Outside the coldpool the distribution is similar to sheared case, however within coldpool intermediate region where moisture flux distribution is stable is absent.

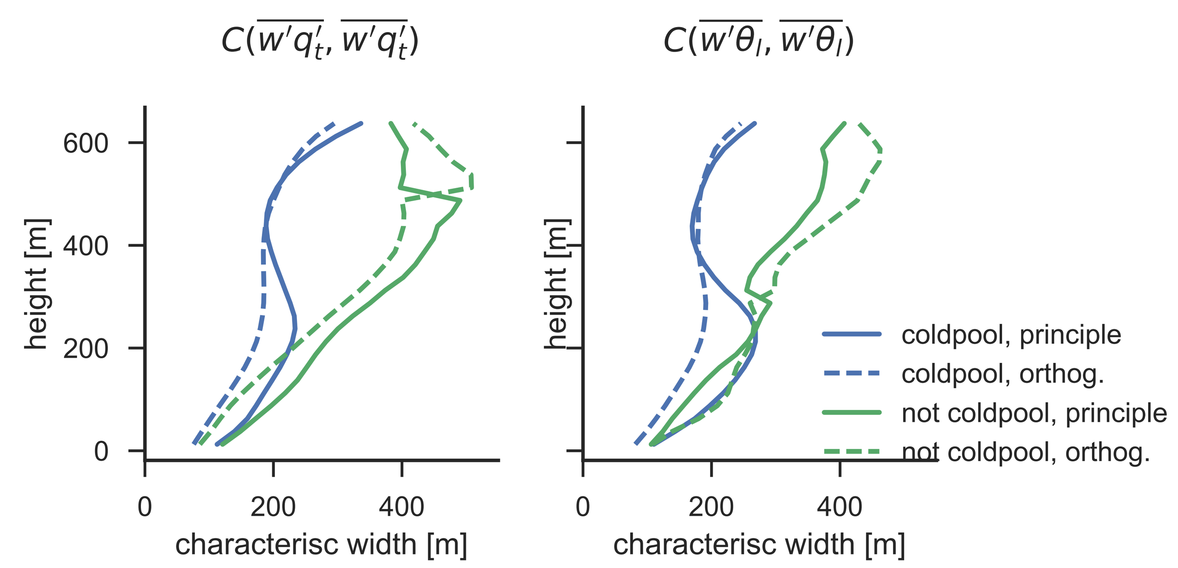

Figure 7: Coherence length-scale profiles inside ($\theta_v < -0.1K$) and outside ($\theta_v > -0.1K$) coldpool region. Both regions show asymmetry of horizontal length-scales of vertical fluxes, however within coldpool horizontal size of coherent structures drastically decreases above $z\ approx 300m$, providing less moisture flux for triggering new clouds.

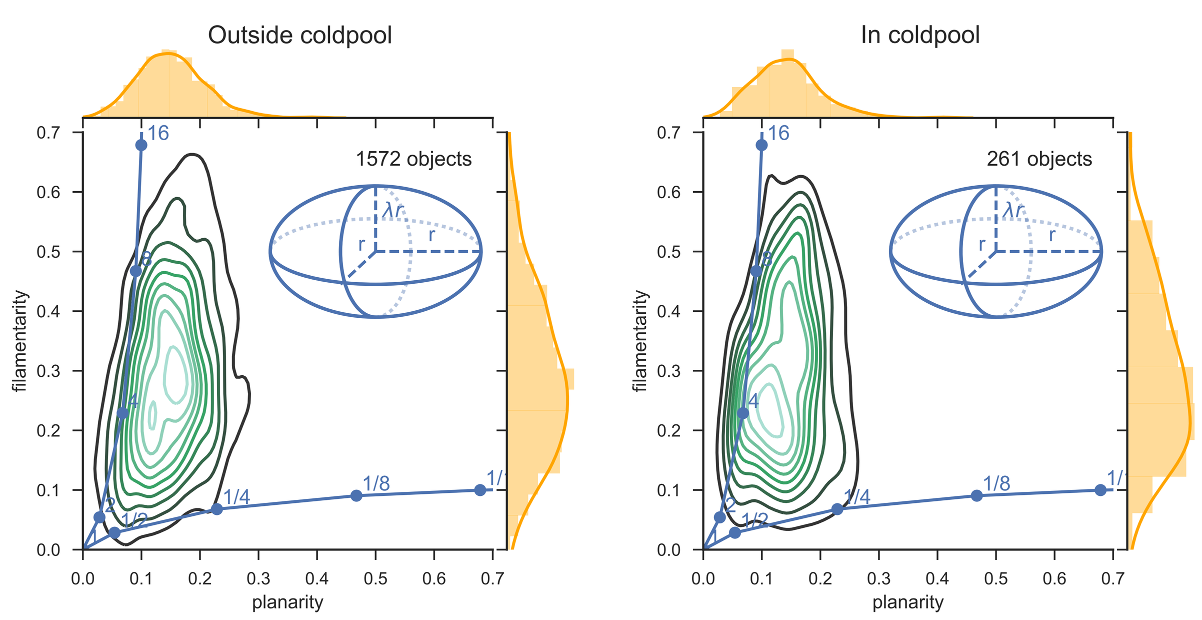

Figure 8: Planarity and filamentarity of structures of vertical moisture flux ($w'q'_t > 0.3 kg/kg \times m/s$). Generally coherent structures inside the coldpool are more filamentary than outside and have a narrower distribution in planarity.

Further work

- Identify coherent structures which *actually* trigger formation of clouds using Lagrangian particle tracking.
- Perform simulations with surface heterogeneity (e.g. soil-moisture variations) and topography to study effect on coherent structures.
- Further spatially and temporially decompose domain where convective aggregation has taken place to study properties of coherent structures during evolution of coldpools.
- Develop parameterisation which produces prediction of distribution of thermal size as well as physical properties at cloud base