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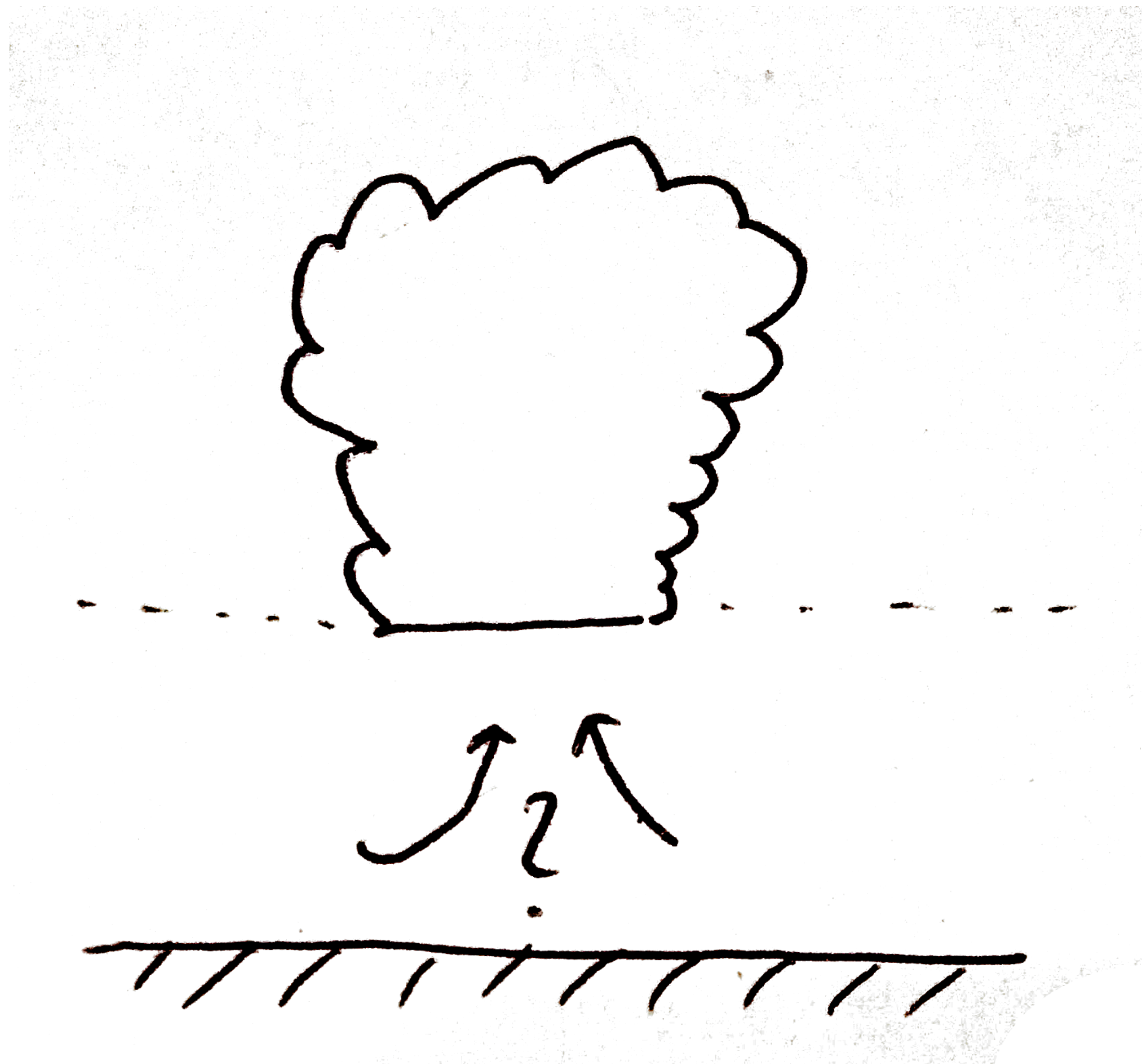
Properties of coherent boundary layer structures and their connection to clouds

Leif Denby, University of Leeds

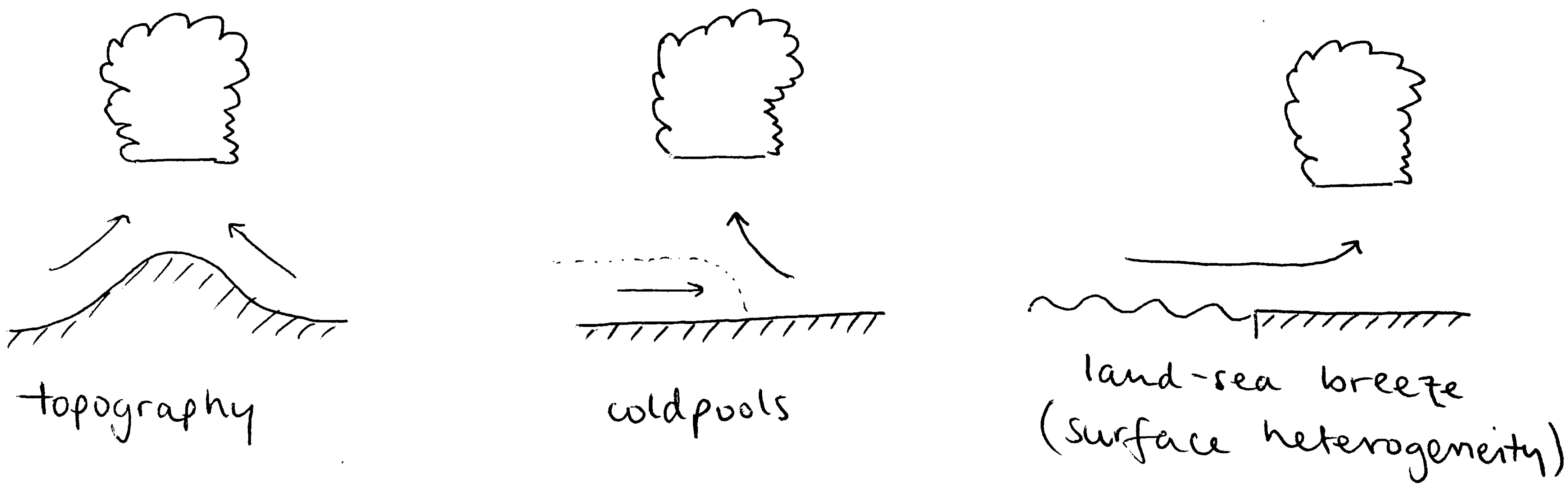
3/2/2018, ParaCon Plenary, Met Office, Exeter

Aim



Aim

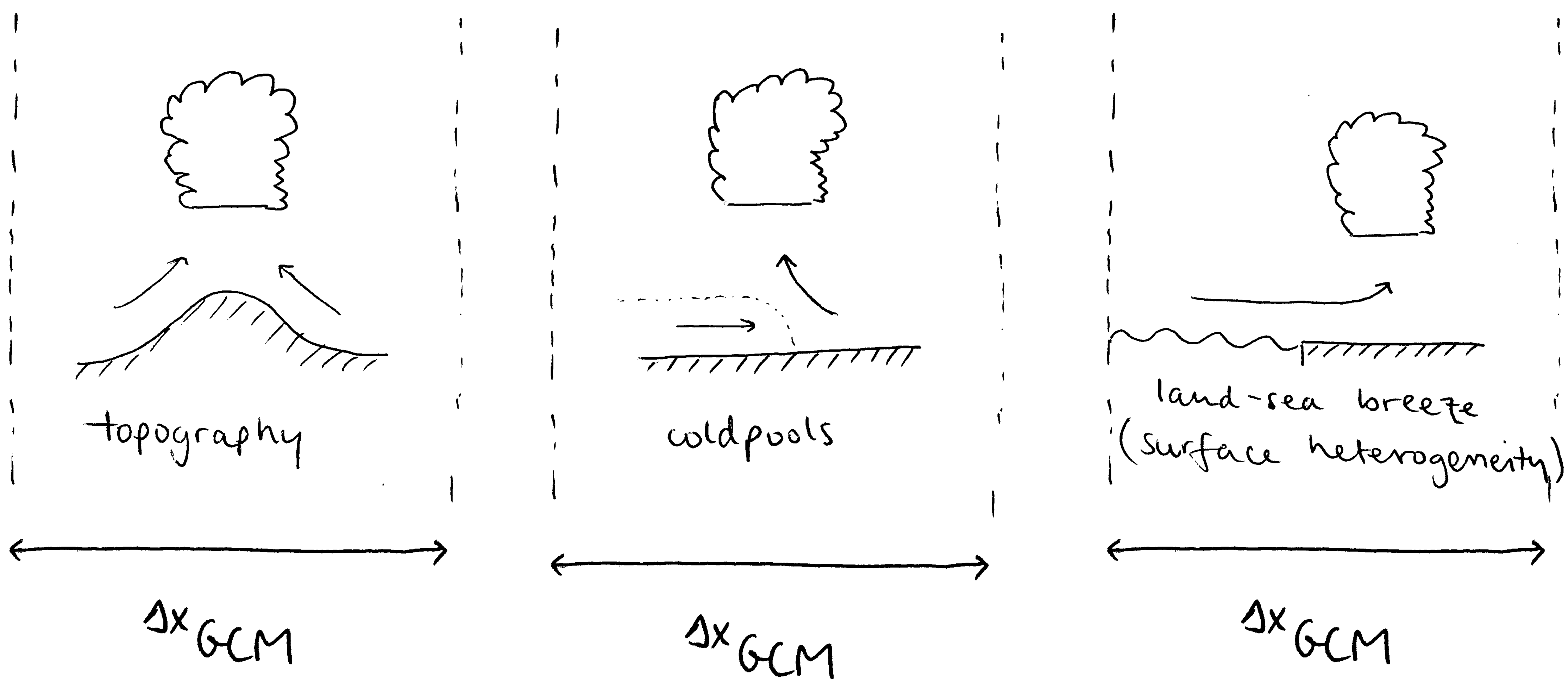
- Describe statistics of boundary layer relevant to triggering convection and the sensitivity to presence of different phenomena



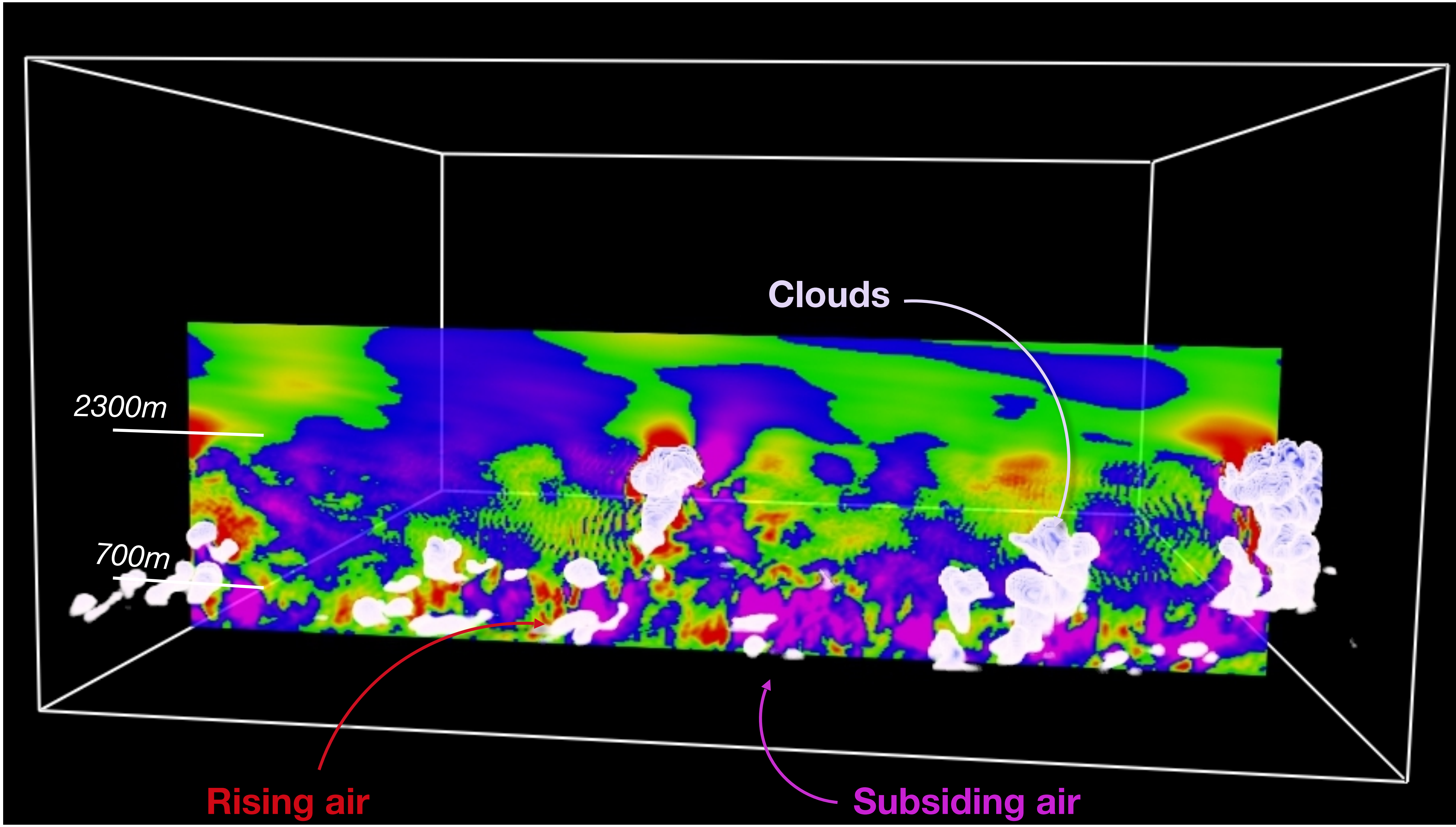
- *"What are the length-scales and magnitudes of perturbations which trigger convection?"*

Why?

- GCMs have too coarse resolution to fully represent convection (O(km))
  - ➡ Trigger (and evolution) of convection must be parameterised
  - ➡ These *sub-grid* features are known to be critical in predicting formation of convection



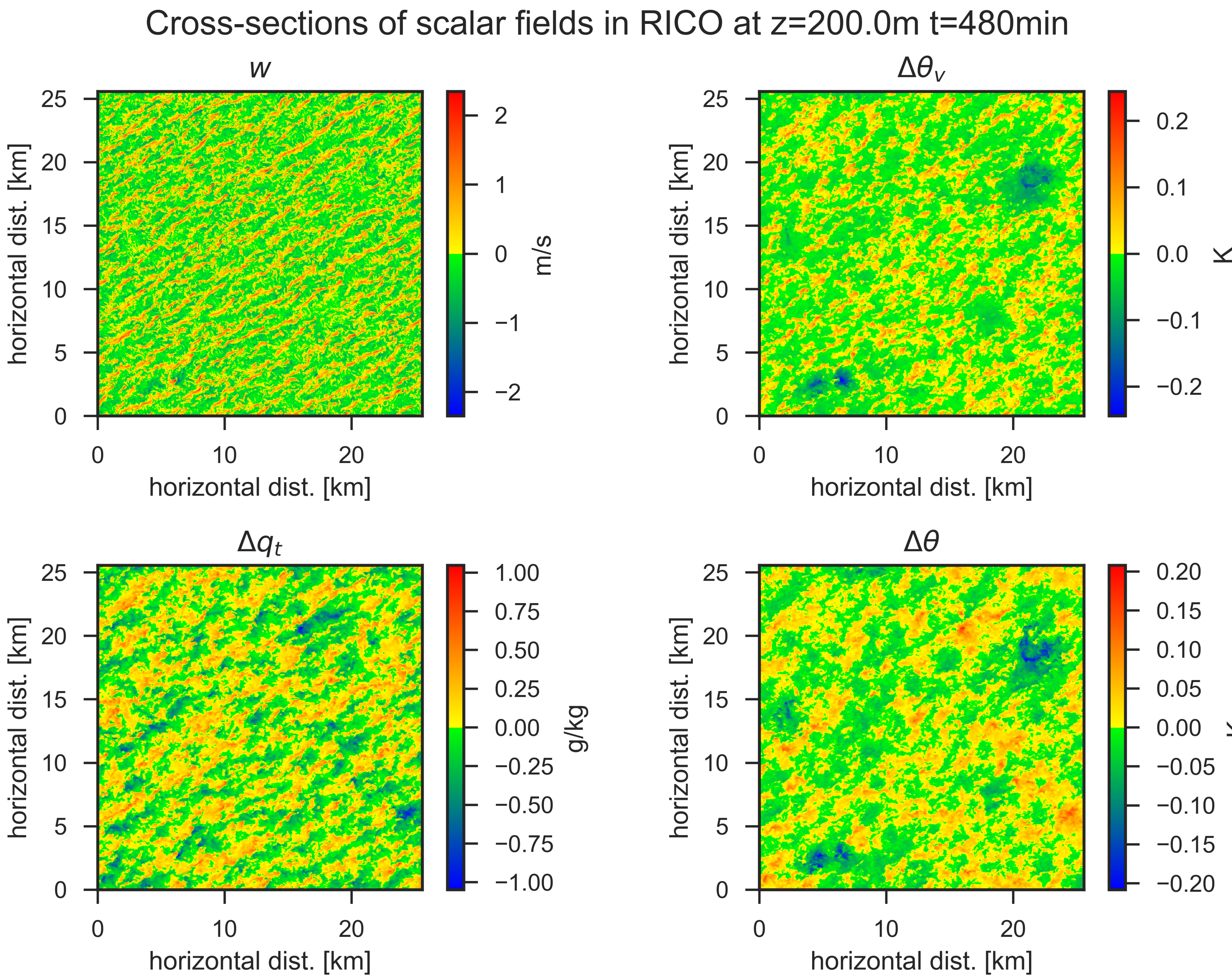
What are the length-scales of variability?



Δx=25m Large-Eddy Simulation, RICO test-case

Rendered with VAPOR

What are the length-scales of variability?



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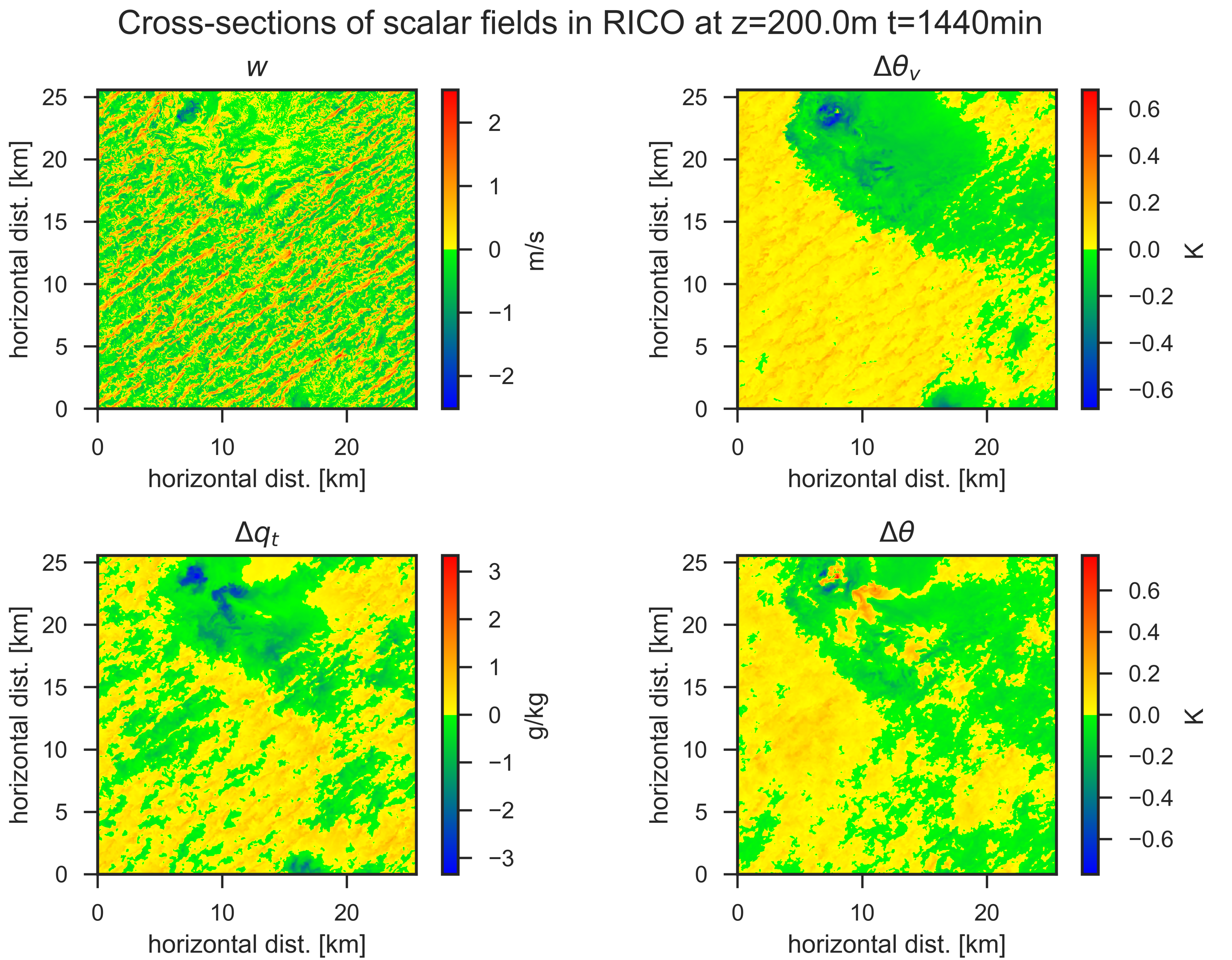
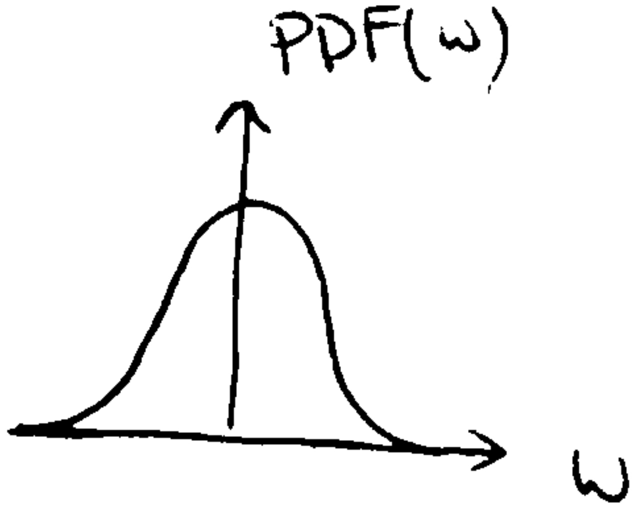
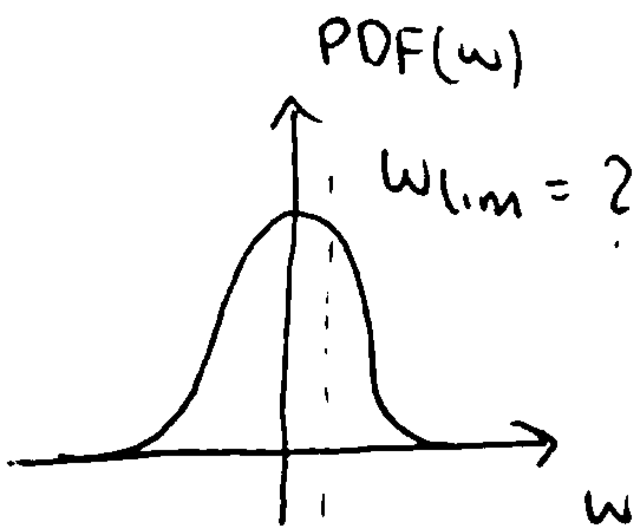


Researching things relevant to convective parameterisation



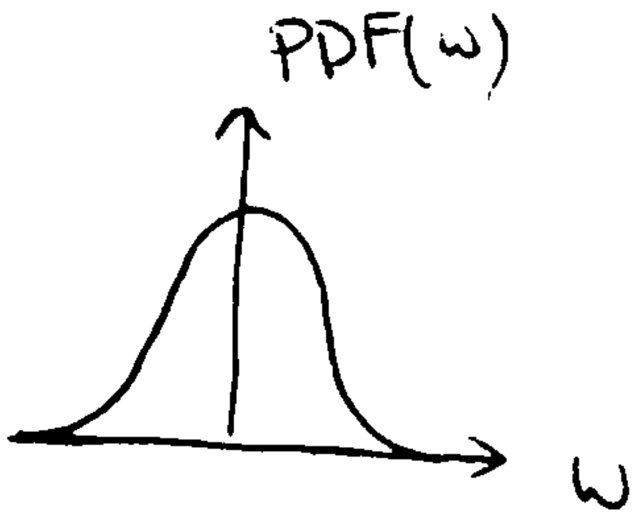
Hierarchy of analysis:

a) Vertical profiles of horizontally integrated properties, e.g. PDFs of scalars (without identifying triggering updrafts)



b) Vertical profiles of identified updraft regions (e.g. *two-fluid* partitioning)
- Is there an optimal partitioning of fluid between updrafts/environment?
- Interested in total BL vertical transport or only thermals which trigger convection?

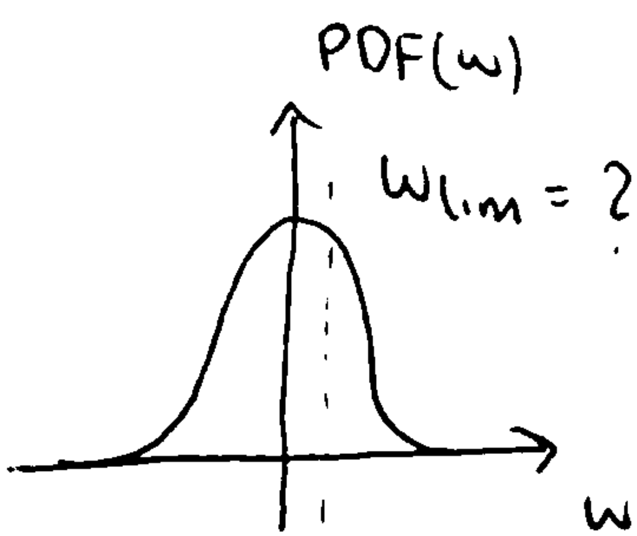
Researching things relevant to convective parameterisation



Hierarchy of analysis:

a) Vertical profiles of horizontally integrated properties, e.g. PDFs of scalars (without identifying triggering updrafts)

tools ready!



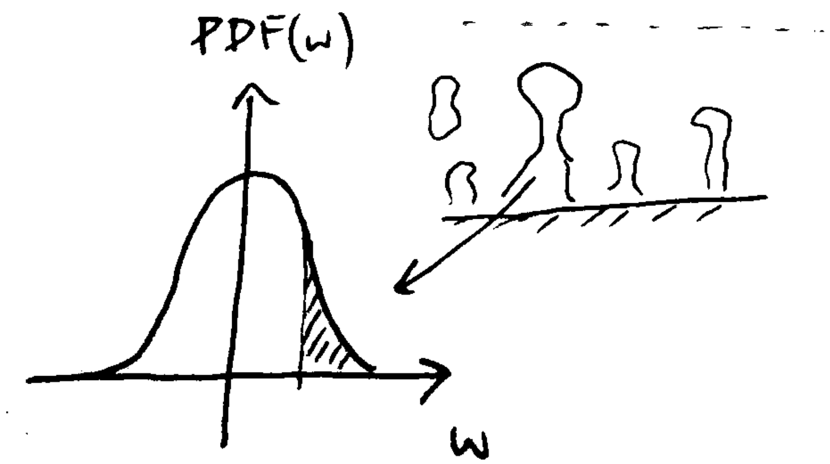
b) Vertical profiles of identified updraft regions (e.g. *two-fluid* partitioning)

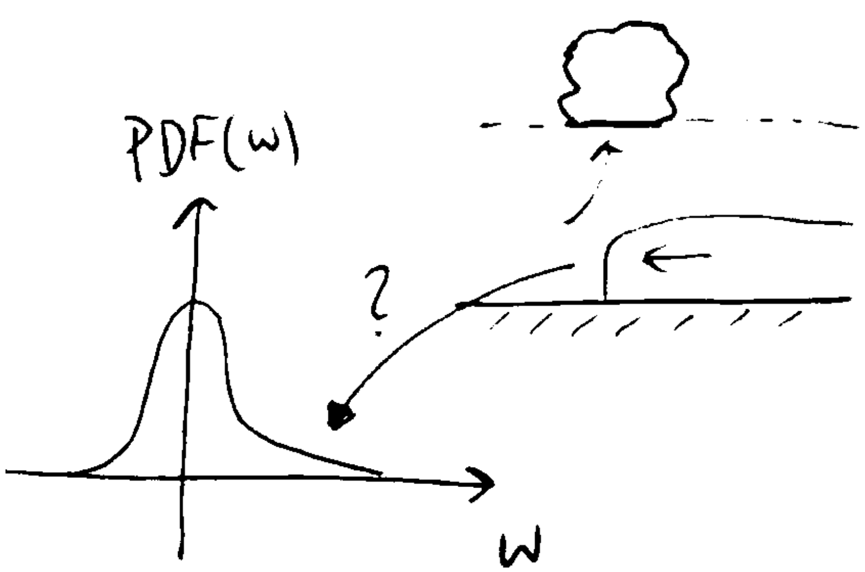
- Is there an optimal partitioning of fluid between updrafts/environment?
- Interested in total BL vertical transport or only thermals which trigger convection?

I think so

Found method to identify these

Researching things relevant to convective parameterisation





Hierarchy of analysis:

…

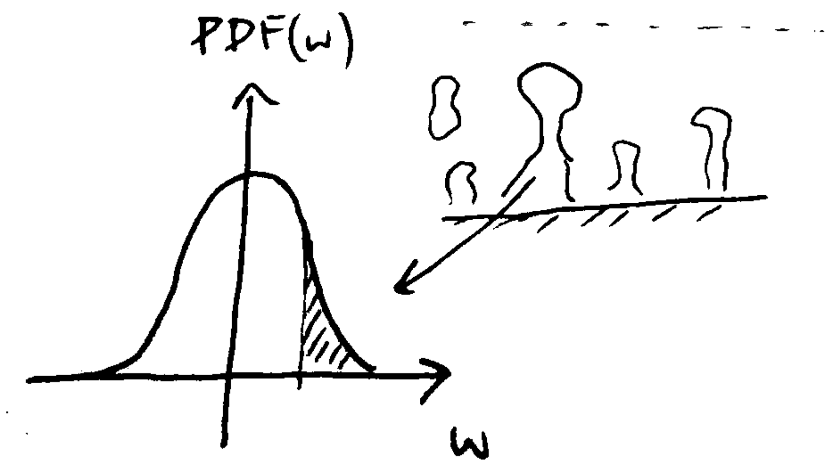
c) Object-based decomposition of horizontal variability

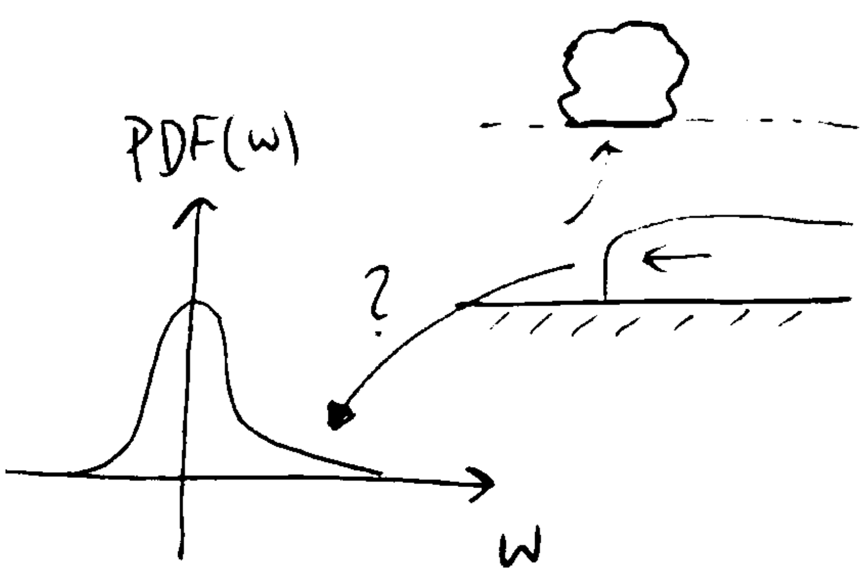
- e.g. reconstruct PDFs using only *N-largest* objects, construct *object size* vs *scalar perturbation* PDFs or identify triggering objects

d) Identify cause of change in vertical profiles and new scalar quantities which parameterise change

- e.g. *the presence of a cold pool with magnitude* $\Delta\theta_v$ *modifies the skewness of the PDF(w) by* $\alpha\Delta\theta_v$

Researching things relevant to convective parameterisation





Hierarchy of analysis:

…

c) Object-based decomposition of horizontal variability

- e.g. reconstruct PDFs using only *N-largest* objects, construct *object size* vs *scalar perturbation* PDFs or identify triggering objects

some interesting results!

d) Identify cause of change in vertical profiles and new scalar quantities which parameterise change

- e.g. *the presence of a cold pool with magnitude* $\Delta\theta_v$ *modifies the skewness of the PDF(w) by* $\alpha\Delta\theta_v$

Ongoing

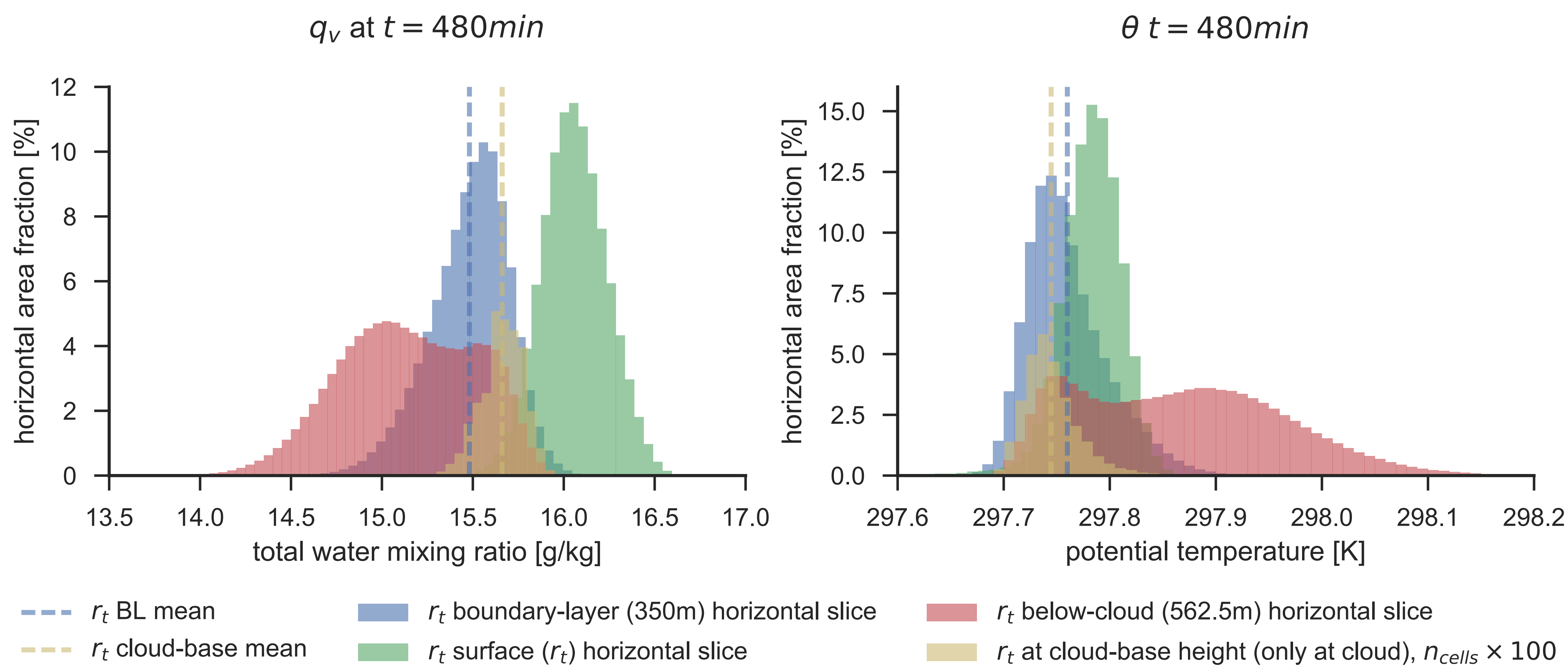
2 topics today

1. Statistical properties of bulk boundary layer and cloud-feeding air

    i. Joint-distributions and characteristic length-scales in boundary-layer

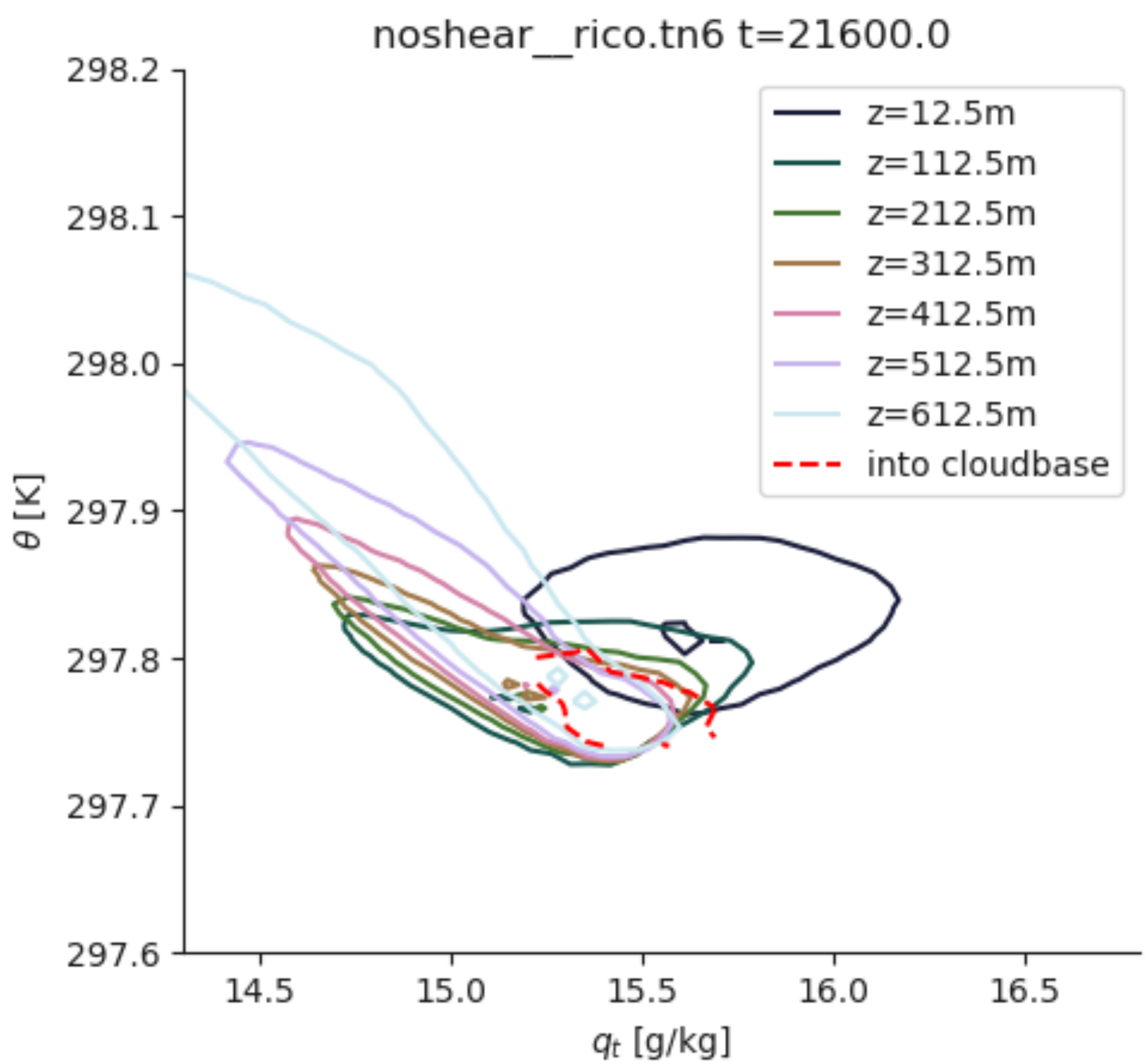
2. Statistical properties of *individual* boundary-layer objects

1. Distributions of moisture and temperature (at interesting heights)



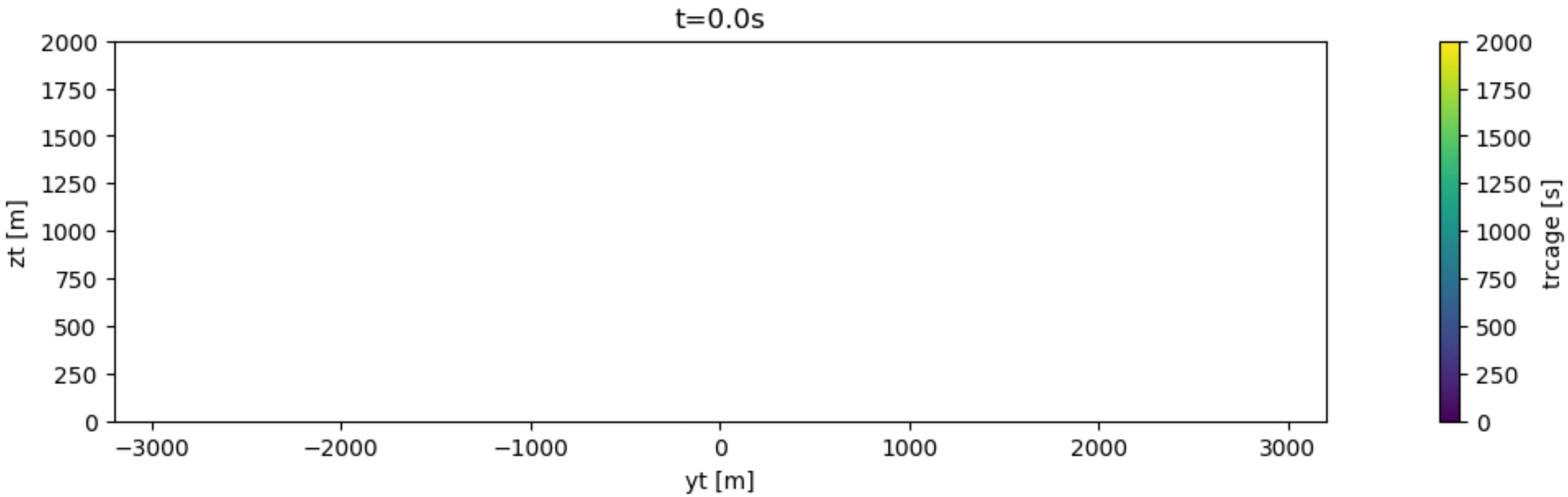
- Air that reaches cloud-level appears to be moister and colder than boundary layer characteristic values
- But *what are the joint distributions (and their height variation)?*

How does water vapour and temperature correlate in the boundary layer?



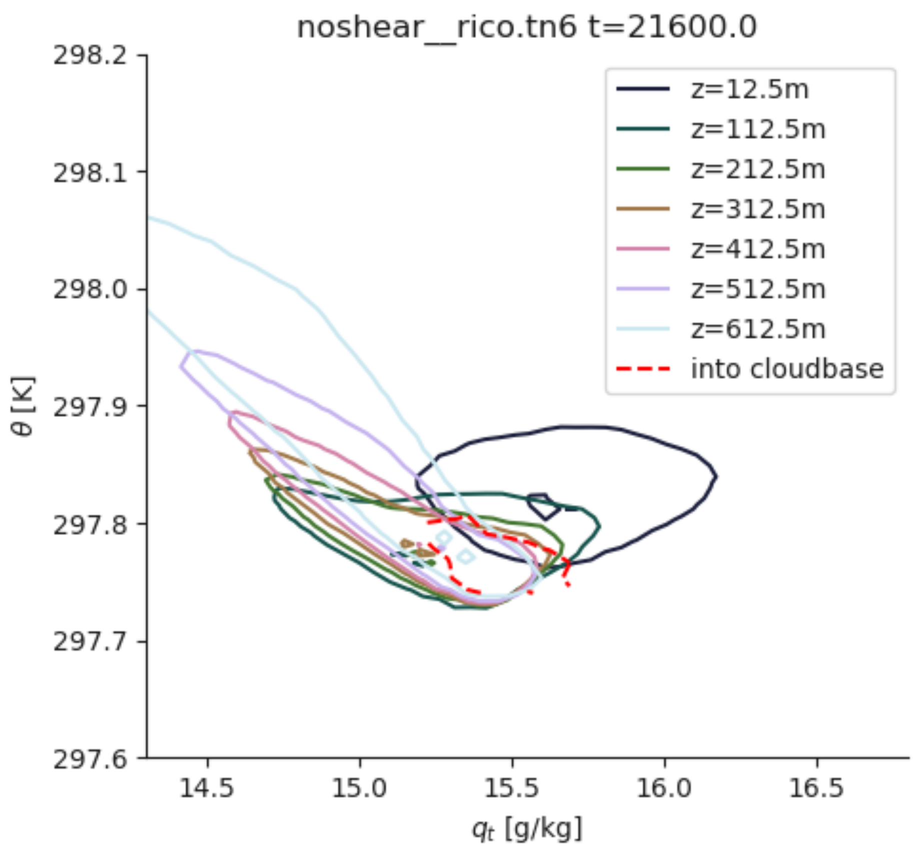
- Inner and outer contour at each height contain regions with top 5% and top 90% concentration of points respectively ("garlic plot")
- Red contour: air Δx below tracked clouds within 3min of appearance => air entering clouds
- How can we *isolate the air that enters clouds*?

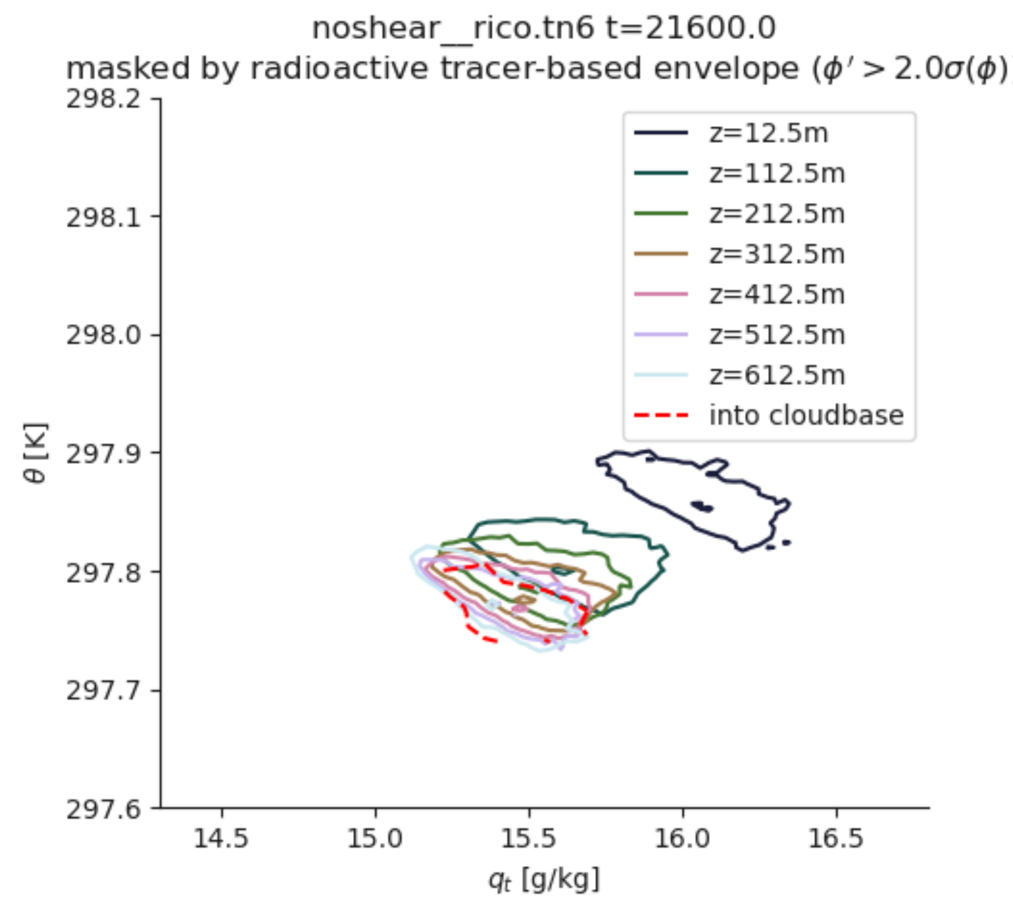
Boundary layer thermals marked with radioactive tracer



- Two tracers (ϕ_1, ϕ_2) with different half-life (τ_1=10min, τ_2=15min) released from surface
- Time since release: $t_{age} = \tau_1 \tau_2 \log(\phi_1/\phi_2)/(\tau_1-\tau_2)$
- Thermal edge defined using deviation from std. div. in horizontal slice: $\phi'(x,y,z) > \sigma(\phi(z))$ (as in Couvreux et al 2010)

Radioactive tracer picks out air entering clouds

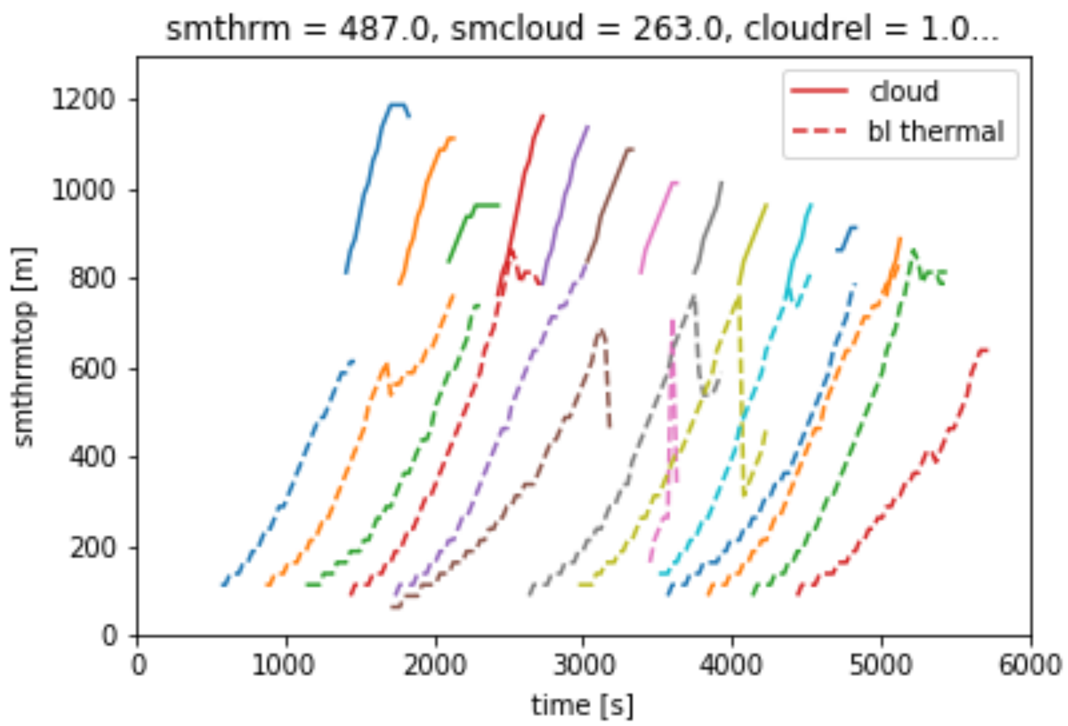




- We can now identify the air that enters clouds and looks at its properties
- In this case the mean and distribution appears translated with height => should be easy to parameterise

(we can also track them…)

Updated cloud-tracking code by Heus 2008 to track thermals, and clouds, and interaction between them

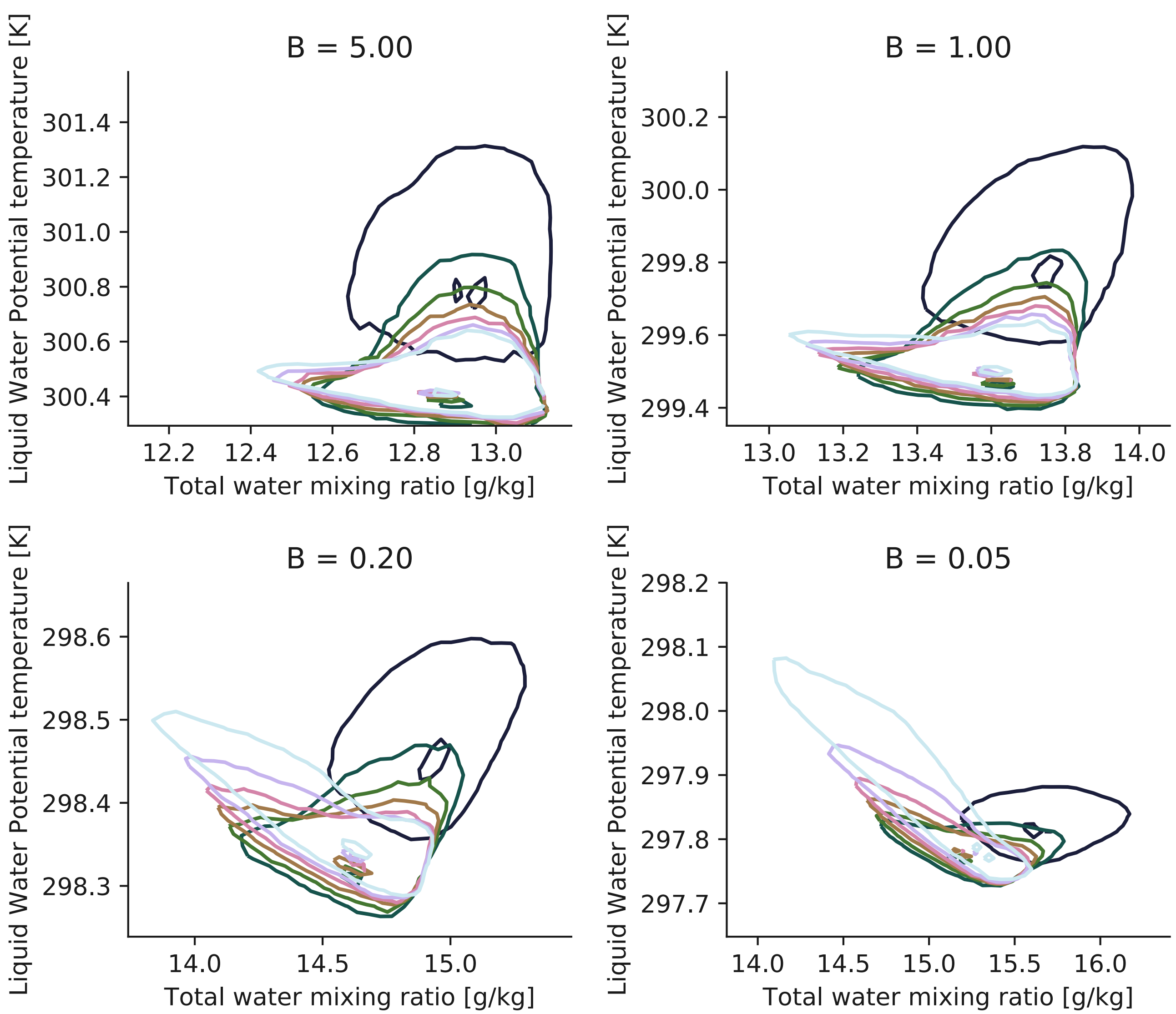


Height of top of individual clouds and thermals that each cloud was triggered by

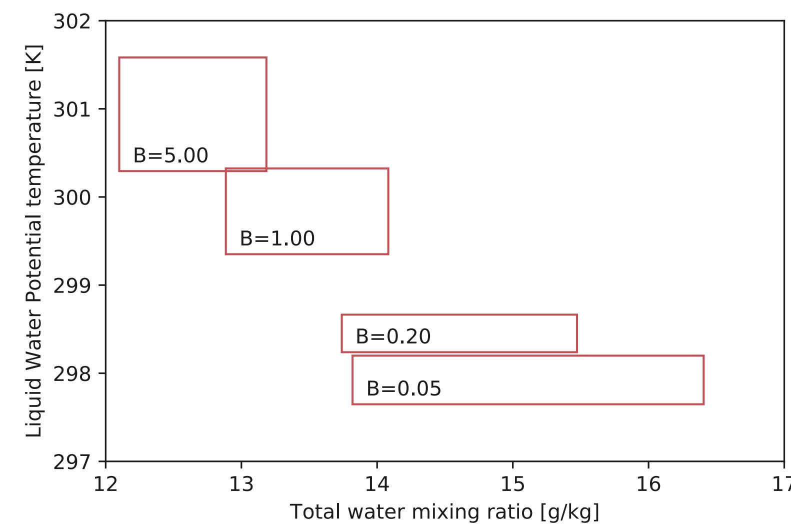
- Both thermals and clouds are tracked separately (using rad. tracer and liquid water)
- Can study properties of air triggering specific clouds
- Currently ~60% clouds have triggering thermals identified. Another trigger mechanism? Investigating cut-offs in tracking

…but that is part of object-based analysis, see later

What happens when we change the Bowen ratio?

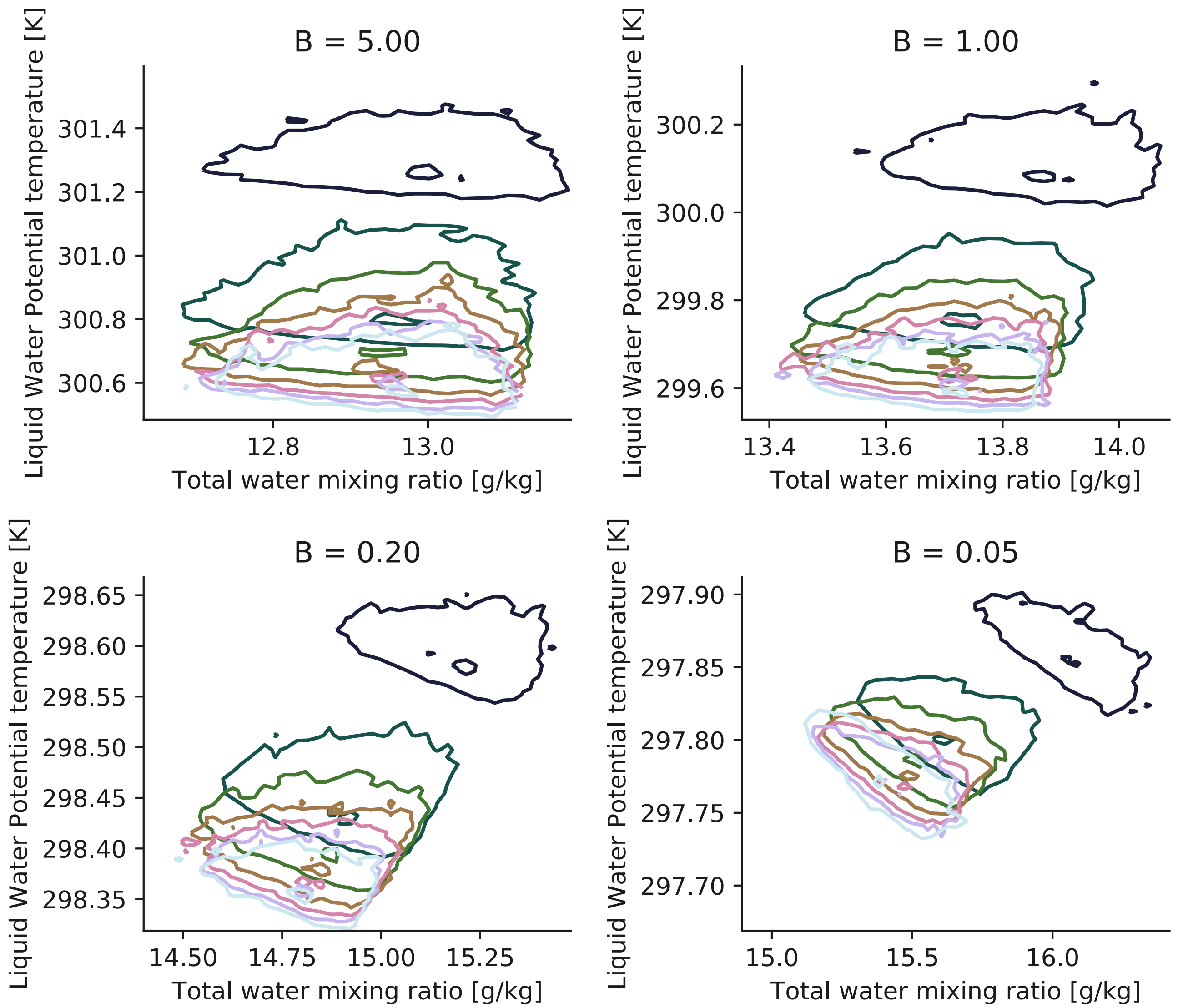


Actual extent of figures on left



- As Bowen ratio is increased change in mean of distribution has less change in moisture (because less moisture is released from surface)

What happens when we change the Bowen ratio? (and pick out cloud-feeding air)



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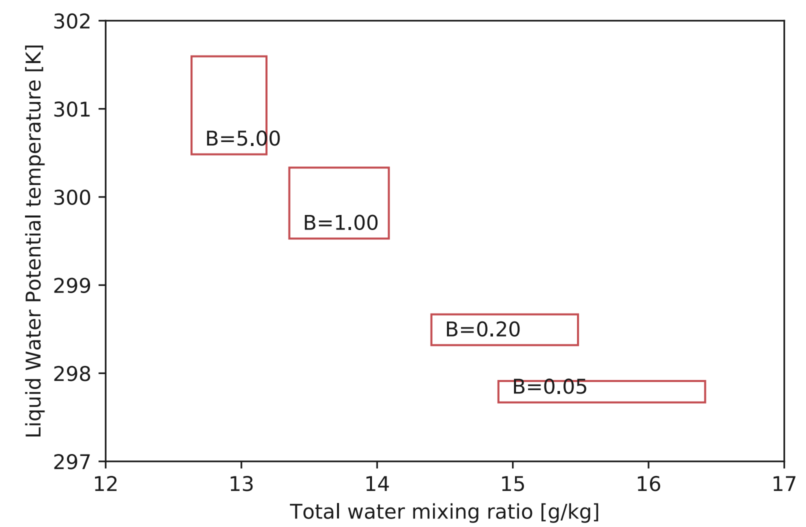


- As Bowen ratio is increased change in mean of distribution has less change in moisture (because less moisture is released from surface)

- All distributions show similar shape displaced with height as air is mixed with boundary layer

1.b. Characteristic length-scales of boundary-layer structures

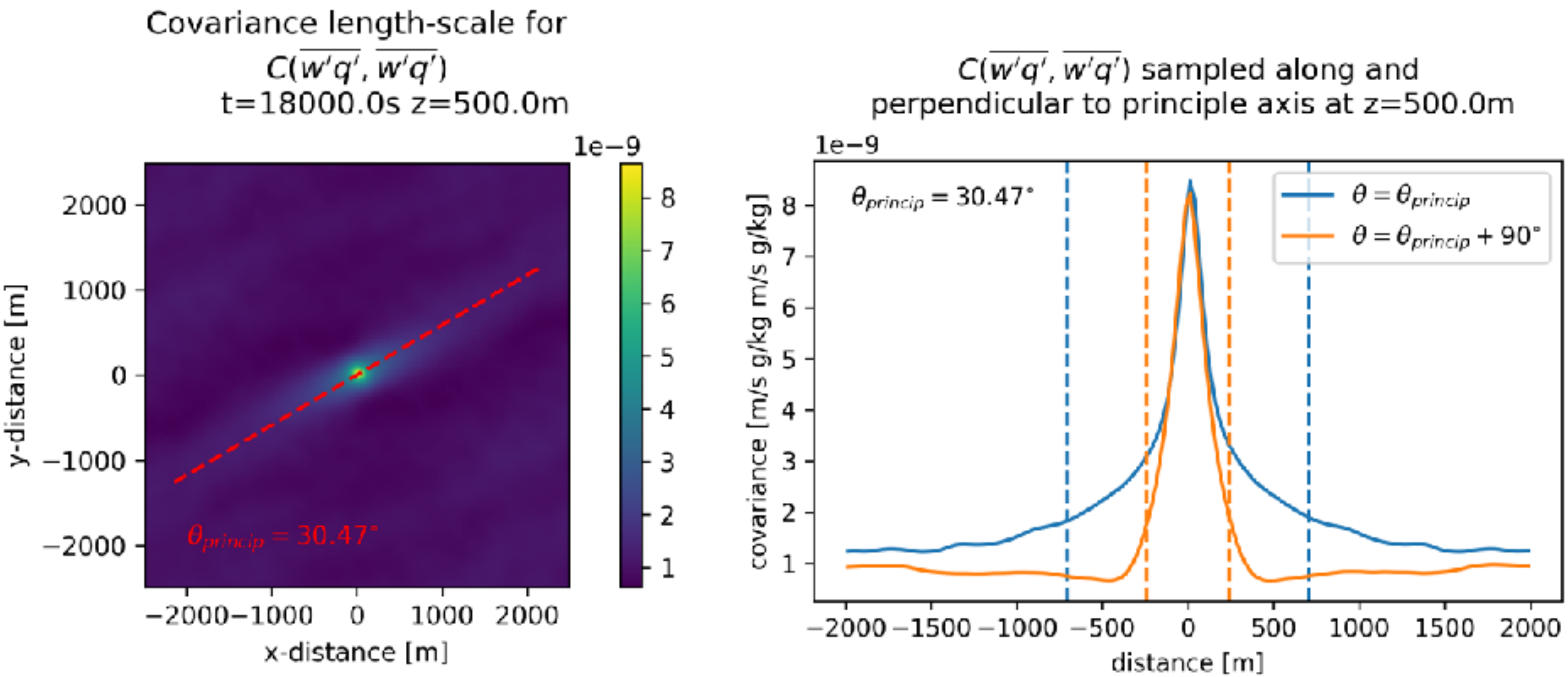
- Two-point correlation of two scalar fields (ϕ and ψ), here taken at same height (z) for both fields

$$c_{\phi\psi}(\xi,\mu,z) = \frac{1}{L_x L_y}\int_0^{L_x}\int_0^{L_y} \phi'(x,y,z)\psi'(x+\xi,y+\nu,z)dxdy$$

- Measures how correlation with distance (in xy-plane) of scalar fields

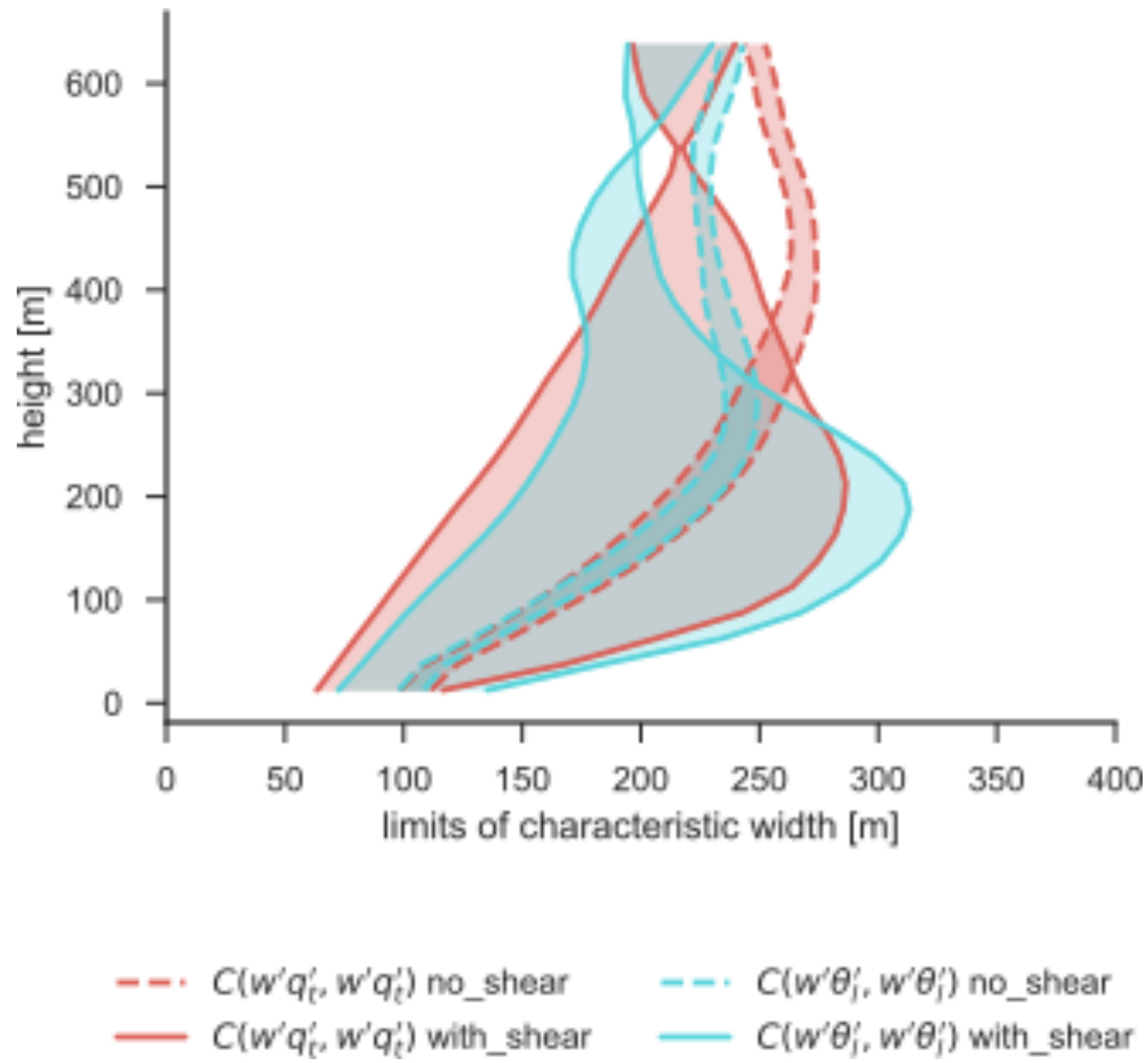
- Used by Tobias and Marston 2016 to identify principle length-scales in 3D cuvette flow

Use of cumulants to study characteristic scales



- Principle axis identified from principle axis of moment of inertia tensor

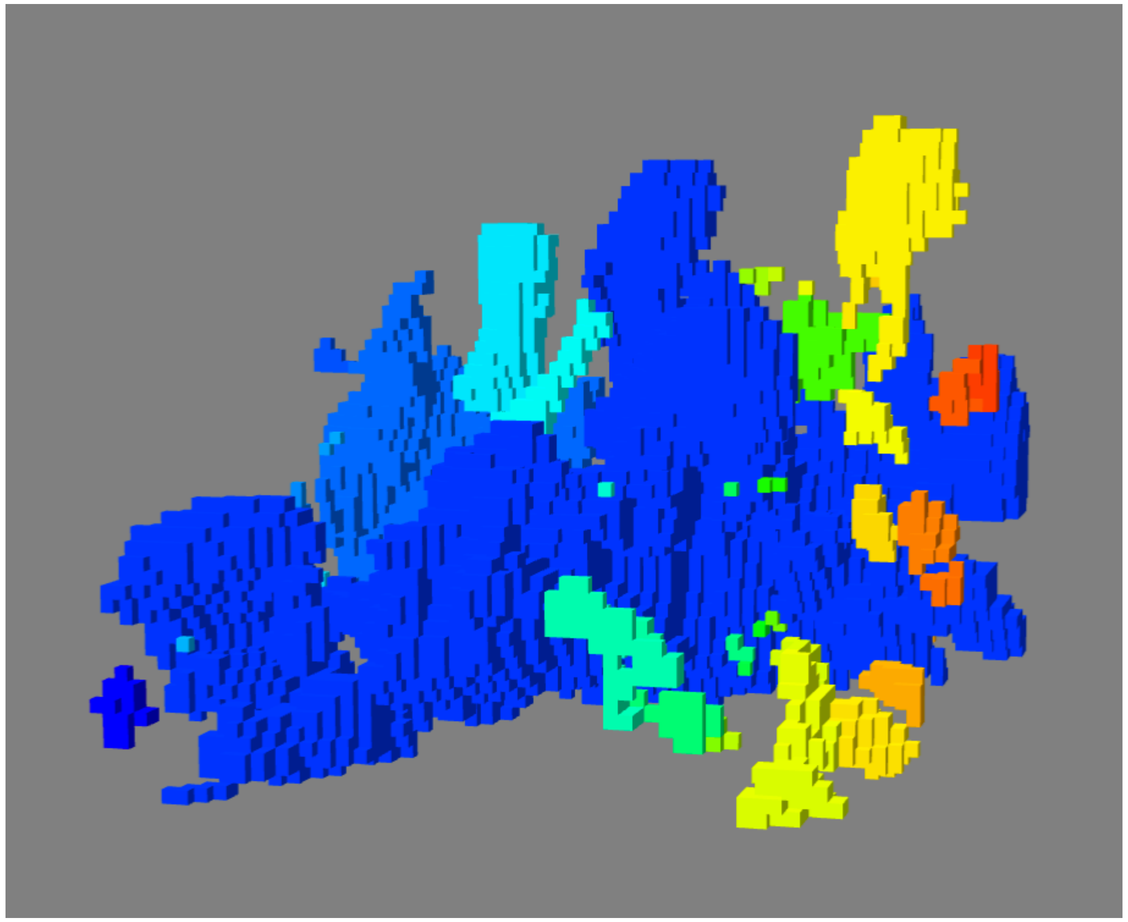
Characteristic length-scales of vertical flux fields



- moisture (latent) and (sensible) heat flux similar length-scale till ~300m.
- shear causes elongation of coherent structures

2. Object-based analysis
Identifying individual objects

- Identify (and later, track in time) boundary layer structures which cause convection to trigger
  - ➡ Developing cloud-tracking code with Steven Boeing
- Use to partition distributions of variability by individual objects (of specific size, volume, shape, etc)



Buoyant elements defined by w > 0.5m/s
in boundary layer of RICO simulation at t=480min

➡ Investigating using object topology as means of classification. Contour-tree and fiber-surfaces analysis with Hamish Carr and PhD student, Leeds

What are characteristic sizes of objects in the boundary layer?

- Use Minkowski functionals to compute characteristic length-scales

$$V_0 = V = \int dV$$

$$V_1 = \frac{A}{6} = \frac{1}{6}\int dS$$

$$V_2 = \frac{H}{3\pi} = -\frac{1}{6\pi}\int dS \nabla \cdot \hat{n}$$

$$\left(V_3 = \frac{1}{4\pi}\int (\kappa_1 \kappa_2) dS \right)$$

$$\Rightarrow$$

$$L = \frac{3V_2}{4V_3}$$

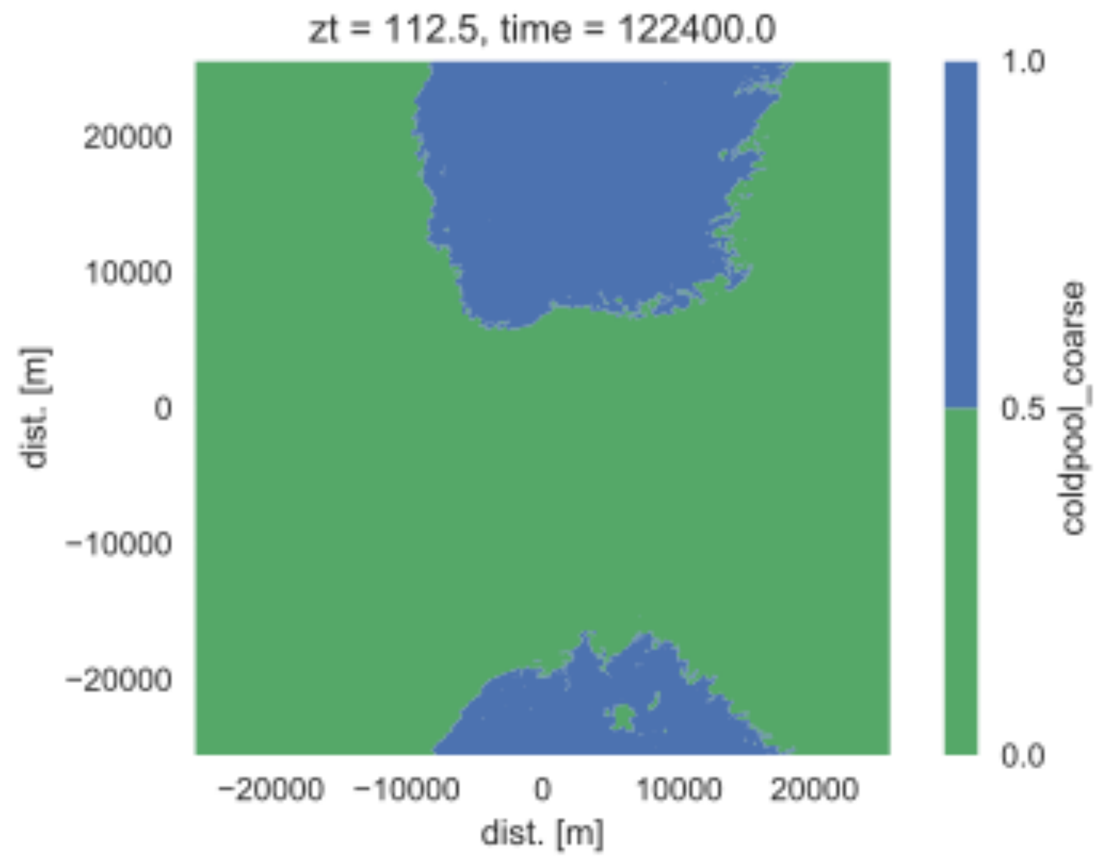
$$W = \frac{2V_1}{\pi V_2}$$

$$T = \frac{V_0}{2V_1}$$

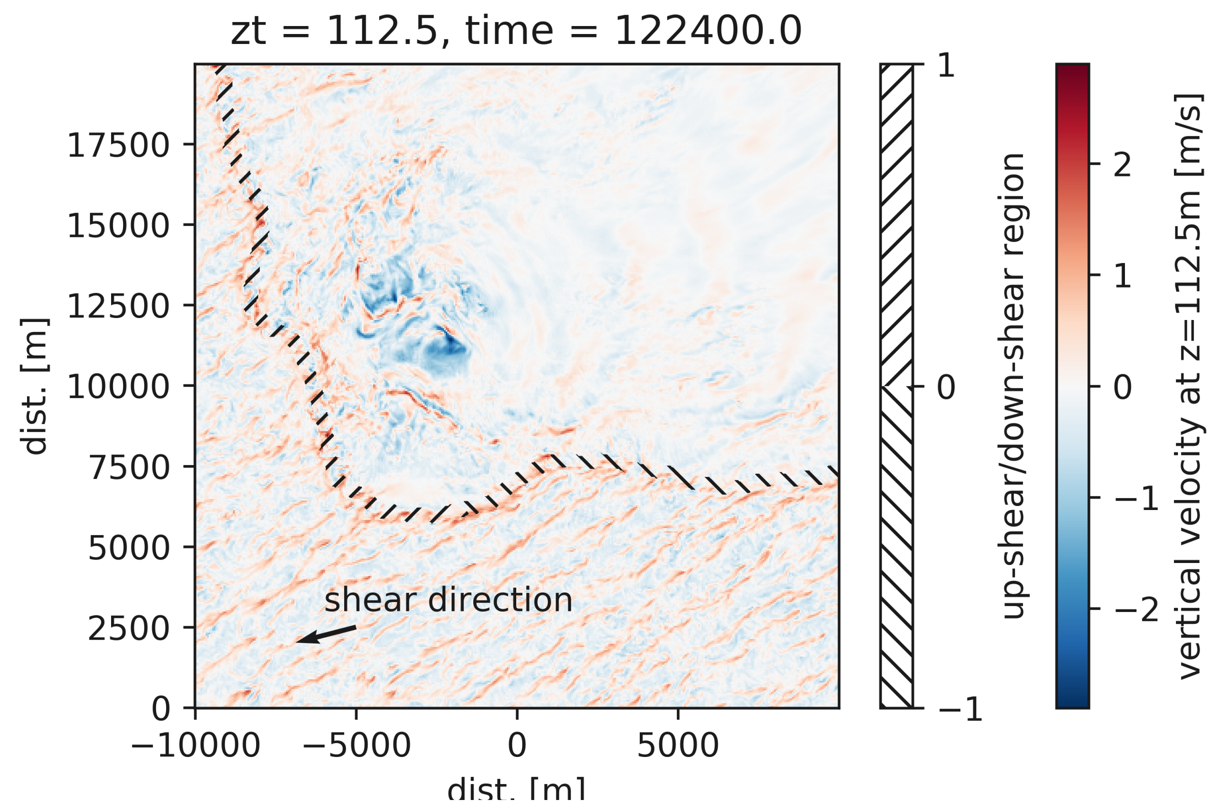
$L \geq W \geq T$ *by construction*

V: volume, A: area, H: mean curvature, κ_1 and κ_2 intrinsic local curvature ($\nabla \cdot \hat{n} = \kappa_1 + \kappa_2$)

Example:
coldpool influence on boundary layer structures



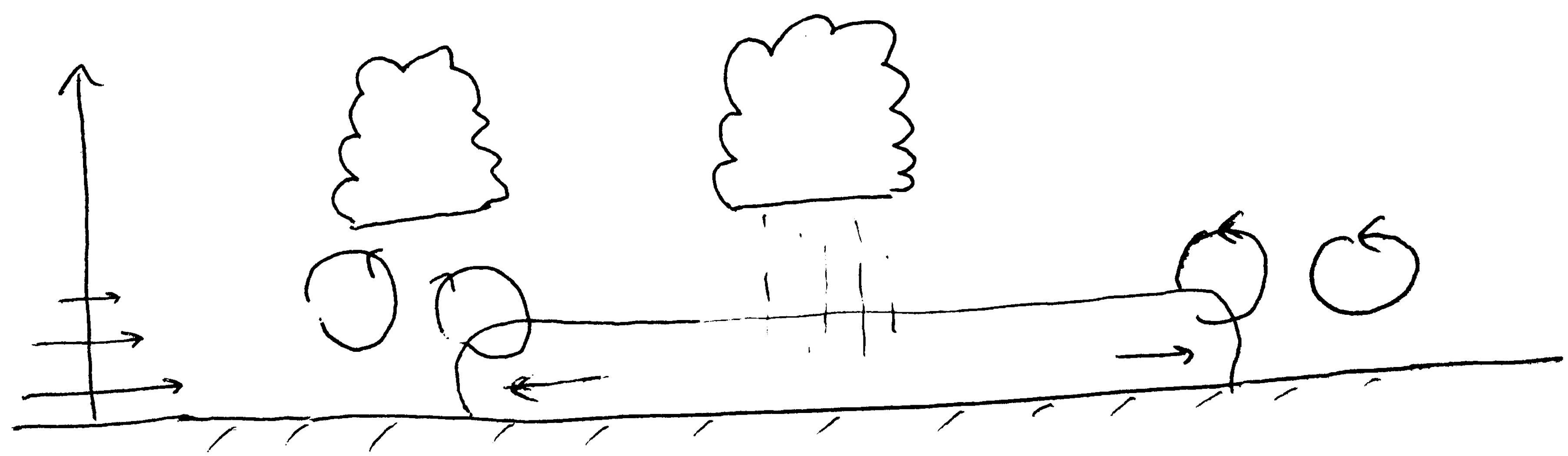
Using density anomaly ($\theta_v' < -0.1K$)
to define coldpool region



Using mean direction of ambient
shear and coldpool edge
orientation to identify up-shear/
down-shear edge

RKW-theory (precipitating clouds)

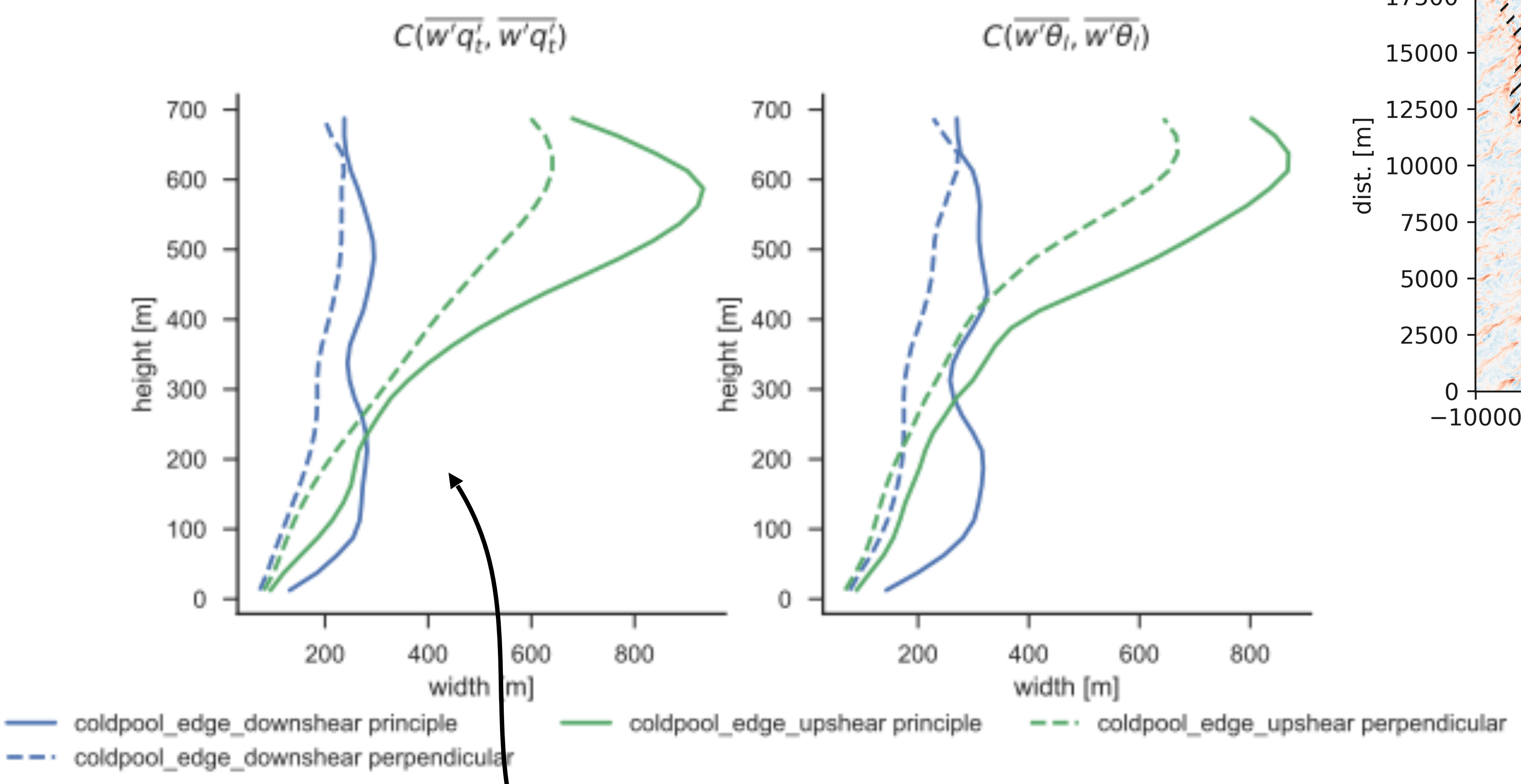
Rotunno, Klemp & Weisman 1980s

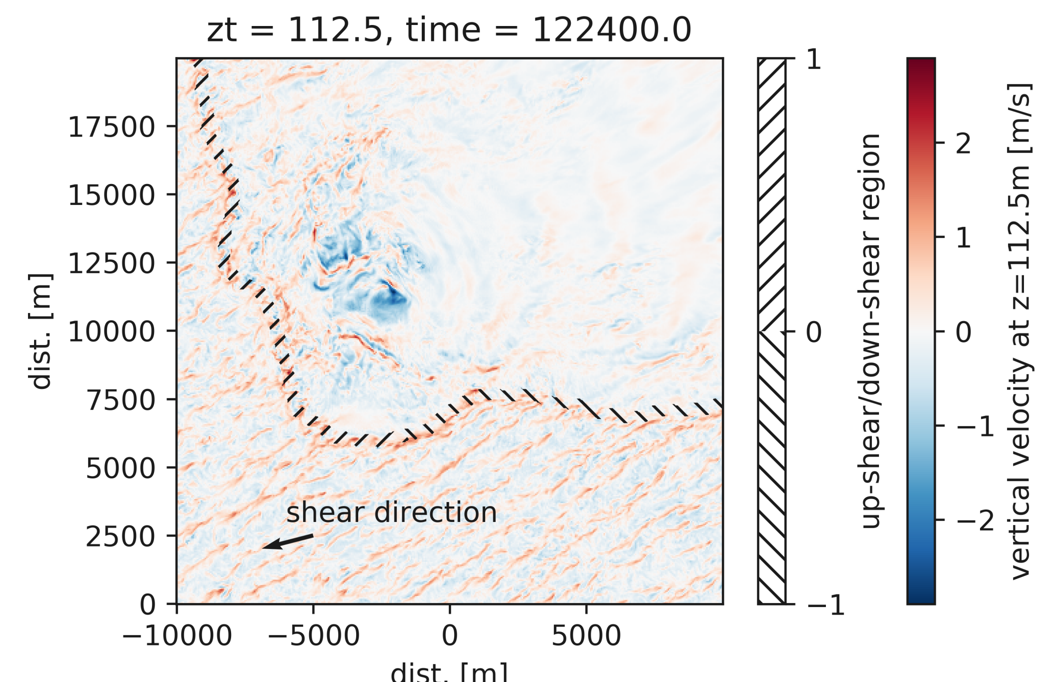


- Evaporation of rain creates density current
- At edge of spreading current (gust front) air is lifted, inducing local vorticity
- When combined with shear of opposite vorticity convection is more strongly forced, can trigger new clouds or self-reinforce existing (super-cells)

Coherence length of BL structures

Upshear and downshear coldpool edge

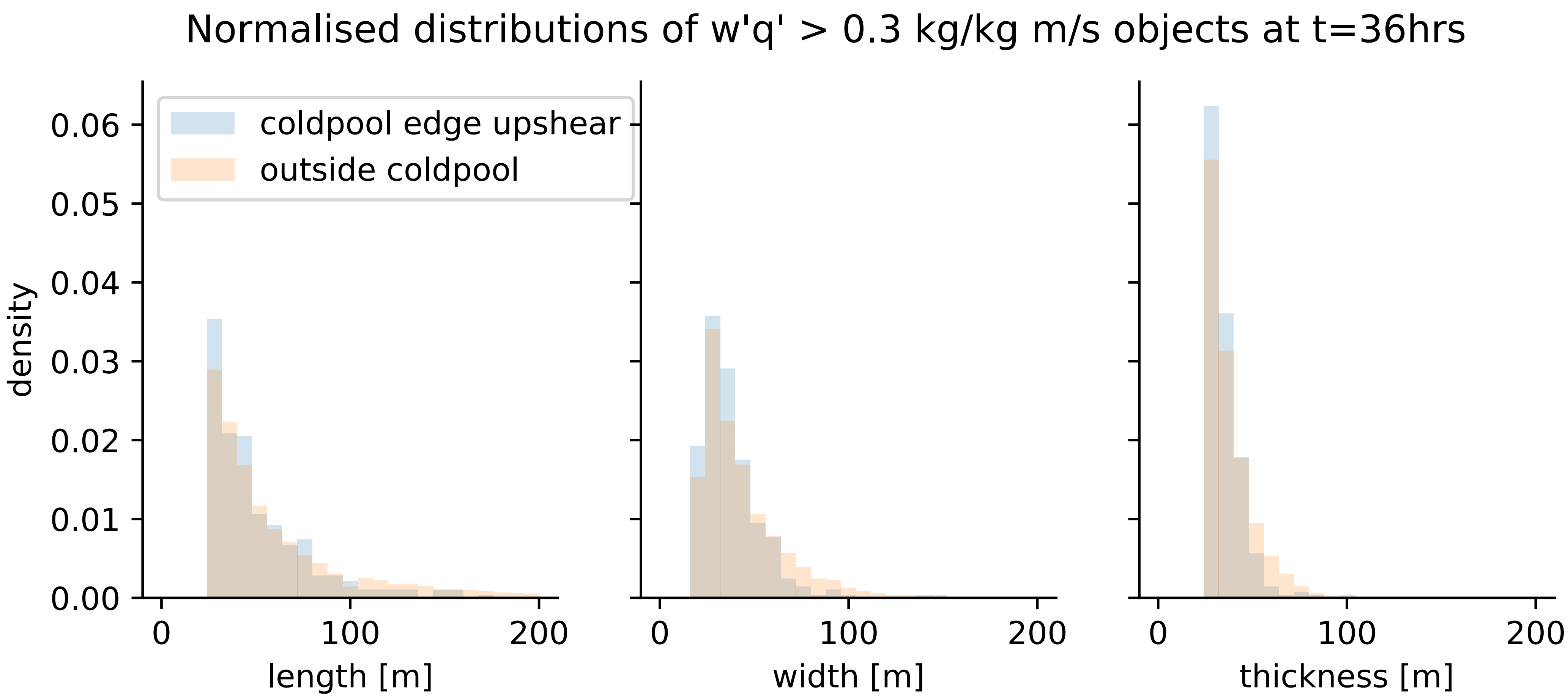




Flux-carrying structures appear
larger on up-shear side

What are the characteristic length-scales of boundary layer structures?

Minkowski functionals of individual objects

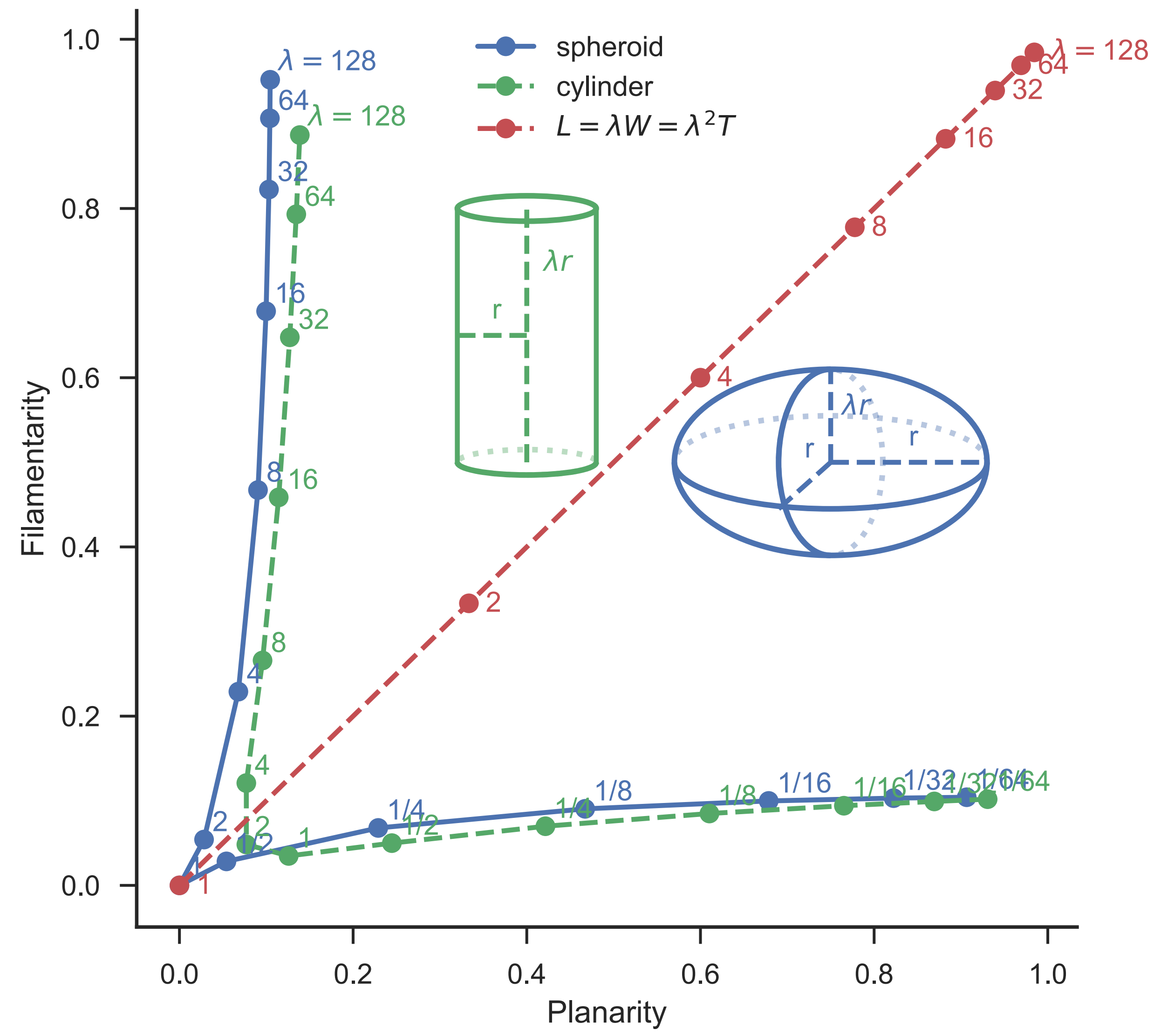


- Objects in up-shear edge are longer, wider and thicker than in bulk of domain

What is shape of objects in the boundary layer?

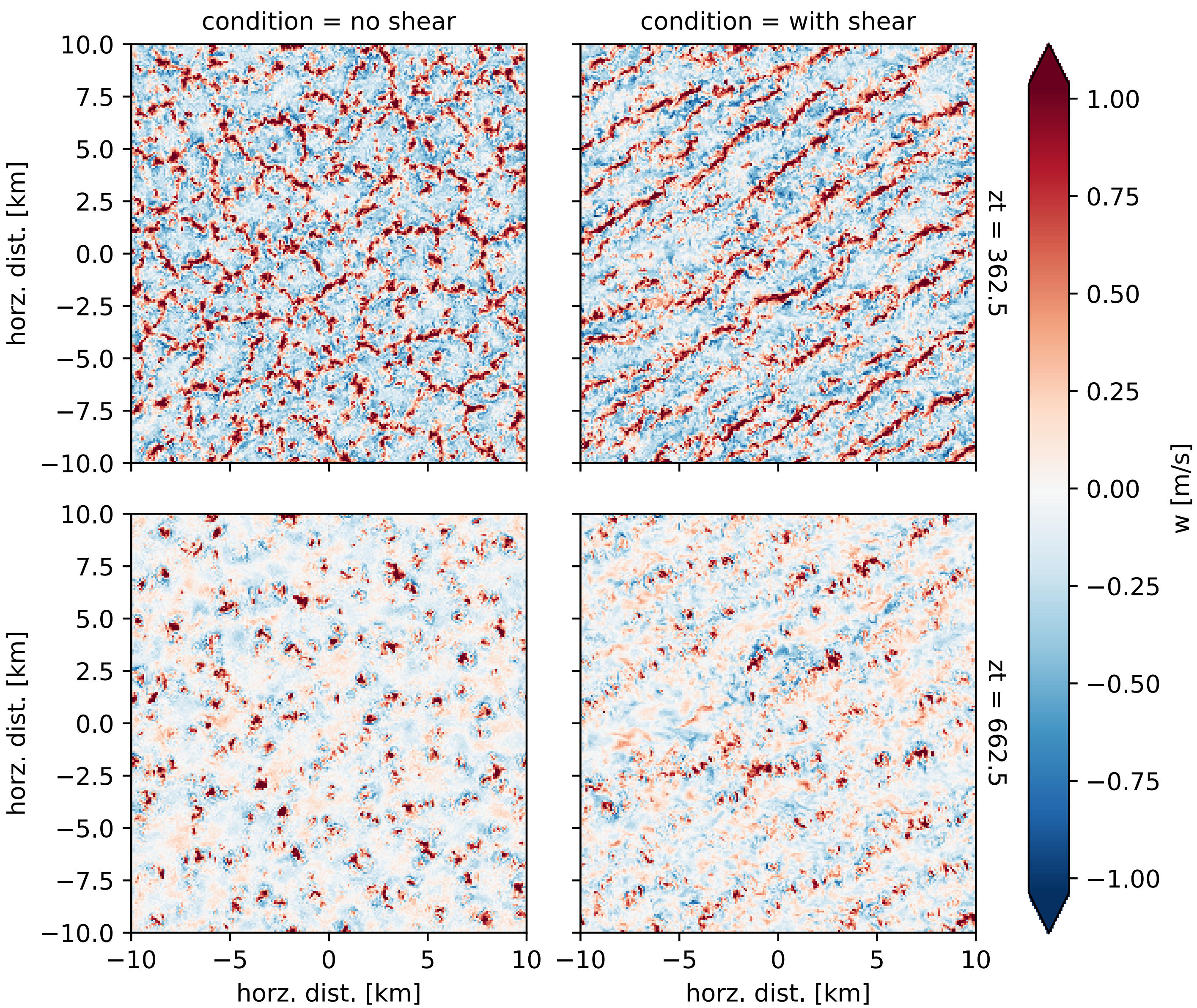
Calculate the planarity (P) and filamentary (F) from Minkowski functional length-scales

$$P = \frac{W - T}{W + T}, F = \frac{L - W}{L + W}$$



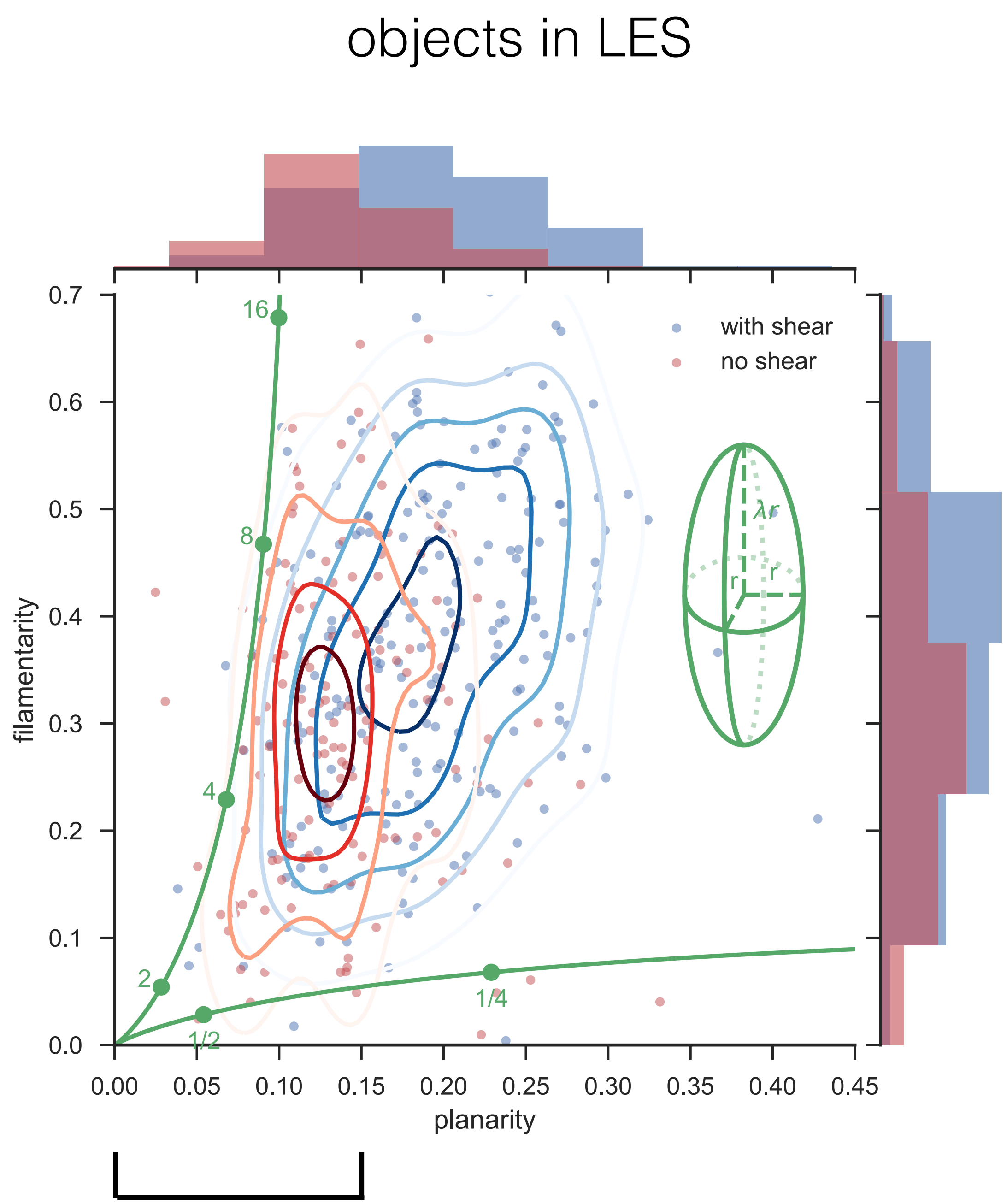
➡ Measures how pencil or disc-like an object is

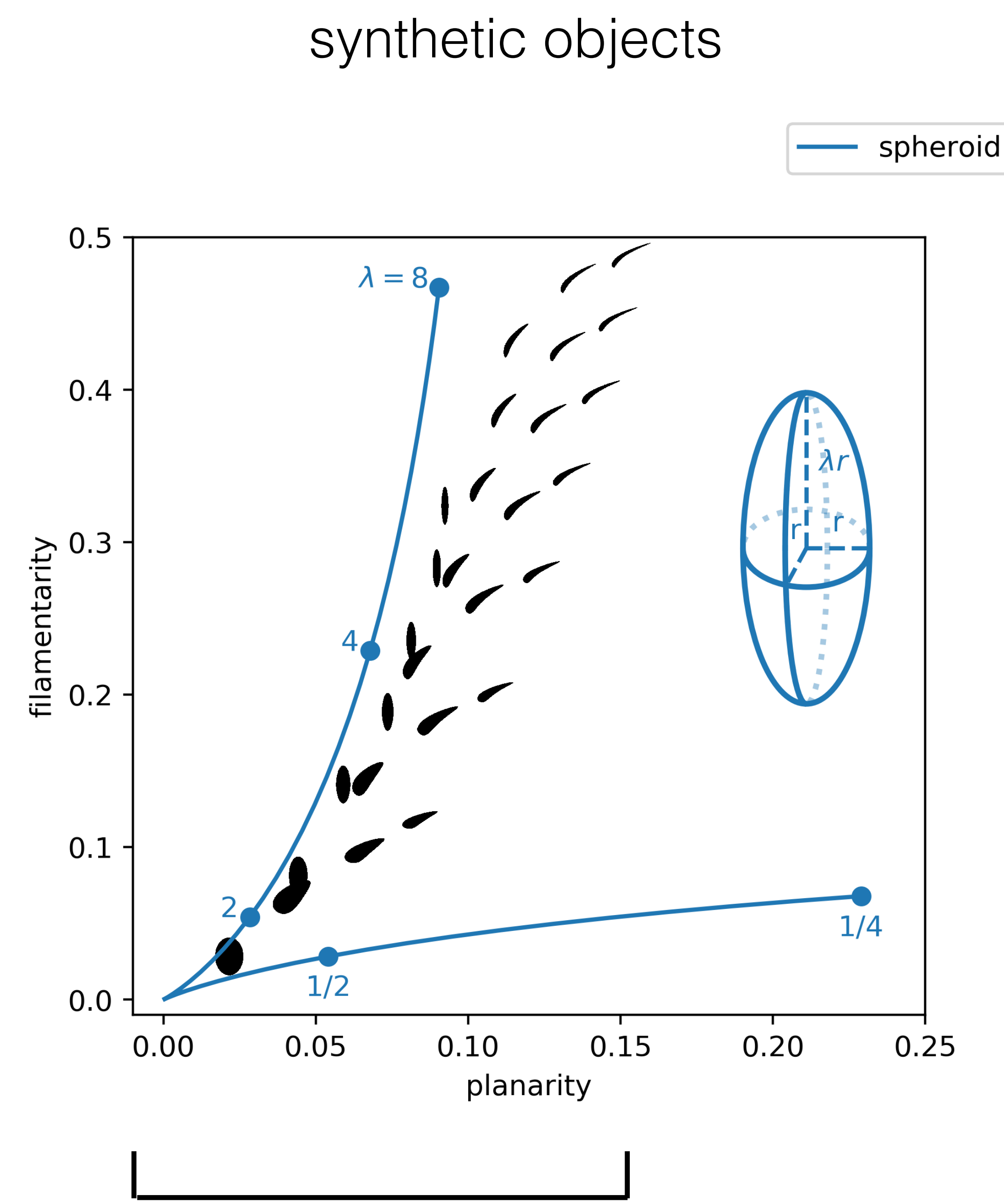
Example:
shear/no-shear RICO-like simulations



- Fixed fluxes (F_S=150W/m^2, F_l=7.0W/m^2)
- Convective cells instead of rolls in boundary layer with shear
- In shear convection appears at ends of rolls?
- Without shear at nodes of cells?

What is shape of objects in the boundary layer?



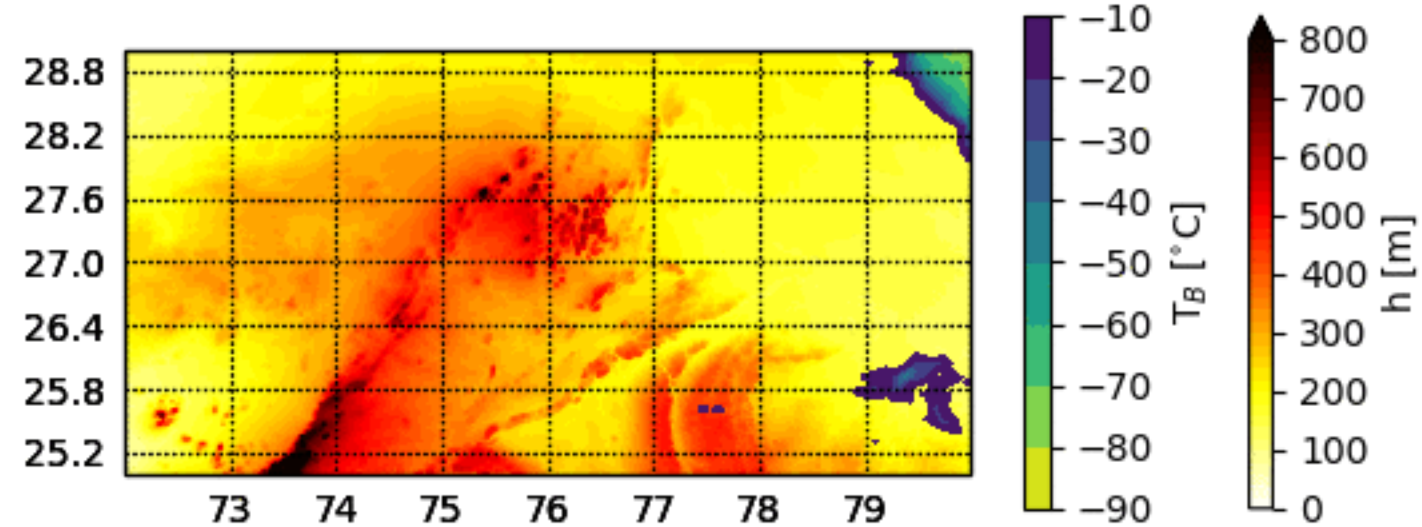


➡ Shear causes structures to become longer and wider by ~30% and ~50% respectively

Identifying large-scale forcing:
Topography test-case over India

- Based off 30th June 2016 INCOMPASS flight B968 near Lucknow, India

- Convection develops from midday over shallow (~300m) topography

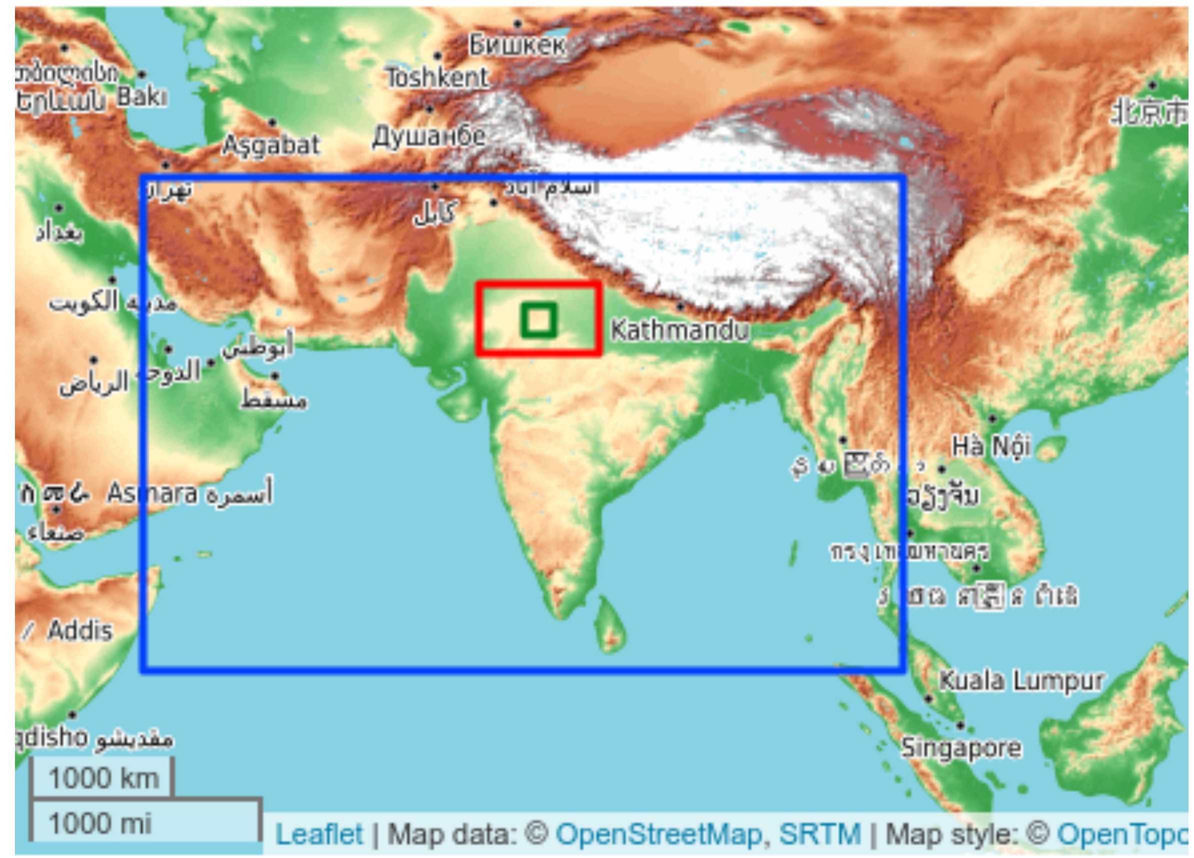


04:30 - 05:00 UTC

EUMETSAT brightness temperature, Emma Barton (CEH)

Case setup

- Using MetOffice Unified Model because MONC/UCLALES can't represent topography
- Setup developed by Chris Dearden (CEMAC Leeds), currently have running:
    - Four-level nest with n320 global and dx=200m inner most nest
- Still to resolve:
    - Soil-moisture initiation, stochastic sampling, feasible domain size

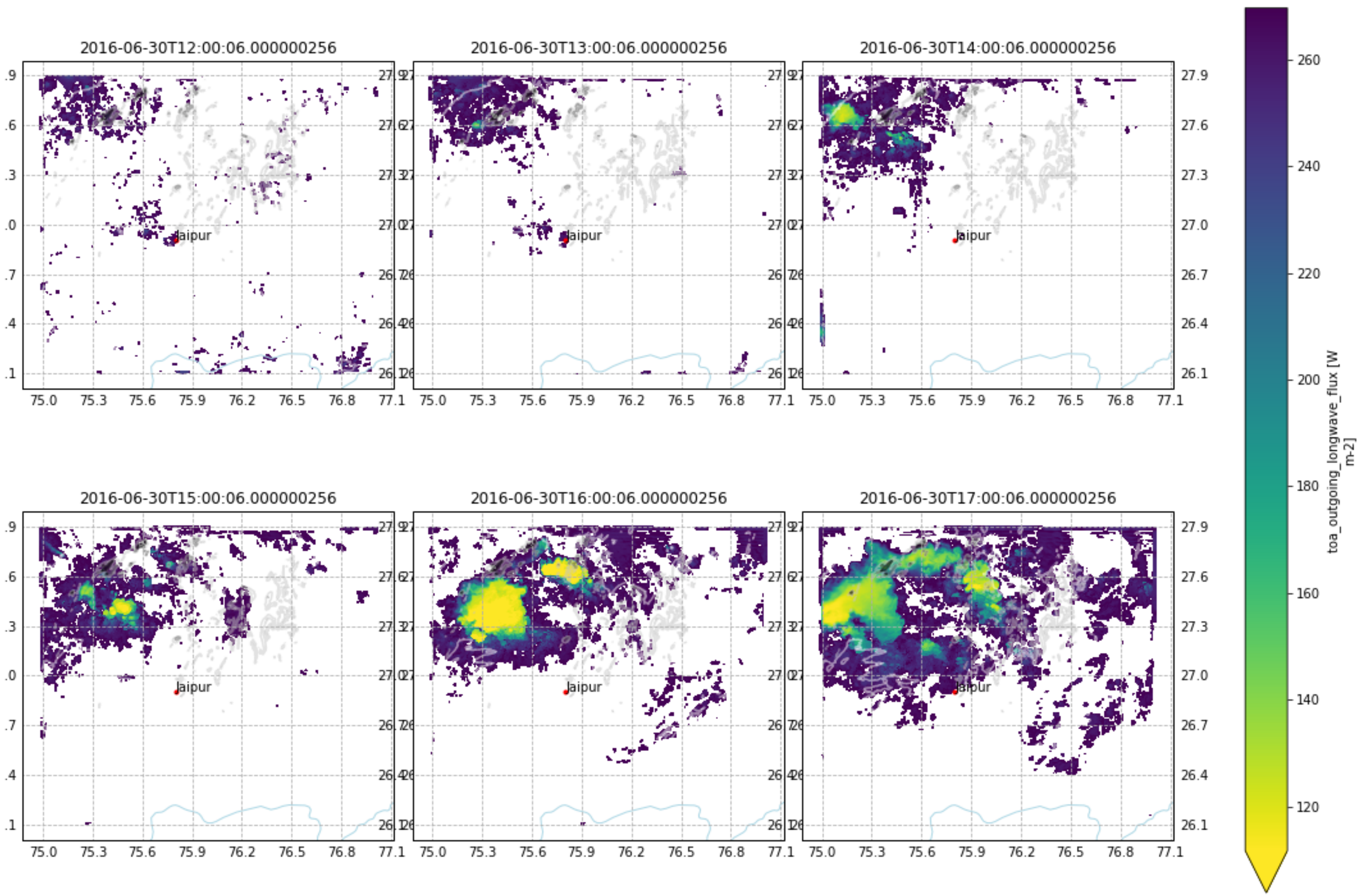


Working on adding radiative tracer release to UM.

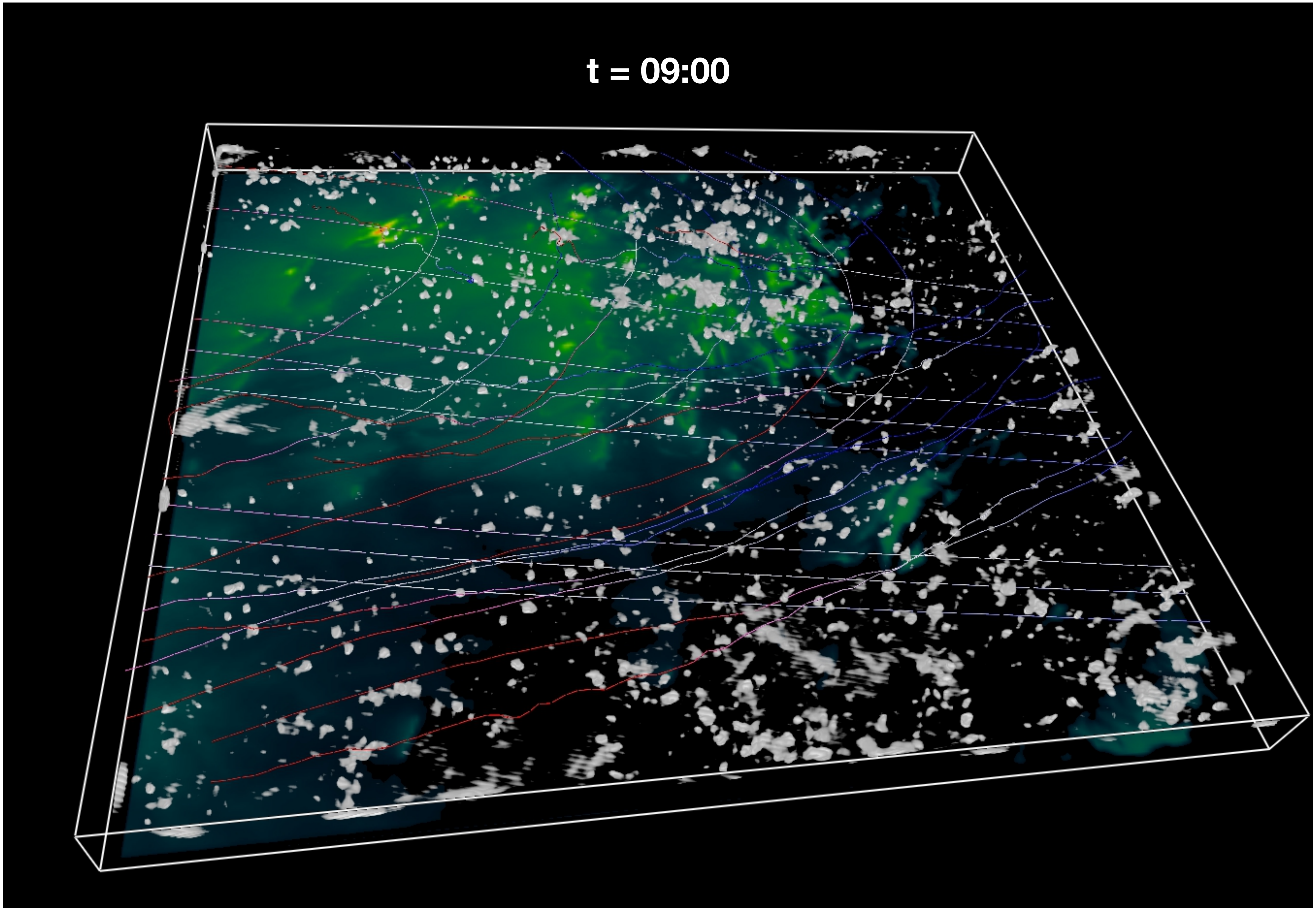
Any MO people around Thursday? 🙂

Does convection develop?

Yes!



What does the flow look like?



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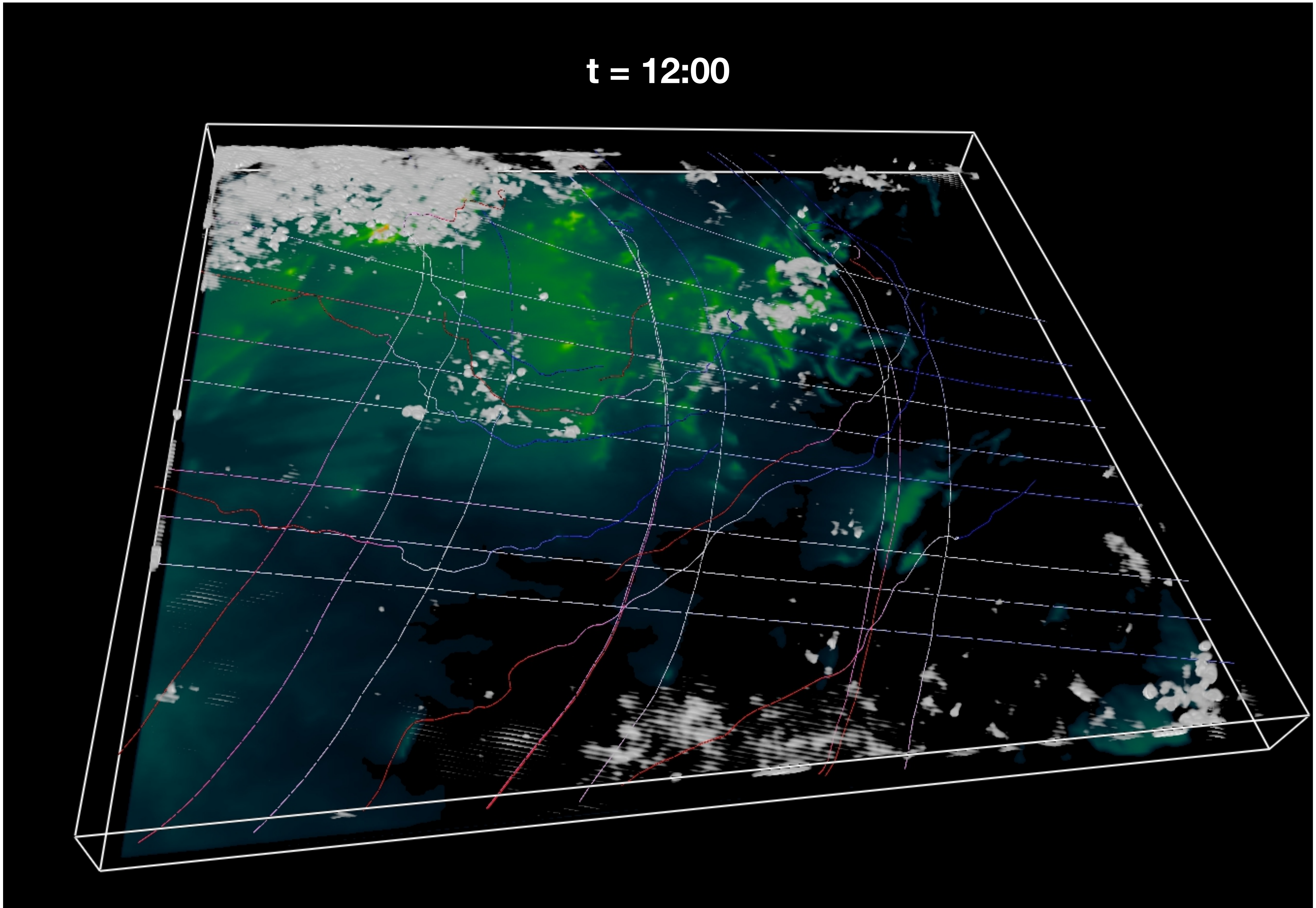

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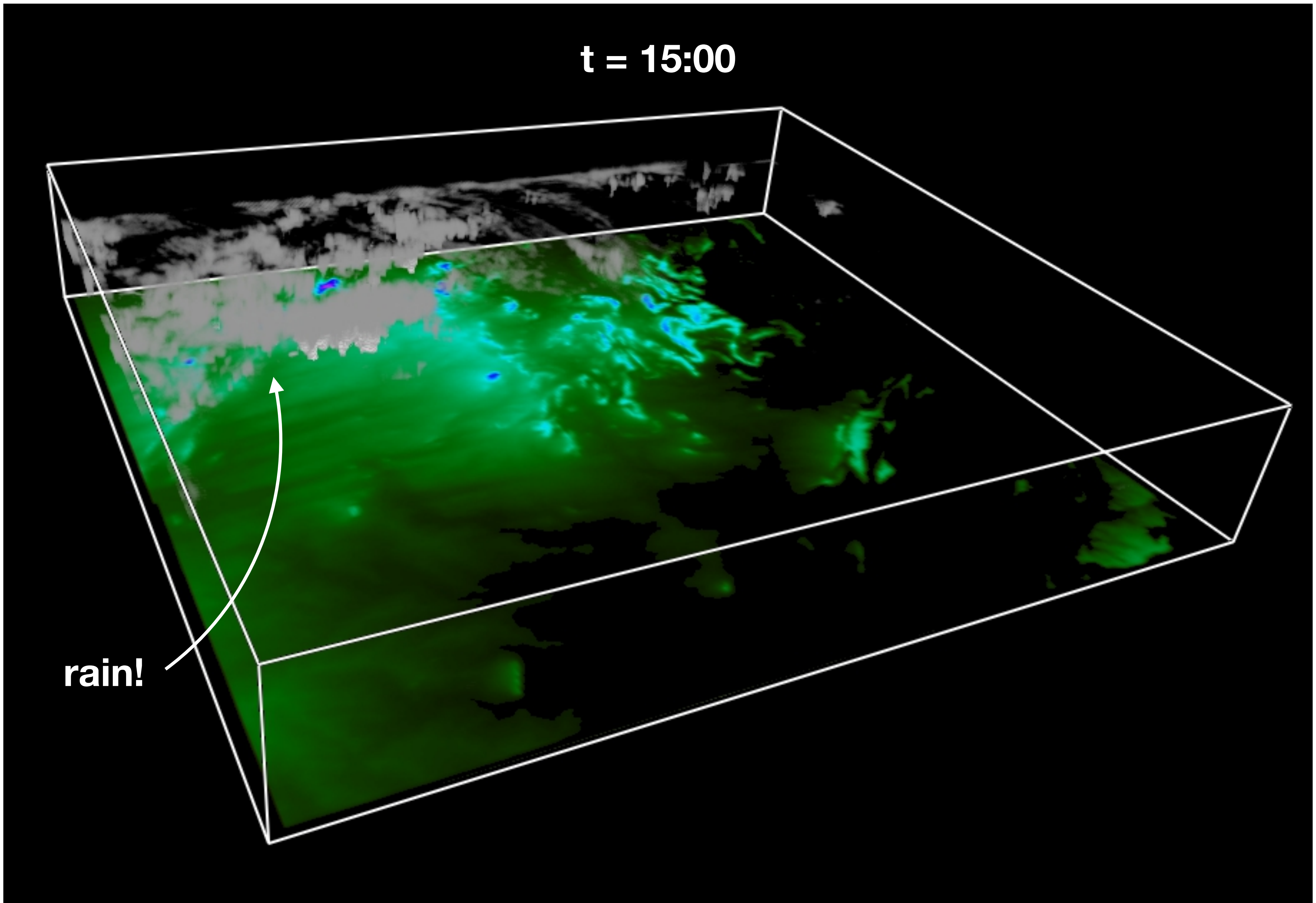

Next steps

Papers being written

1. Demonstration of cumulants and Minkowski functionals as means to quantify bulk and object-based properties of atmospheric fluids with coherent structures

2. Investigation of the effect of changing Bowen-ratio on properties coherent structures in the boundary layer

Ongoing work:

I. Developing topography test-case to do parameter study (bulk surface moisture flux and topography height)

II. Setting up/finding cases with deeper convection and diurnal cycle

III. Developing predictive model for properties of boundary-layer coherent structures

Thank you!

Questions?