UNIVERSITY OF LEEDS

The “invisible touch” that leads to cloud formation

Leif Denby

21/10/2019, ICAS internal seminar

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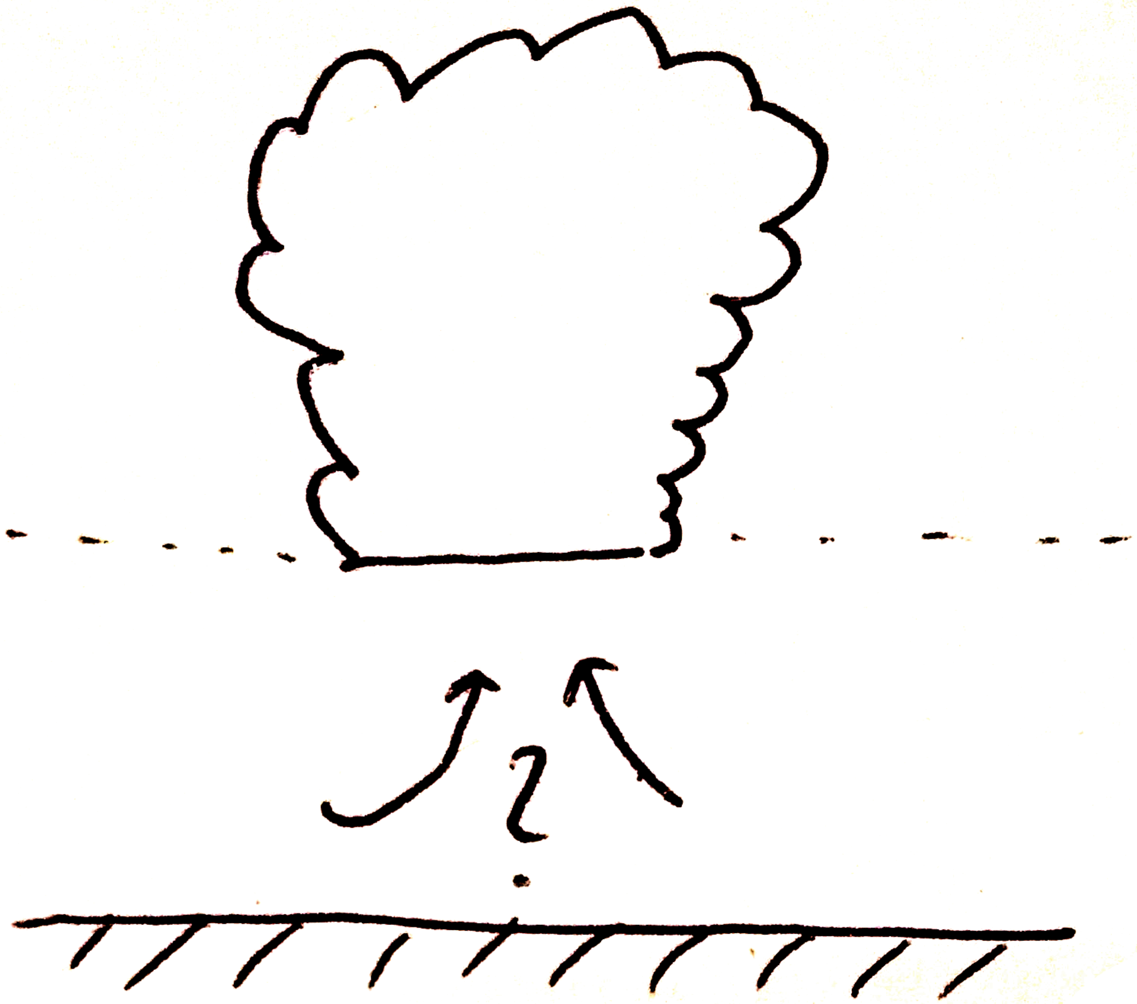
21/10/2019, ICAS internal seminar

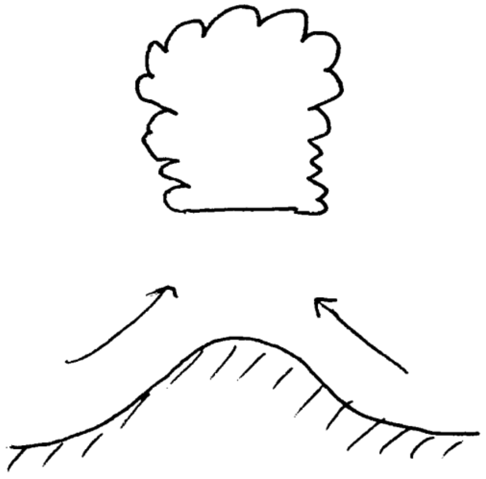
In the mountains of northern Mallorca

Aim

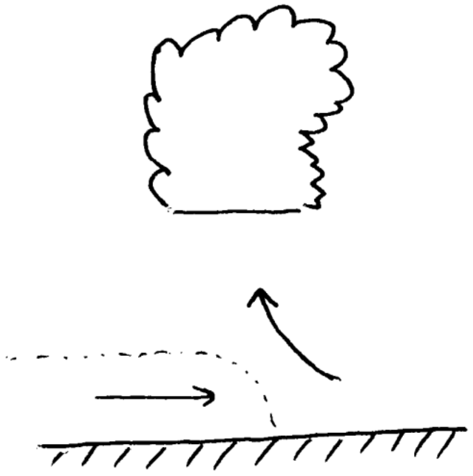


Aim

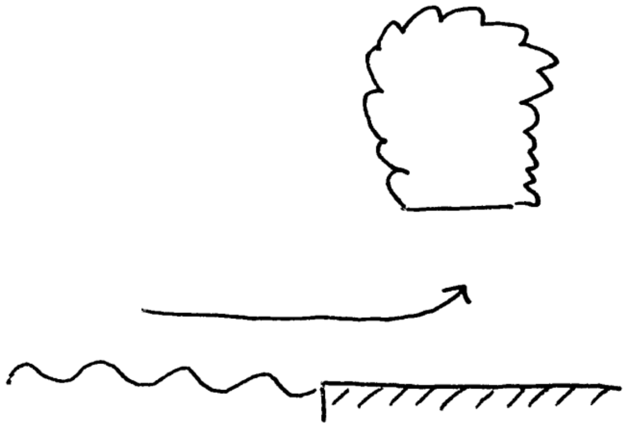
- Describe statistics of boundary layer relevant to triggering convection and the sensitivity to presence of different phenomena



topography



coldpools

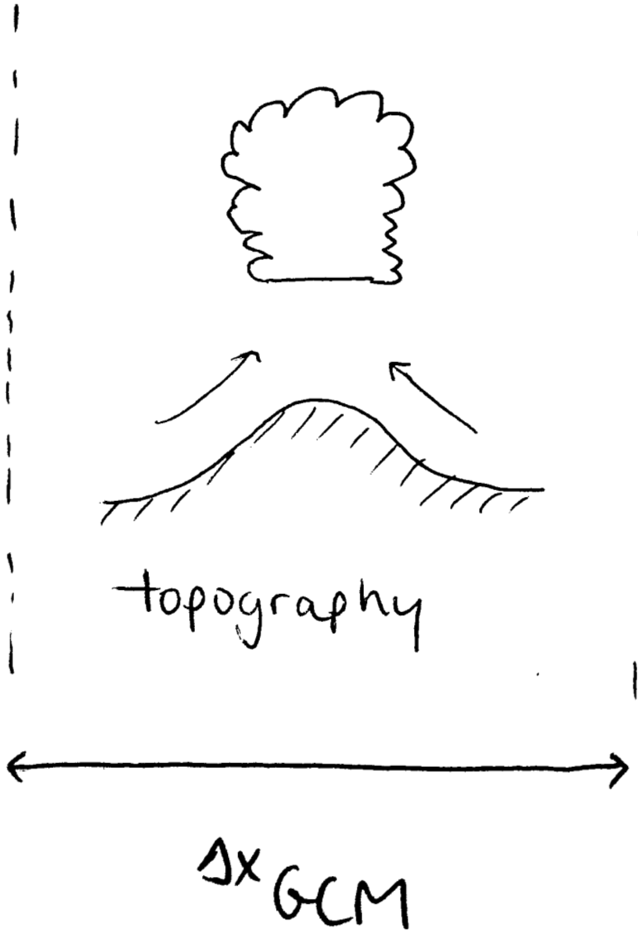


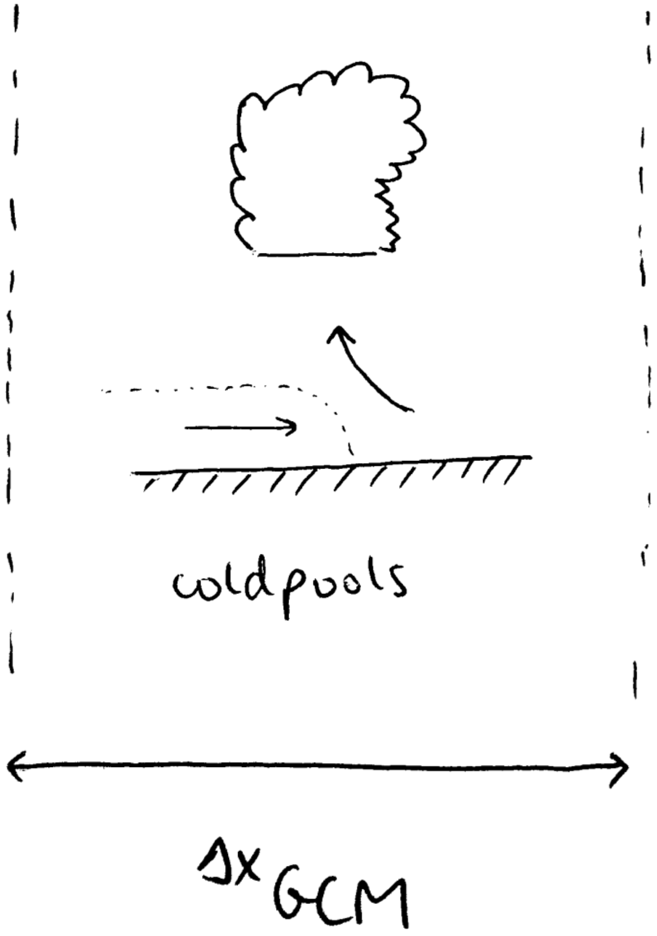
land-sea breeze
(surface heterogeneity)

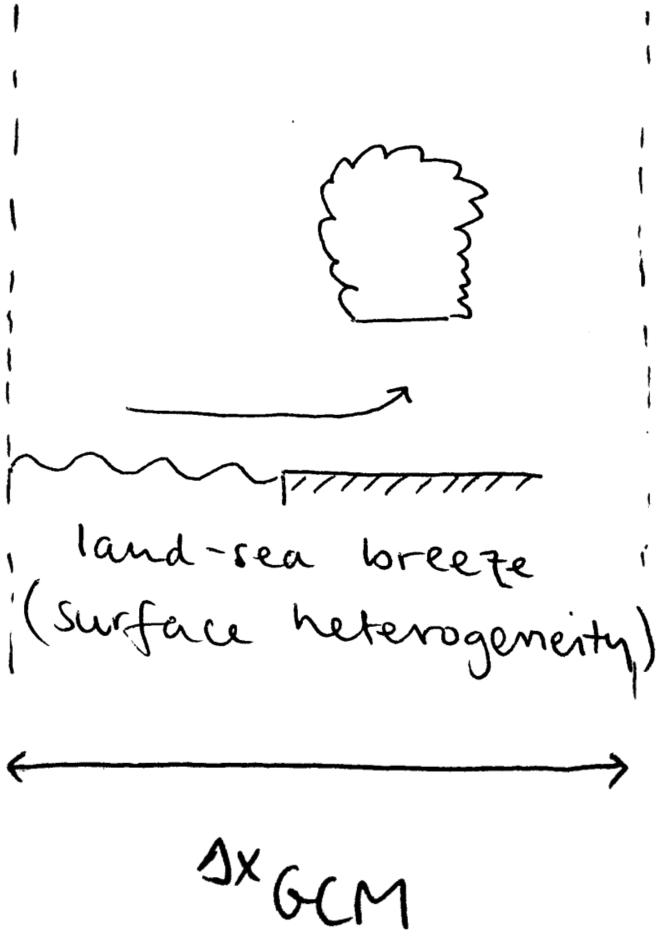
- *"What are the length-scales and magnitudes of perturbations which trigger convection?"*

Why?

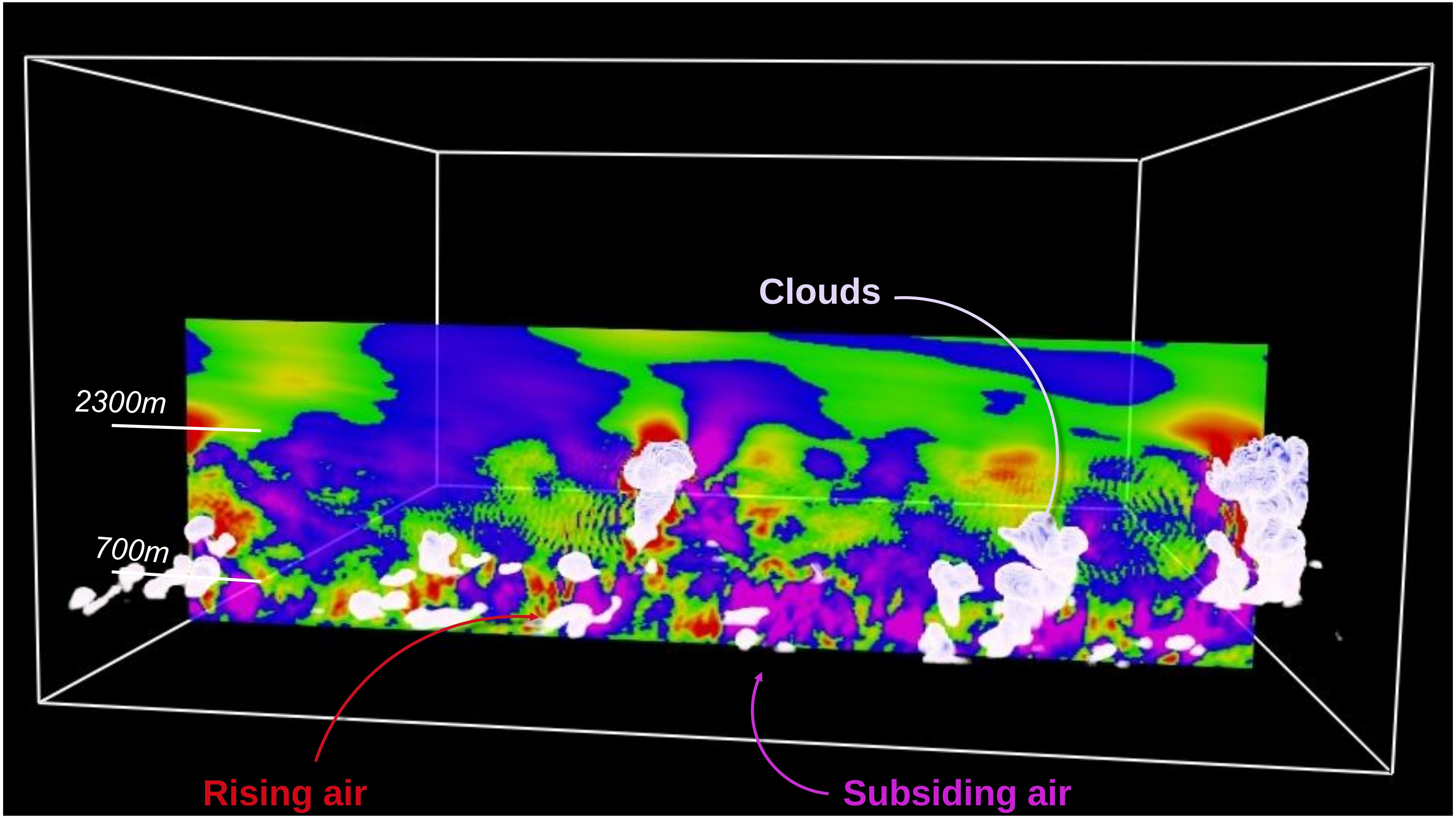
- GCMs have too coarse resolution to fully represent convection (O(km))
  - Trigger (and evolution) of convection must be parameterised
  - These *sub-grid* features are known to be critical in predicting formation of convection







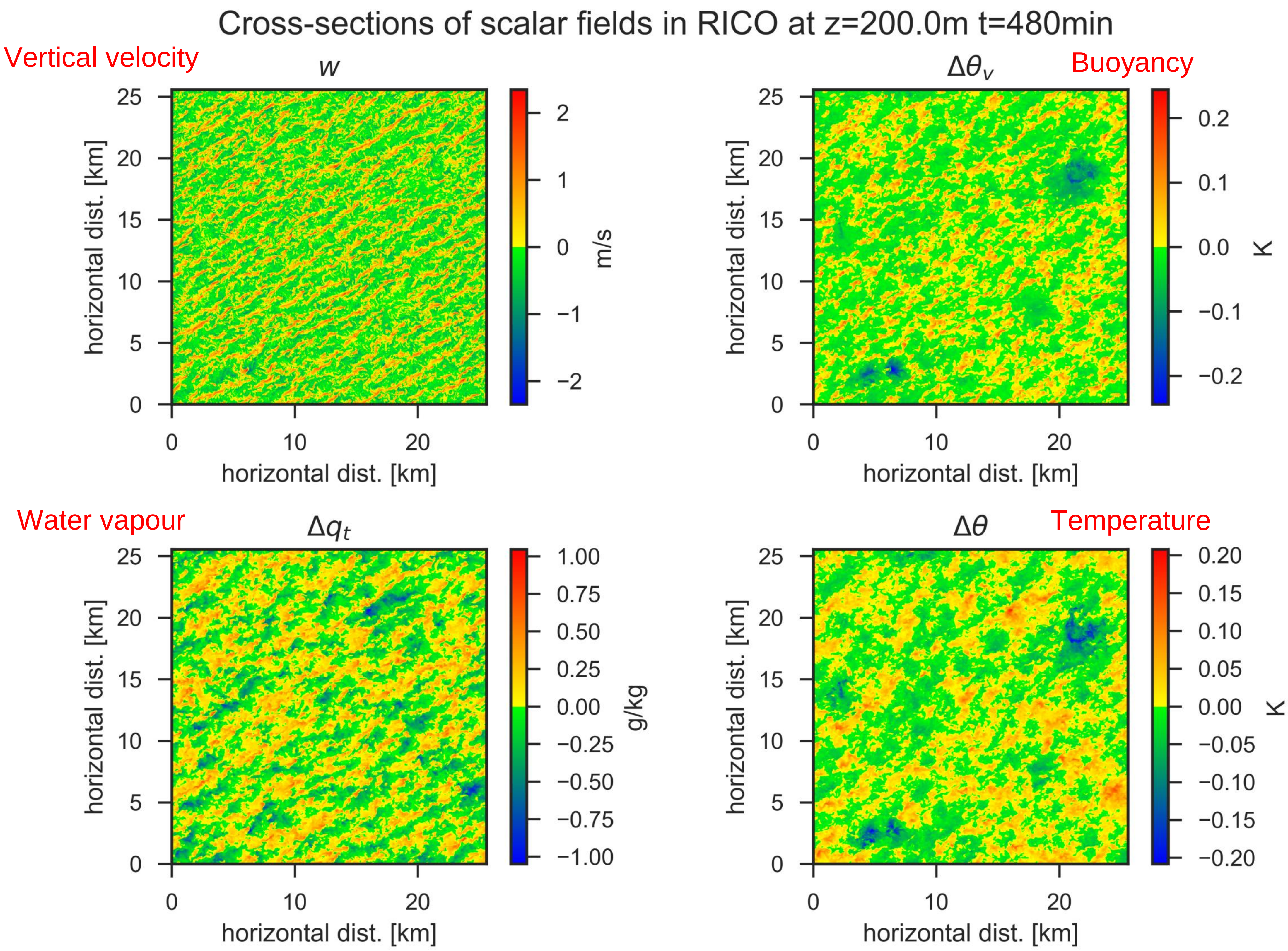
What are the length-scales of variability?



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

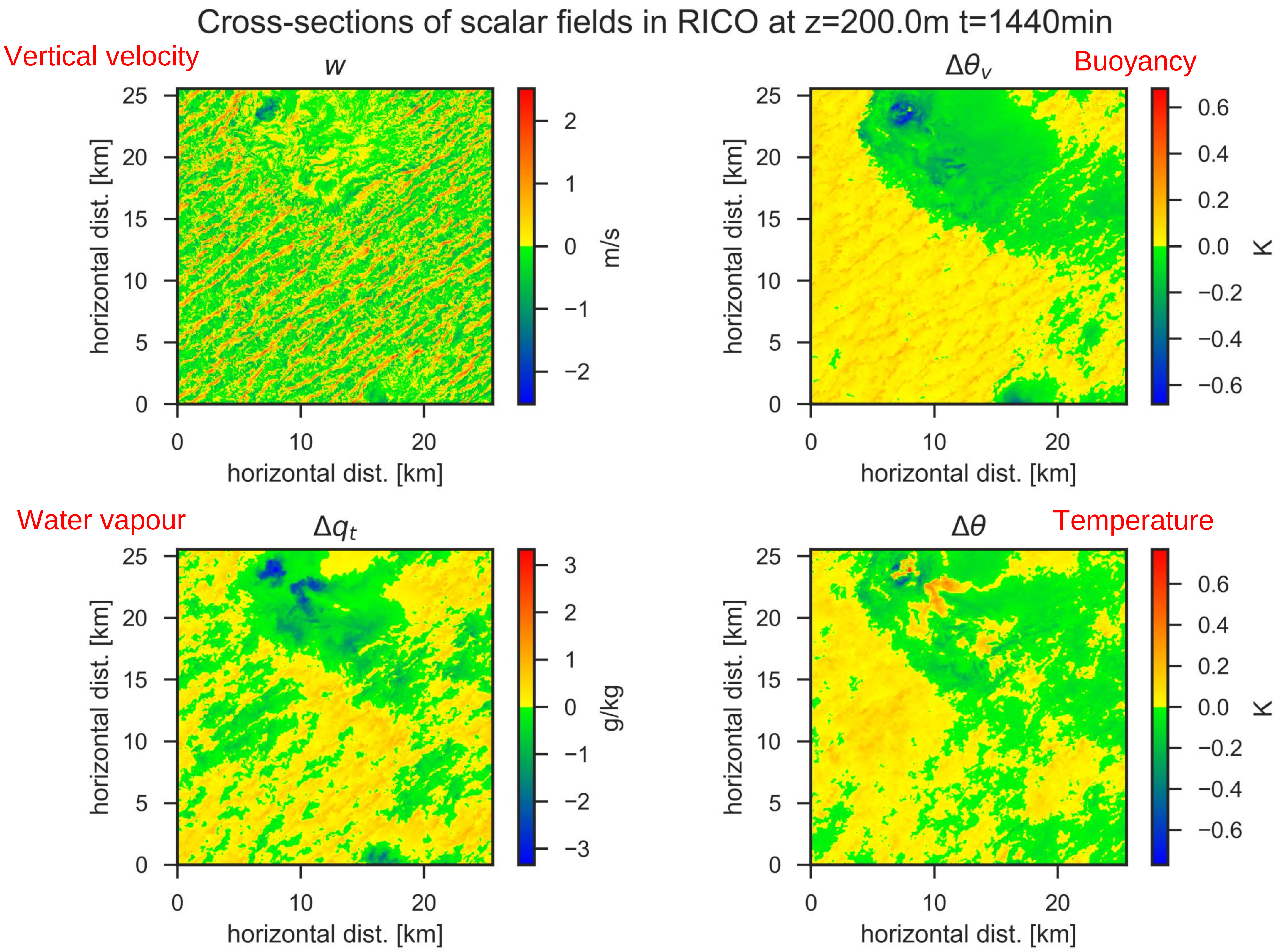
Rendered with VAPOR

What are the length-scales of variability?



Cross-sections of scalar fields in RICO at z=200.0m t=480min

What are the length-scales of variability?



Cross-sections of scalar fields in RICO at z=200.0m t=1440min

Vertical velocity

Buoyancy

Water vapour

Temperature

Key questions

1. What defines a cloud-forcing coherent structure?
2. What are the properties of these structures?

Steps to answering:

1. Quantify the different characteristic scales of physical fields. Can one of them define a coherent structure?
2. Come up with **method to define structures**
3. Quantify characteristic **properties** of **coherent structures**

Key questions

1. What defines a cloud-forcing coherent structure?

2. What are the properties of these structures?

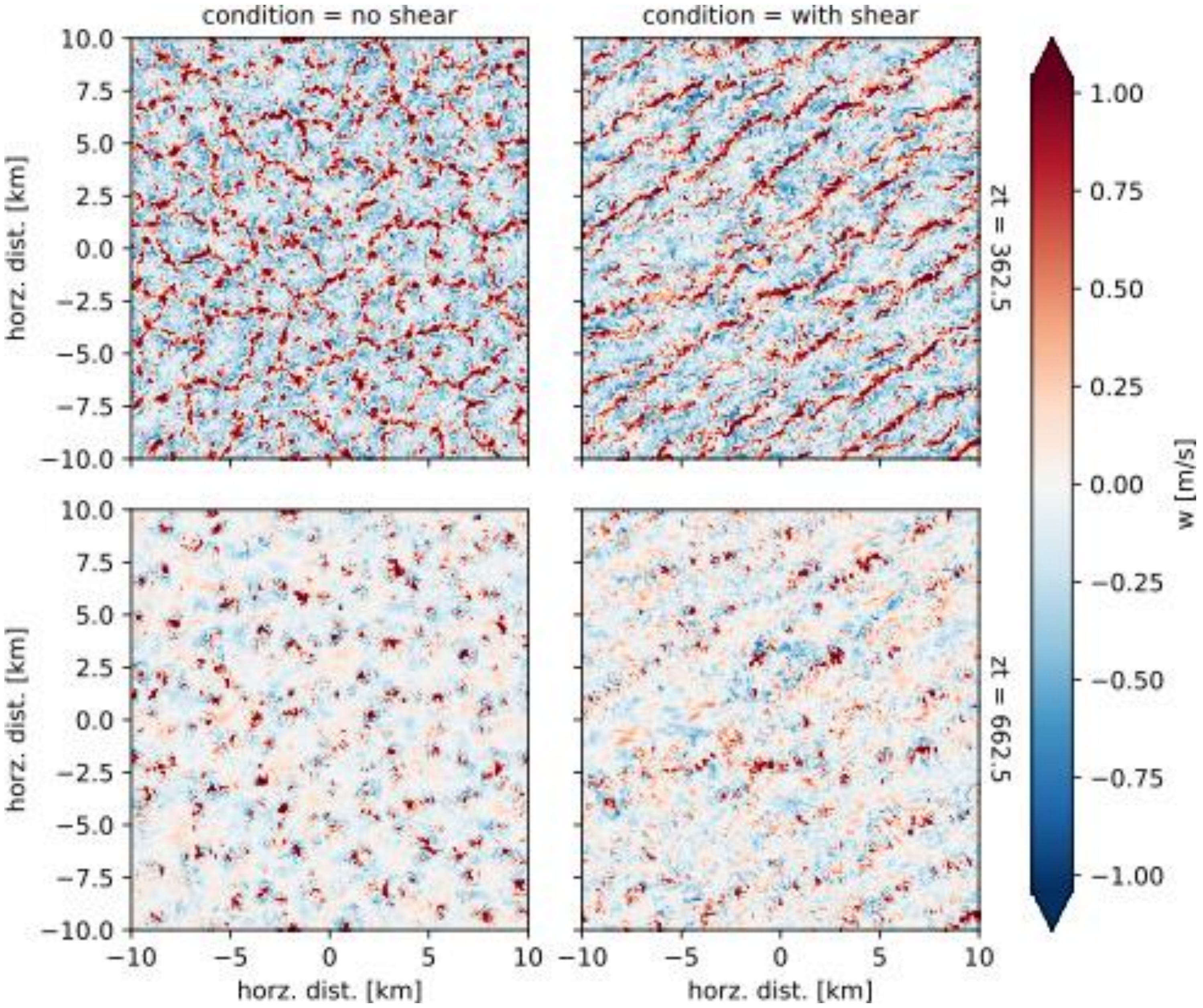
Steps to answering:

1. Quantify the different characteristic scales of physical fields. Can one of them define a coherent structure?
   (spoiler: no)

2. Come up with **method to define structures**
   (spoiler: surface released passive tracer works well)

3. Quantify characteristic **properties** of **coherent structures**
   (spoiler: they are long and thin, shear makes them thinner)

Simulations used:
shear/no-shear RICO-like setup



- 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

1) Bulk characteristics of the boundary layer

example: characteristic length-scales

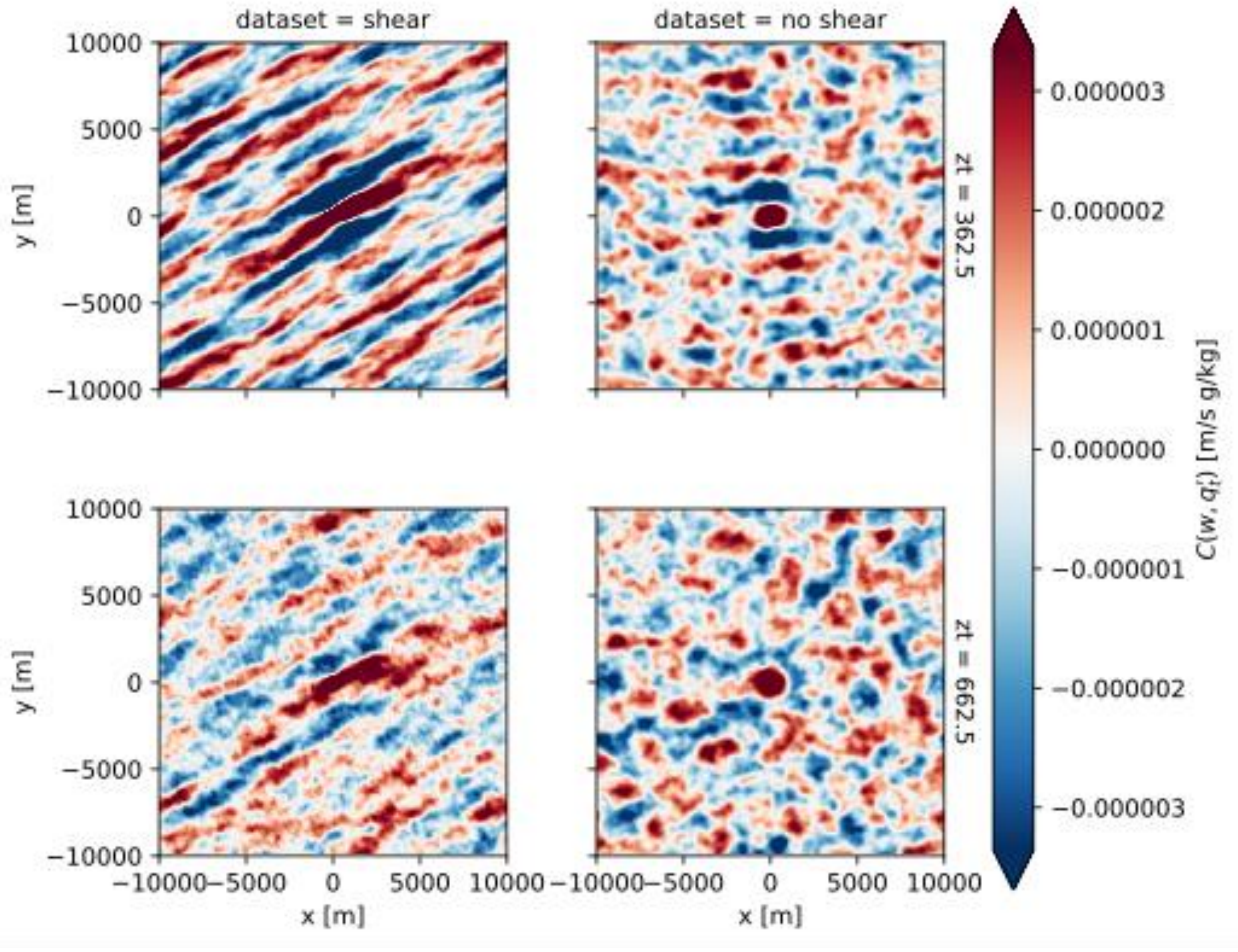
1.b. Characteristic length-scales of boundary-layer structures

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

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

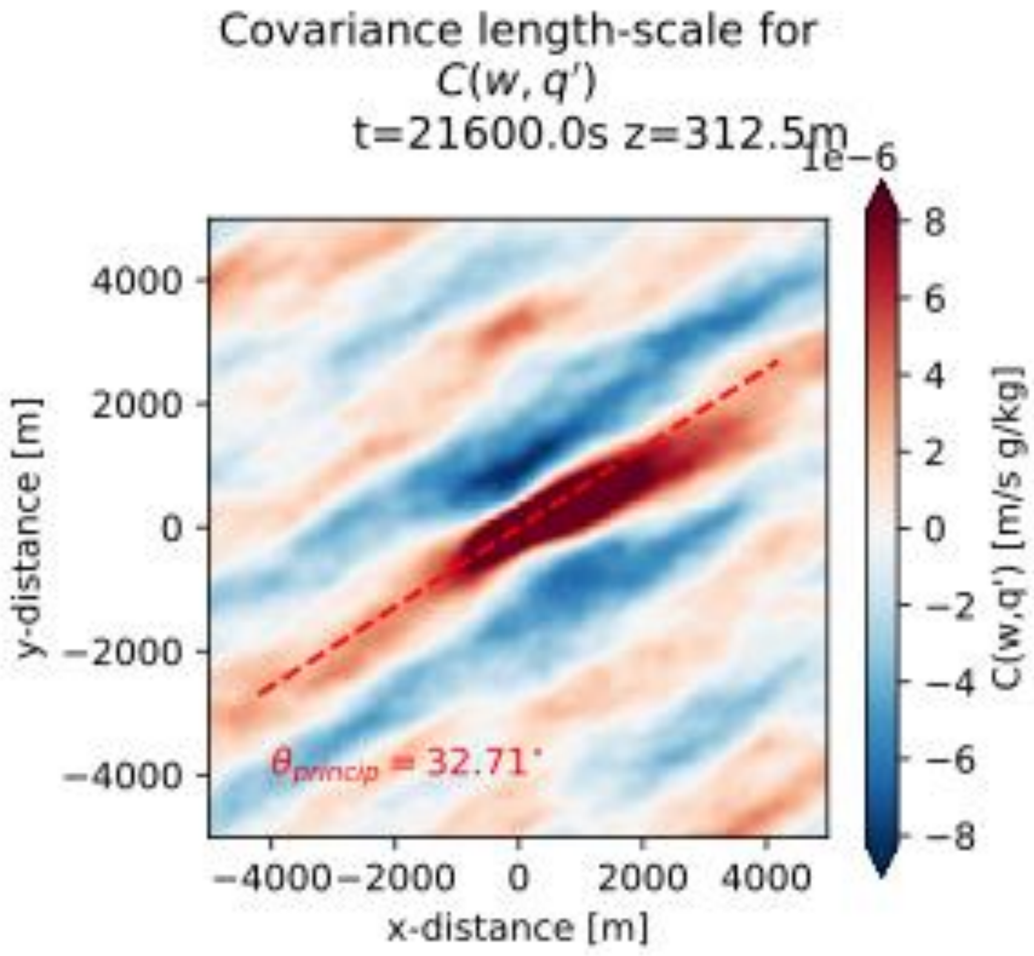
- Measures how correlation with distance (in xy-plane) of scalar fields
- Used by Tobias and Marston 2016 to identify principle length-scales diffusive transport in 3D Couette flow

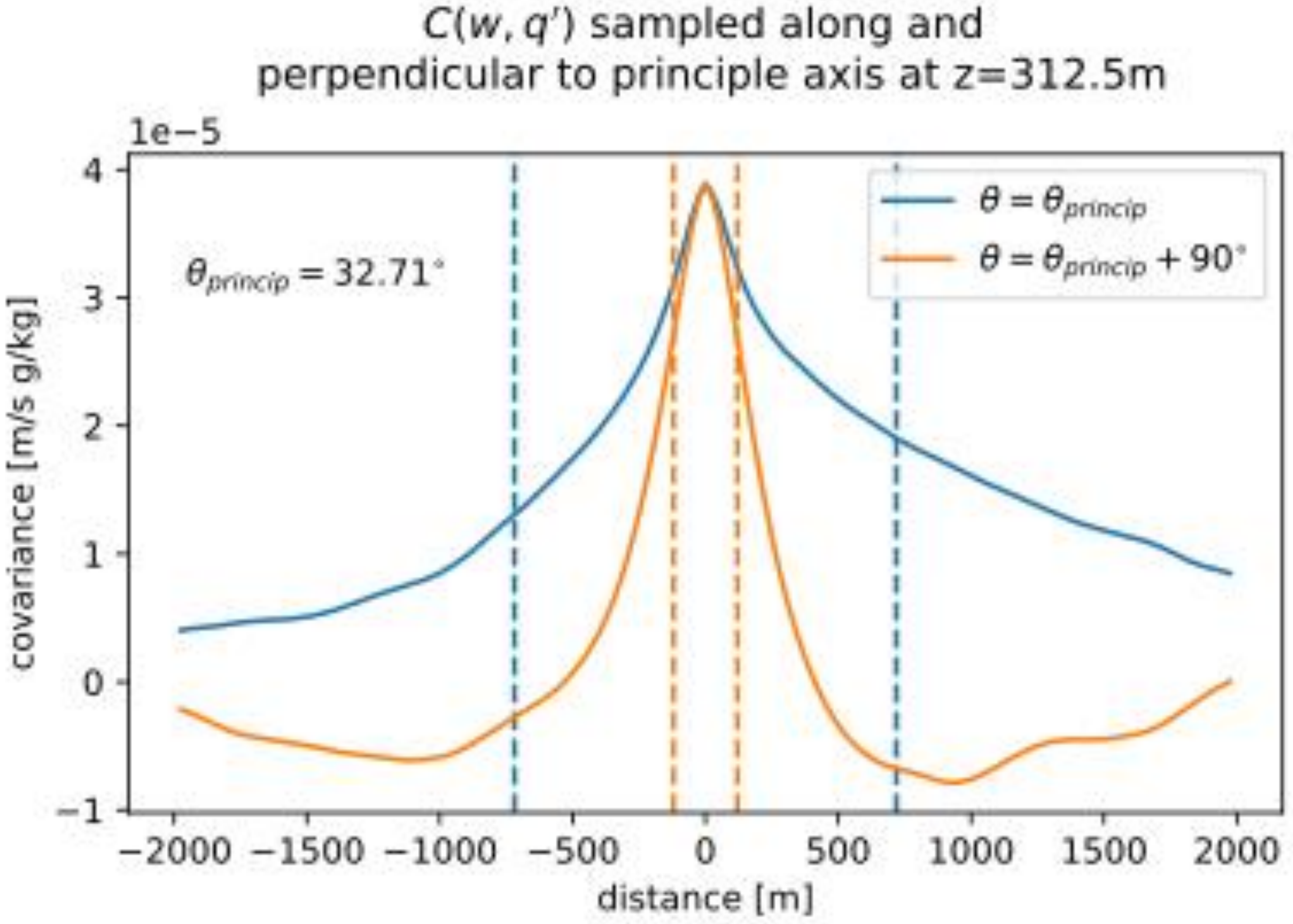
Use of cumulants to study characteristic scales



- With shear coherence is increased in direction of shear
  - Coherence stronger in mid boundary-layer than at cloud-base
- Non-sheared case *does* show coherence length-scale, characteristic scale of convective cells?
  - Similar scale to cross-shear coherence length-scale?

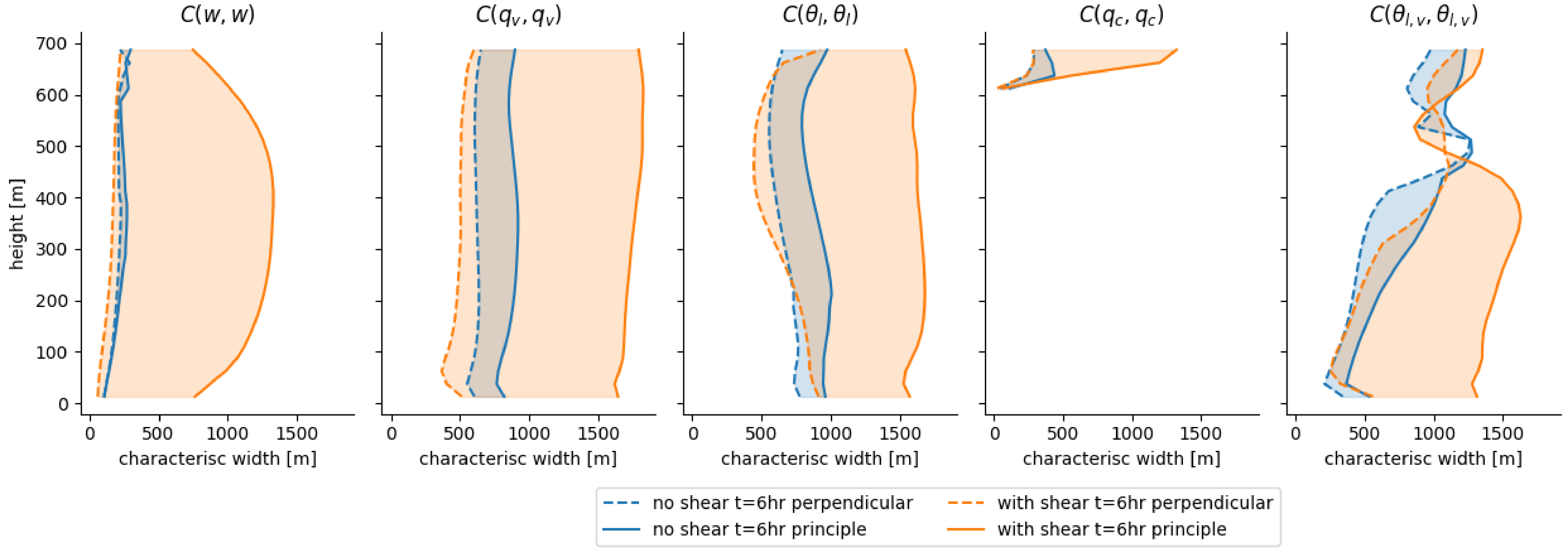
Use of cumulants to study characteristic scales





- Direction of strongest coherence from principle axis of moment of inertia tensor
- Coherence length-scale calculated as moment of covariance

Characteristic horizontal scales of different fields



- Wind-shear causes clear elongation of coherence in all fields
- Different scales clearly seen, vertical velocity narrowest, followed by water vapour and temperature. Buoyancy scale becomes meaningless at z~500m (structures becomes negatively buoyant)

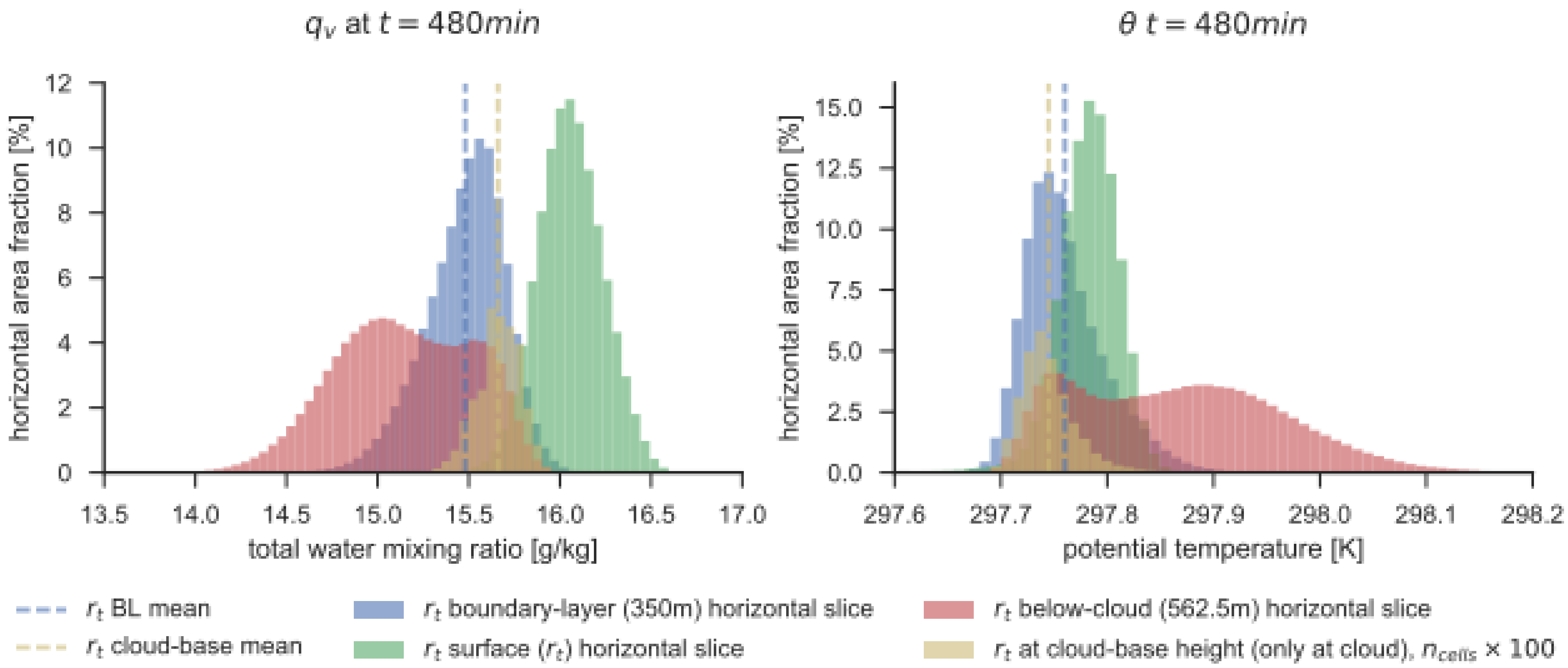
BUT:

- Only considering boundary layer in bulk here, what about individual structures? How do we defines these?

2) Decomposing joint distributions in the boundary layer

Identifying coherent structures

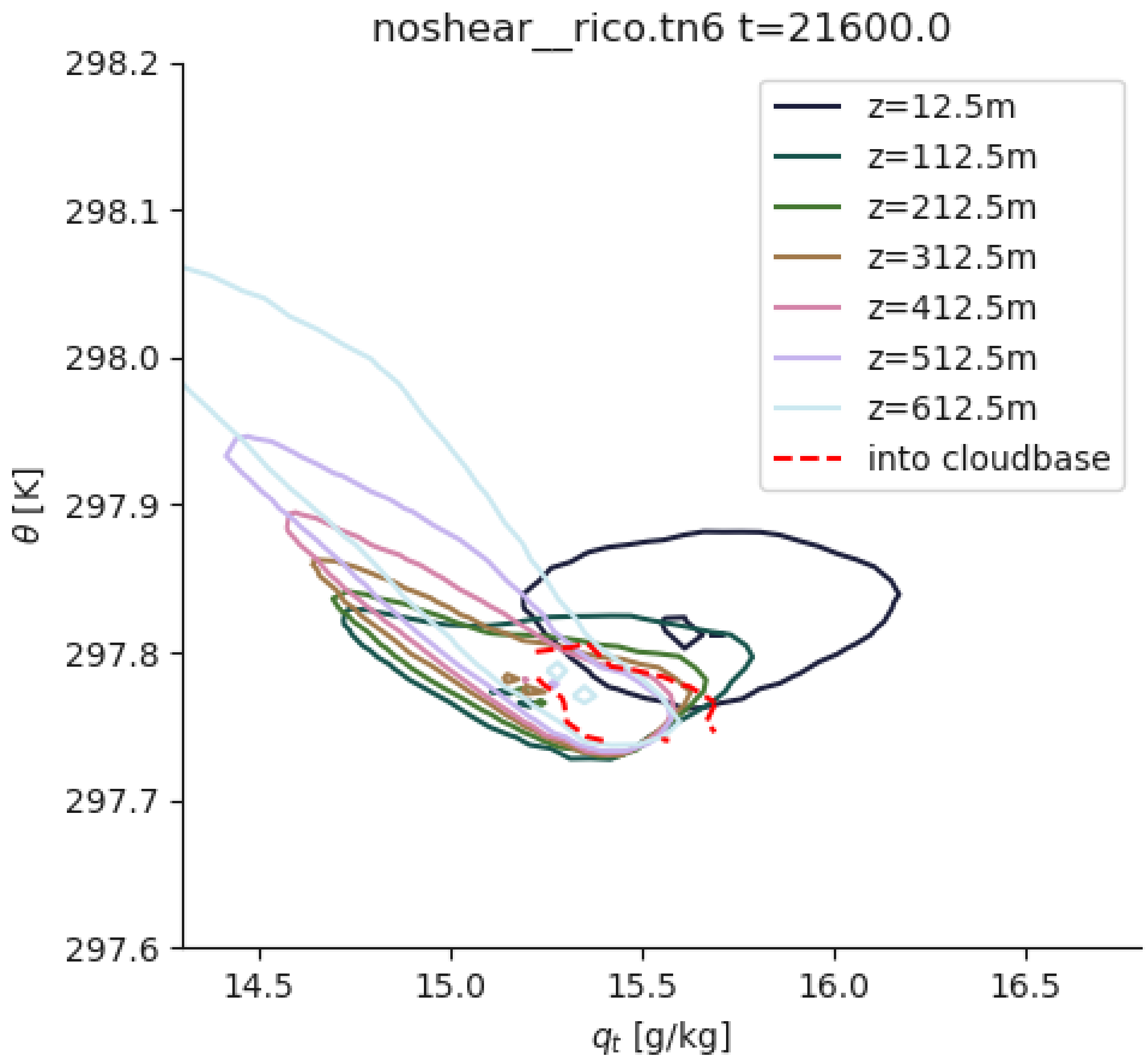
1. Distributions of moisture and temperature (at interesting heights)



- Air that reaches cloud-level appears to be moister and colder than boundary layer characteristic values

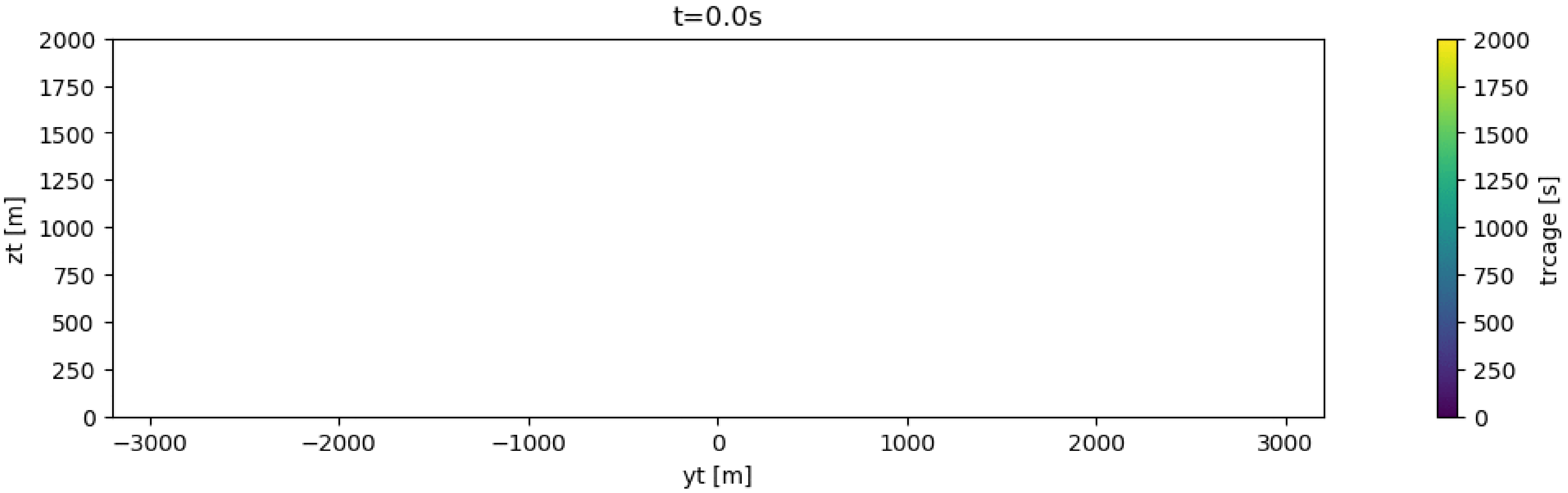
- But *what are the joint distributions (and their height variation)?*

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 (grid-spacing) 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

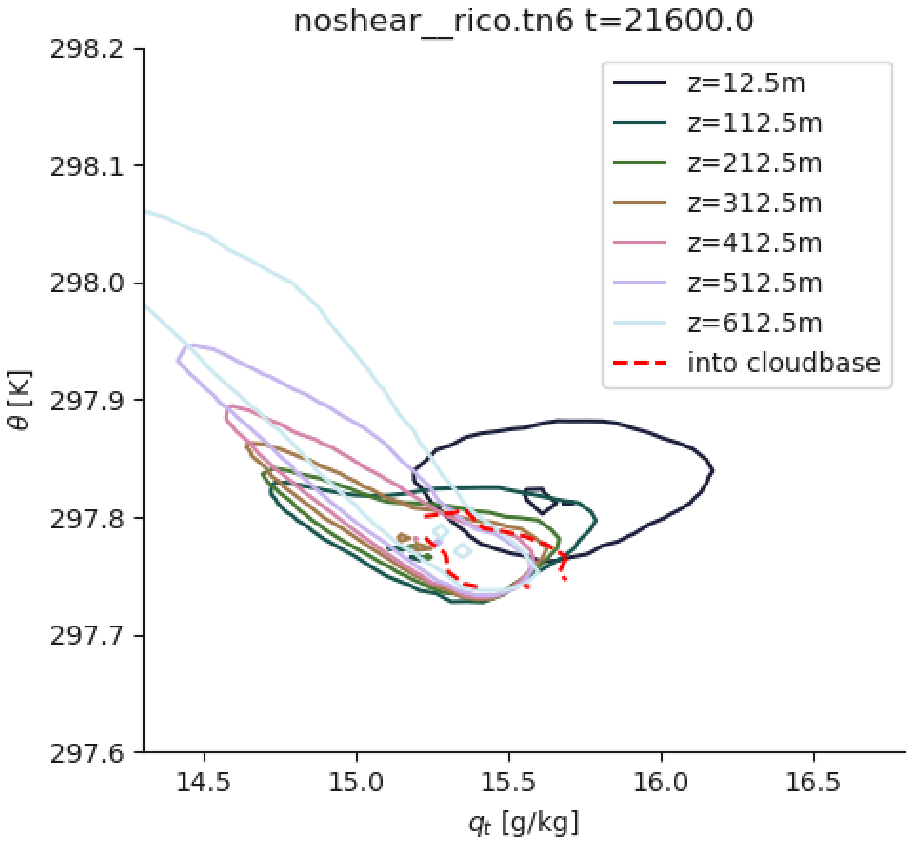


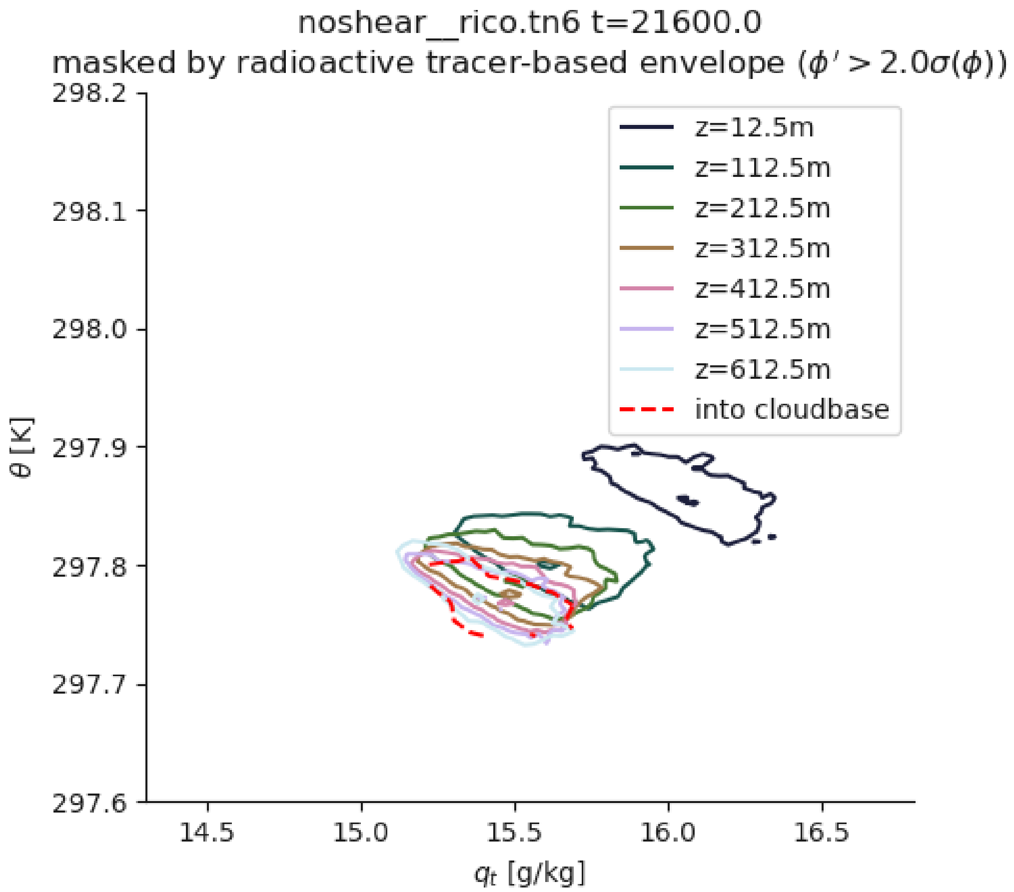
- Two tracers (φ_1, φ_2) with different half-life (τ_1=10min, τ_2=15min) released from surface

- Time since release: $t_{age} = \tau_1\tau_2\log(\varphi_1/\varphi_2)/(\tau_1-\tau_2)$

- Thermal edge defined using deviation from std. div. in horizontal slice: $\varphi'(x,y,z) > \sigma(\varphi(z))$ (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

3) properties of individual coherent structures

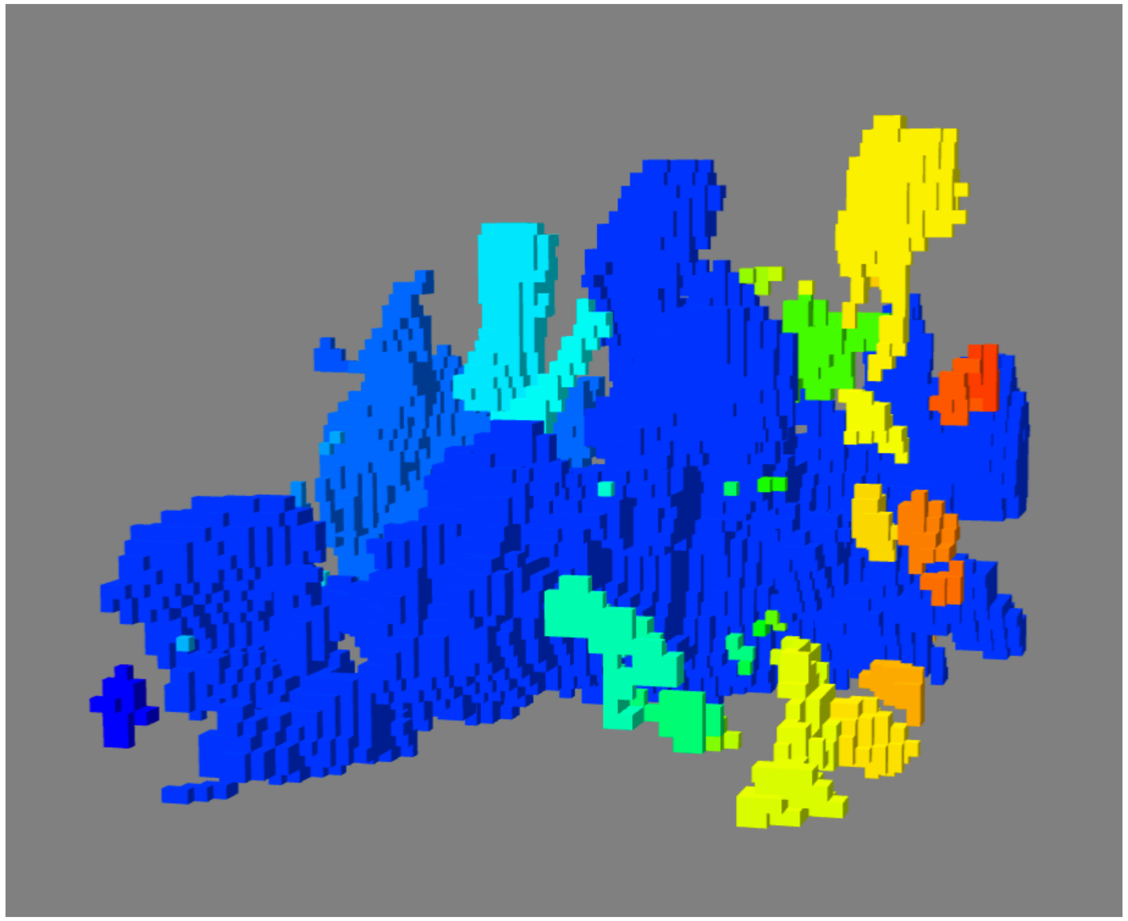
3. Object-based analysis

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 Peter Hristov, Leeds

What are characteristic sizes of objects in the boundary layer?

- Use Minkowski functionals to compute characteristic length-scales

$$V_0 = V = \int dV$$

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

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

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

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

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

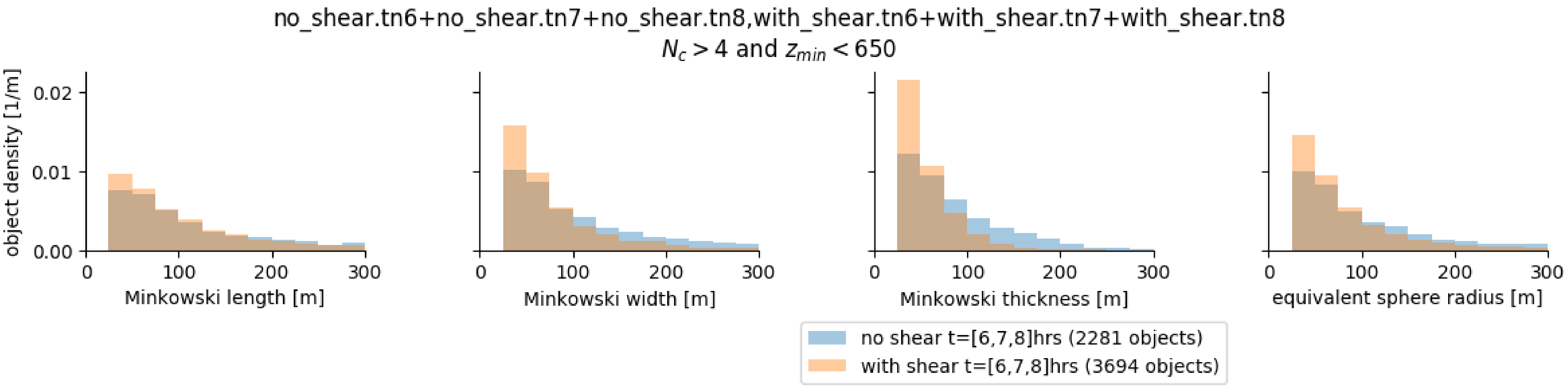
$$T = \frac{V_0}{2V_1}$$

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

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

- L, W and T are normalized to equal the radius when applied to a sphere

Distribution of object length-scales



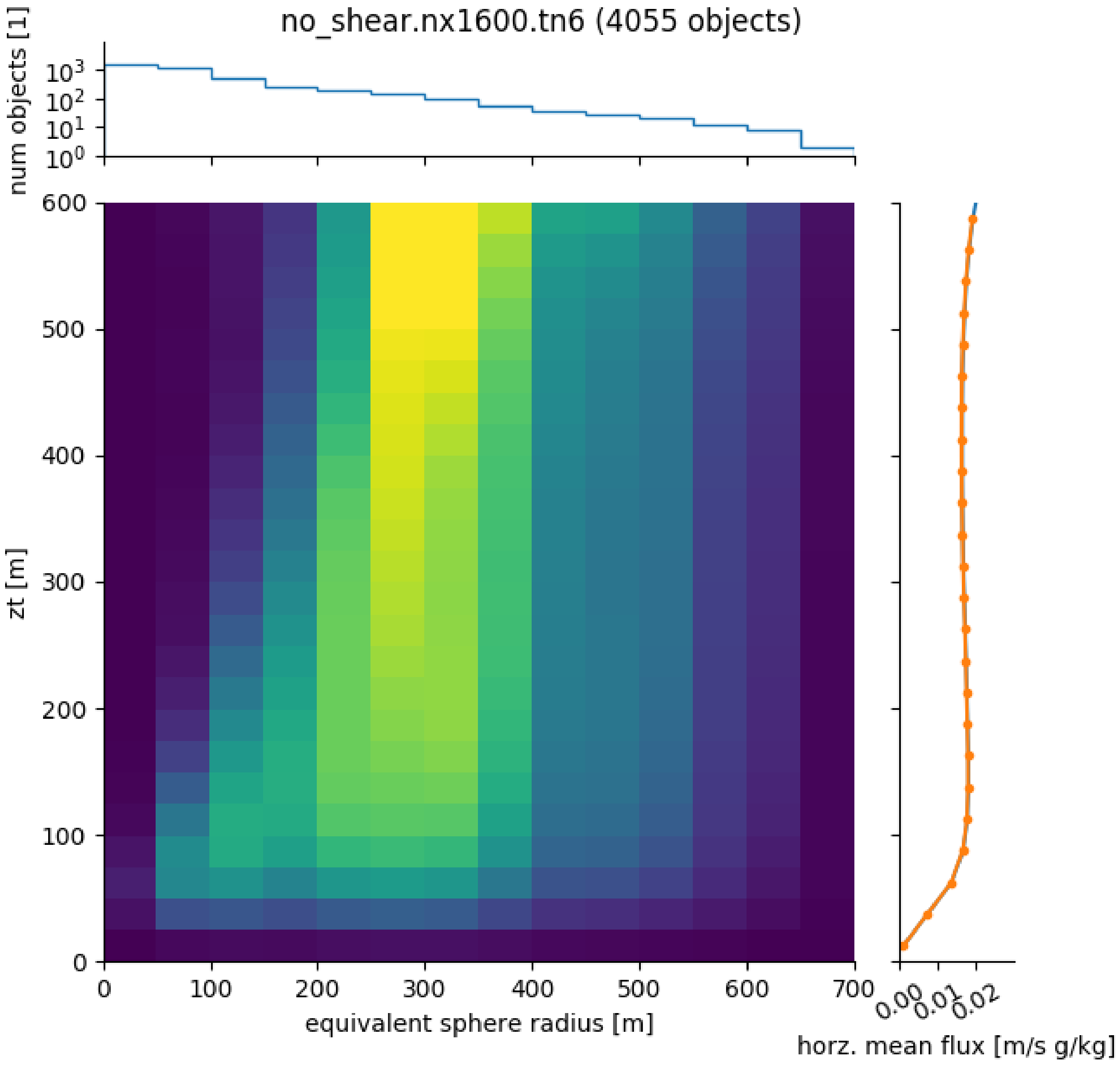
- Objects in presence of shear generally thinner than when no shear is present

- More large volume (equivalent sphere radius) objects without shear

BUT:

- What about objects that actually make clouds? What size objects dominate for example vertical water vapour transport?

Decomposing moisture flux by object size and height

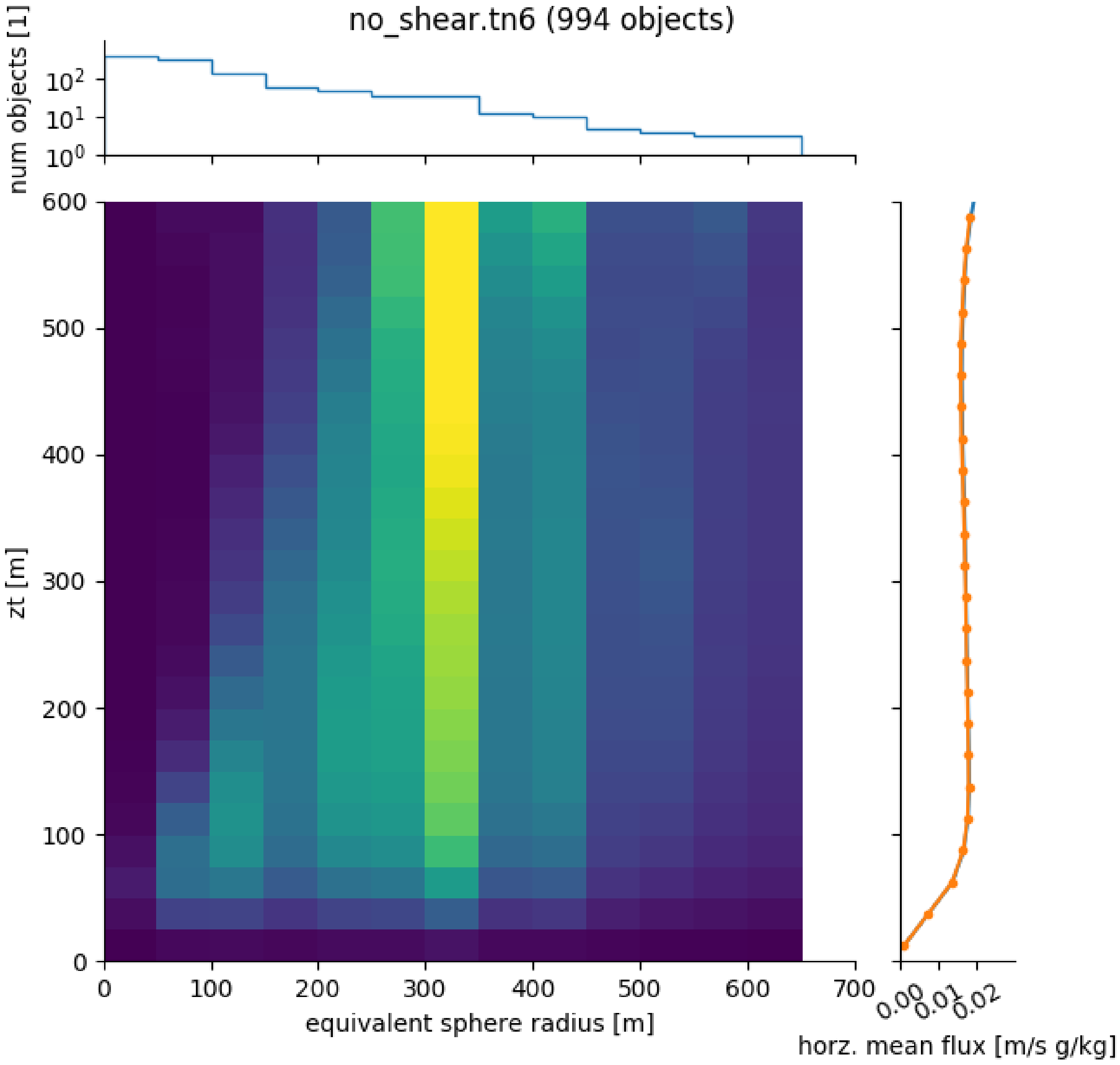


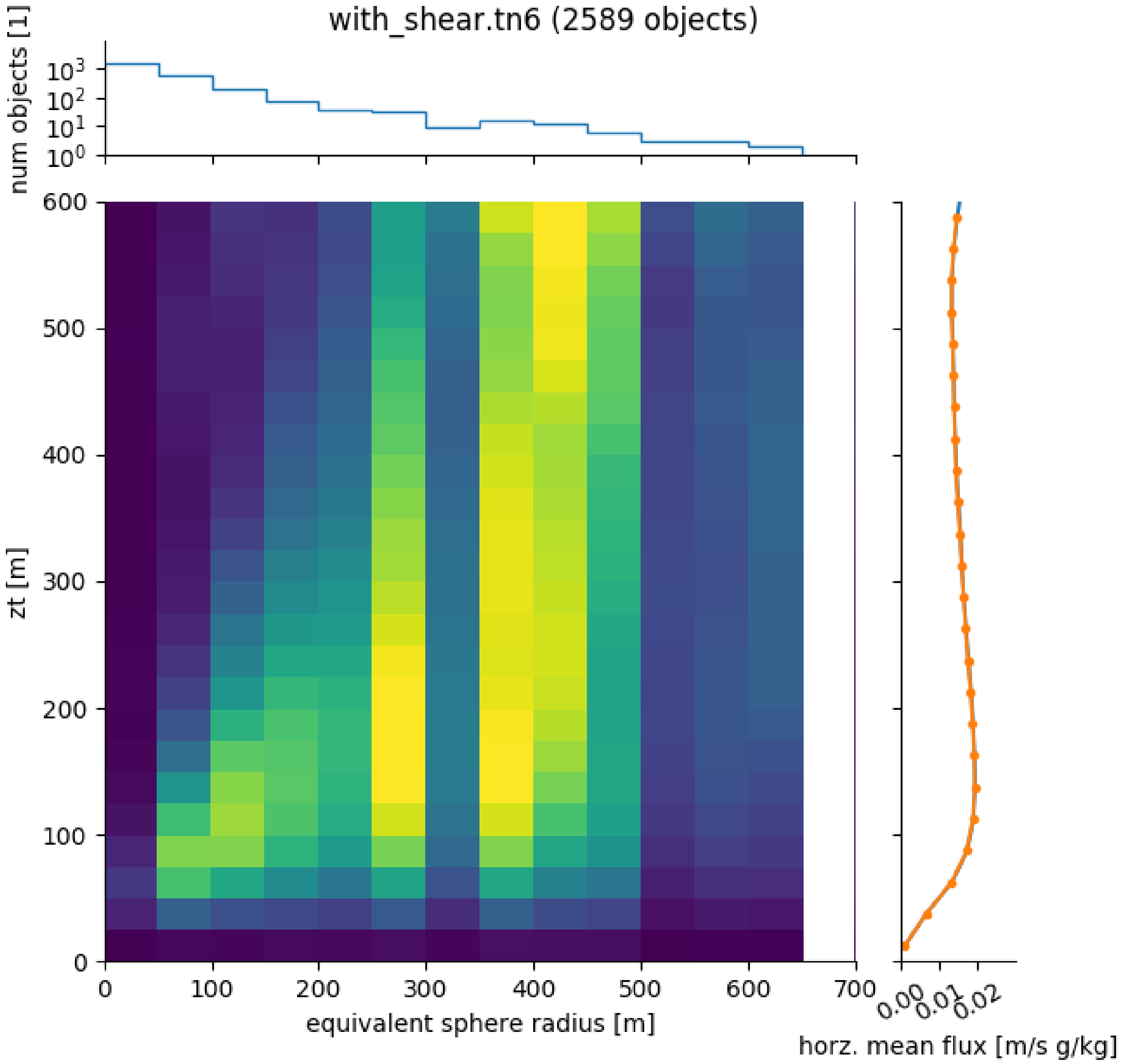
Total vertical moisture flux broken down into contribution at a given height by object size

- In bulk of boundary layer objects of r_{equiv}~300m dominate (only ~100 objects)
- Near surface smaller scales dominate, but large size-range of objects contribute

many  or few  ?

Decomposing moisture flux by object size and height





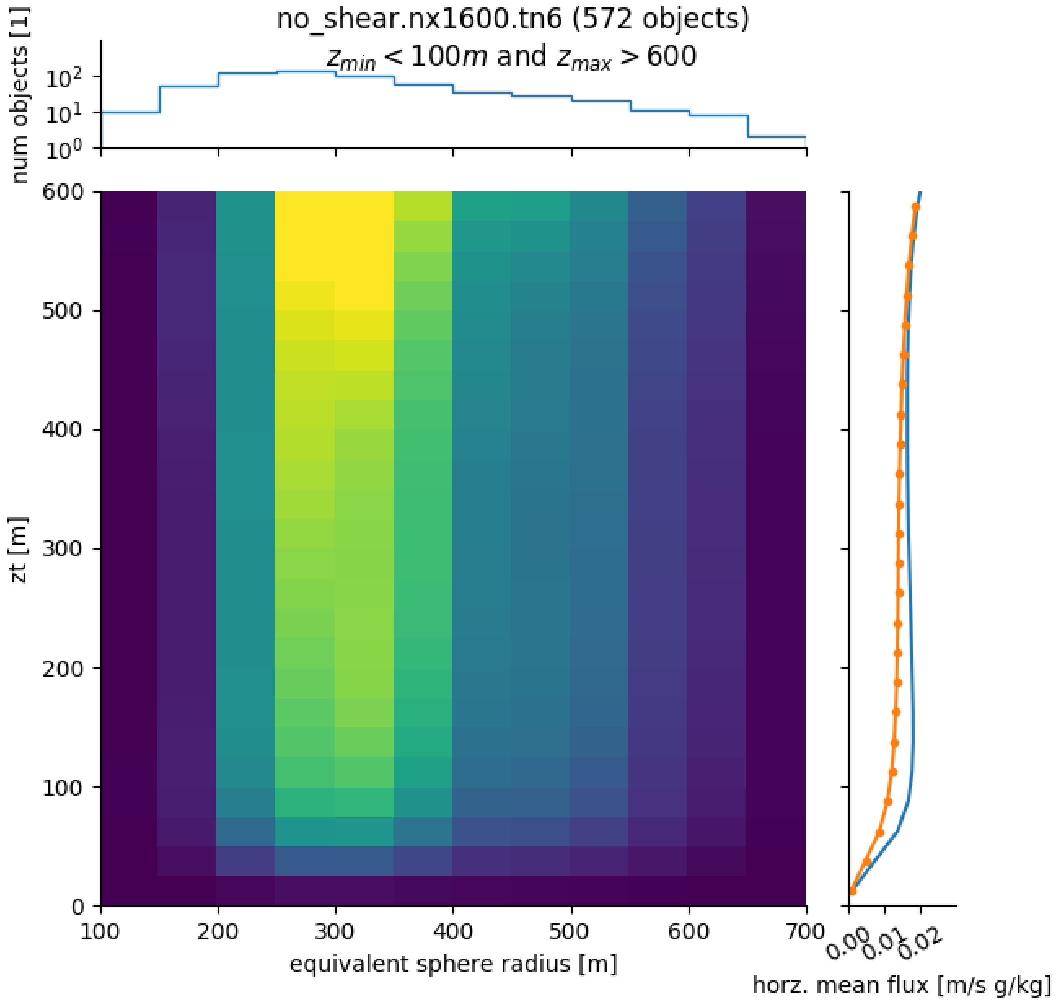
With shear range of scales which contribute is larger and average dominating scale is larger too

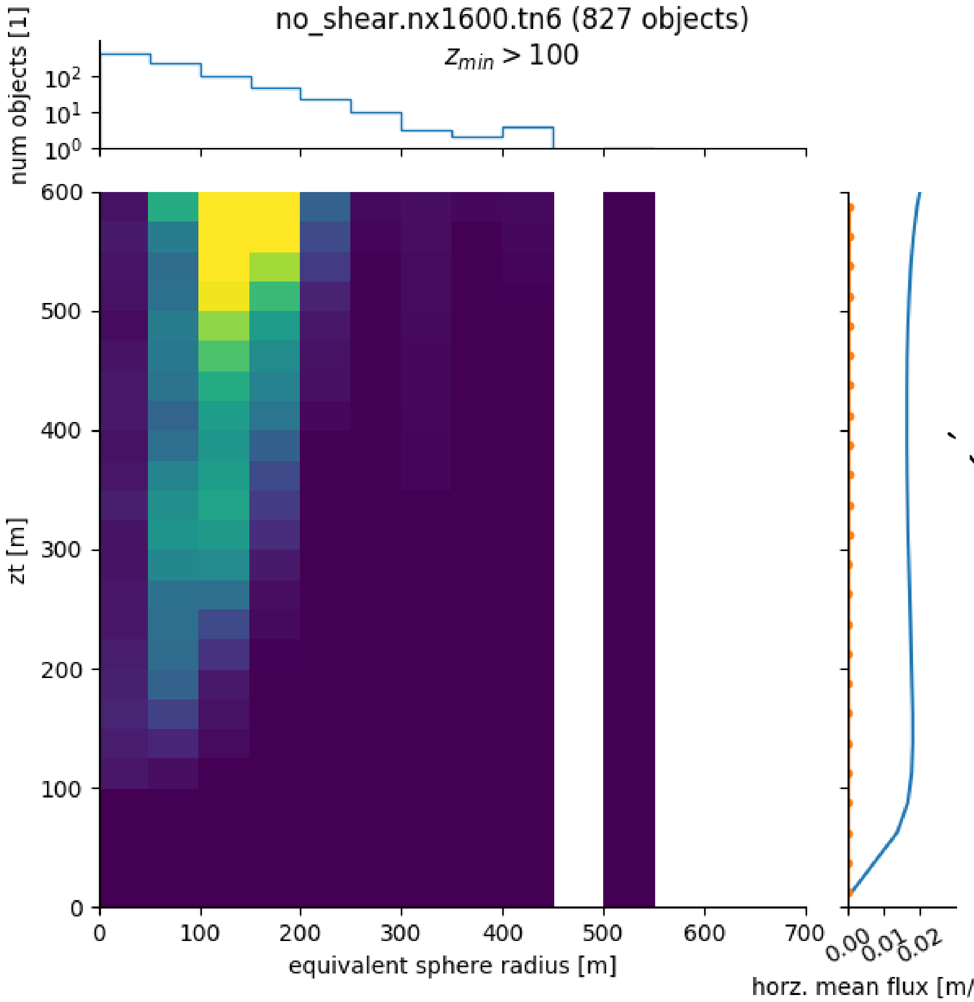
Plume vs thermal?

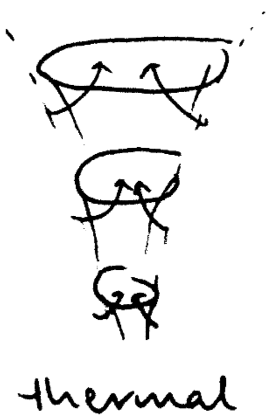
Flux decomposition allows us to assert whether flux-dominating structure are attached to surface

Attached to surface
and extending to cloud layer

Detached from surface



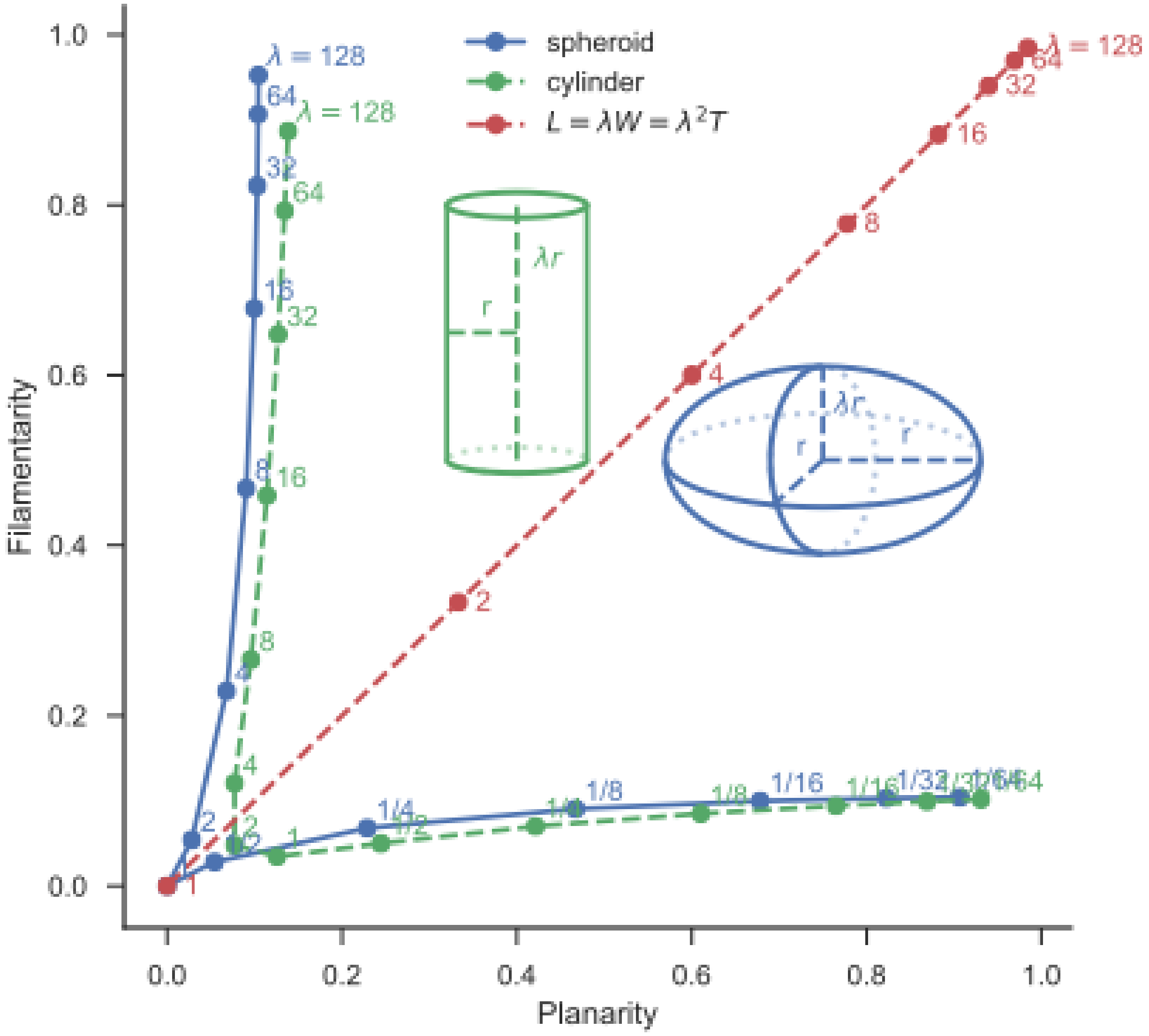




- Almost all of vertical moisture flux is carried by objects which extend below z~100m

What is shape of objects in the boundary layer?

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



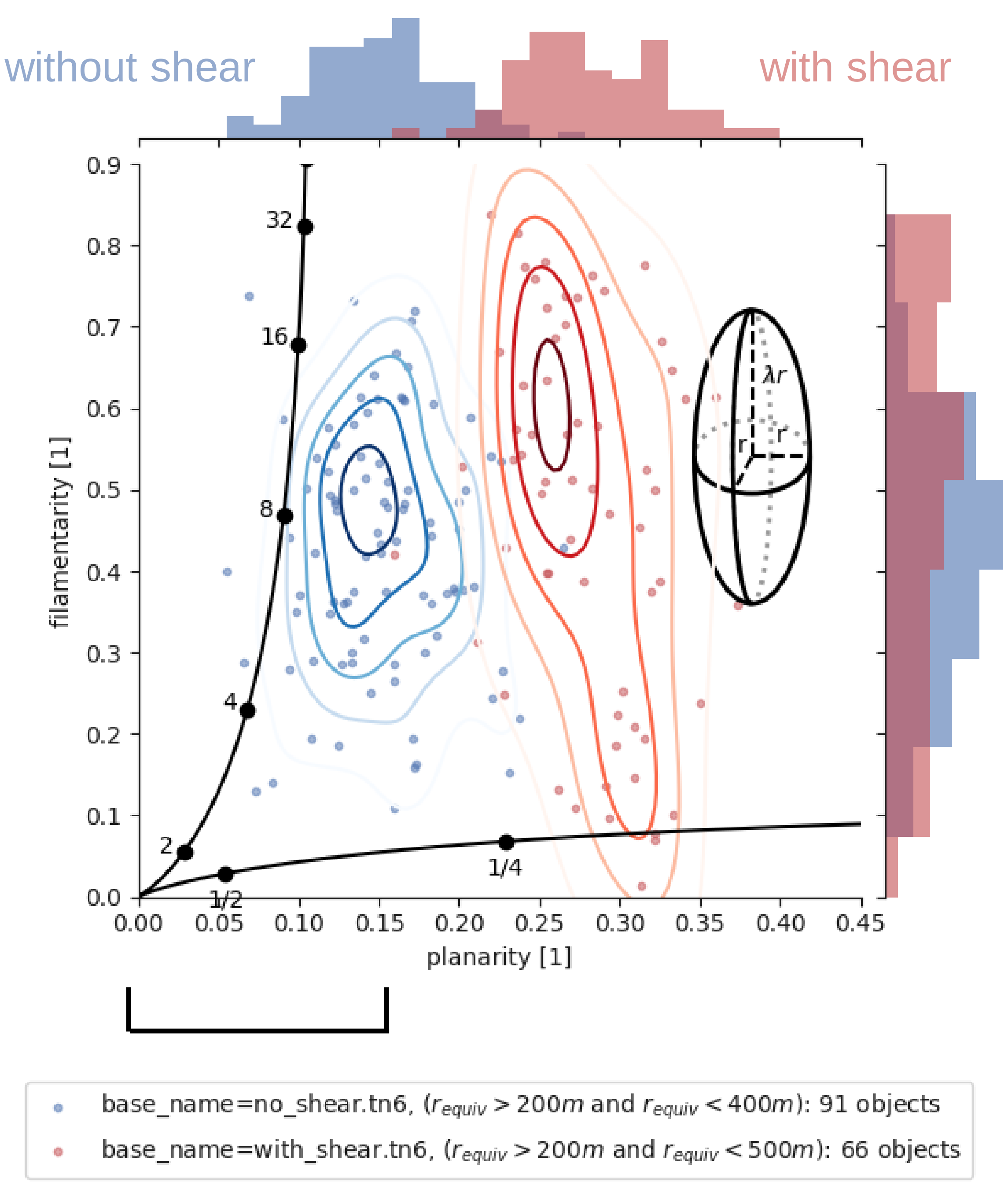
$$P = \frac{W - T}{W + T}, F = \frac{L - W}{L + W}$$

→ Measures how pencil or disc-like an object is

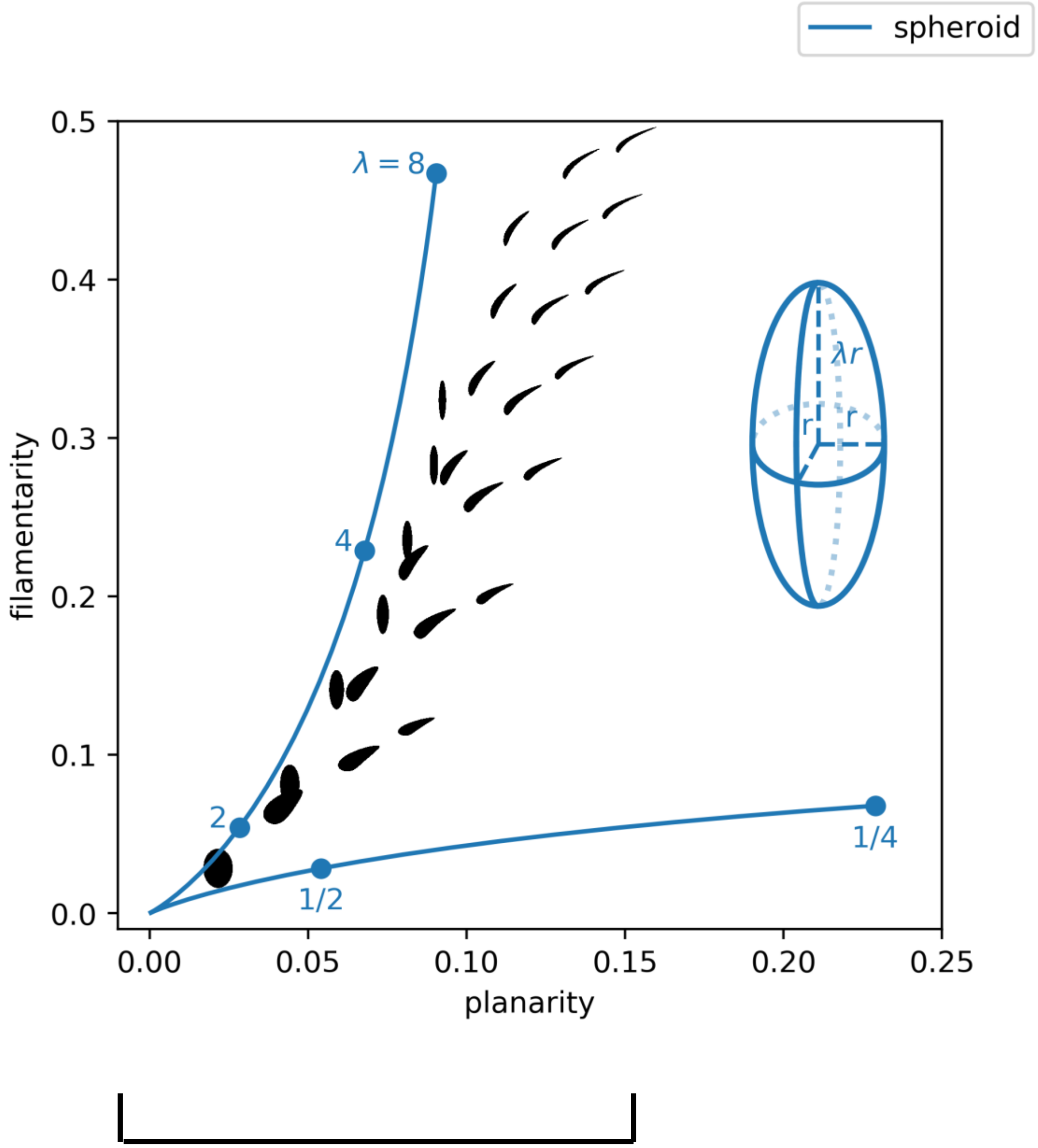
What is shape of objects in the boundary layer?

objects in LES

$z_{min} < 100m$



synthetic objects



→ Shear causes structures to become longer and wider by ~30% and ~80% respectively

Summary

- Physical fields all vary on different length-scales

  → can’t define a coherent object by limit values of a single variable (e.g. positive vertical velocity)

- Surface-released decaying (“radioactive”) tracer tracks air that enters newly-formed clouds

  → good method for defining cloud-triggering structures

- Vertical moisture flux is dominated by

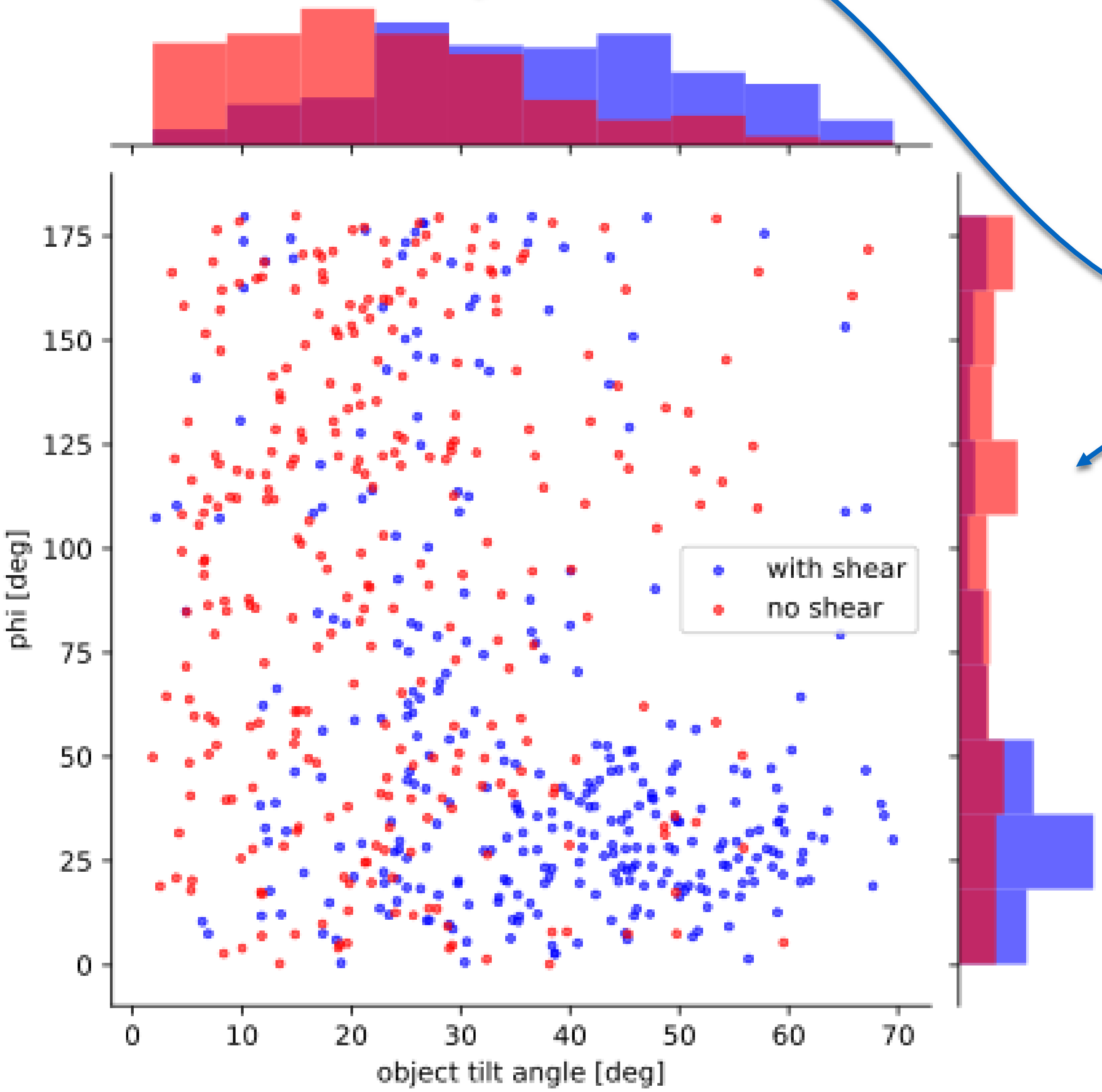
  → coherent structures of intermediate length-scale, scale is dependent on amount of ambient shear

  → Plumes (surface-attached coherent structures) rather than thermals

Thank you!

Questions?

Are the objects oriented with cumulant direction?

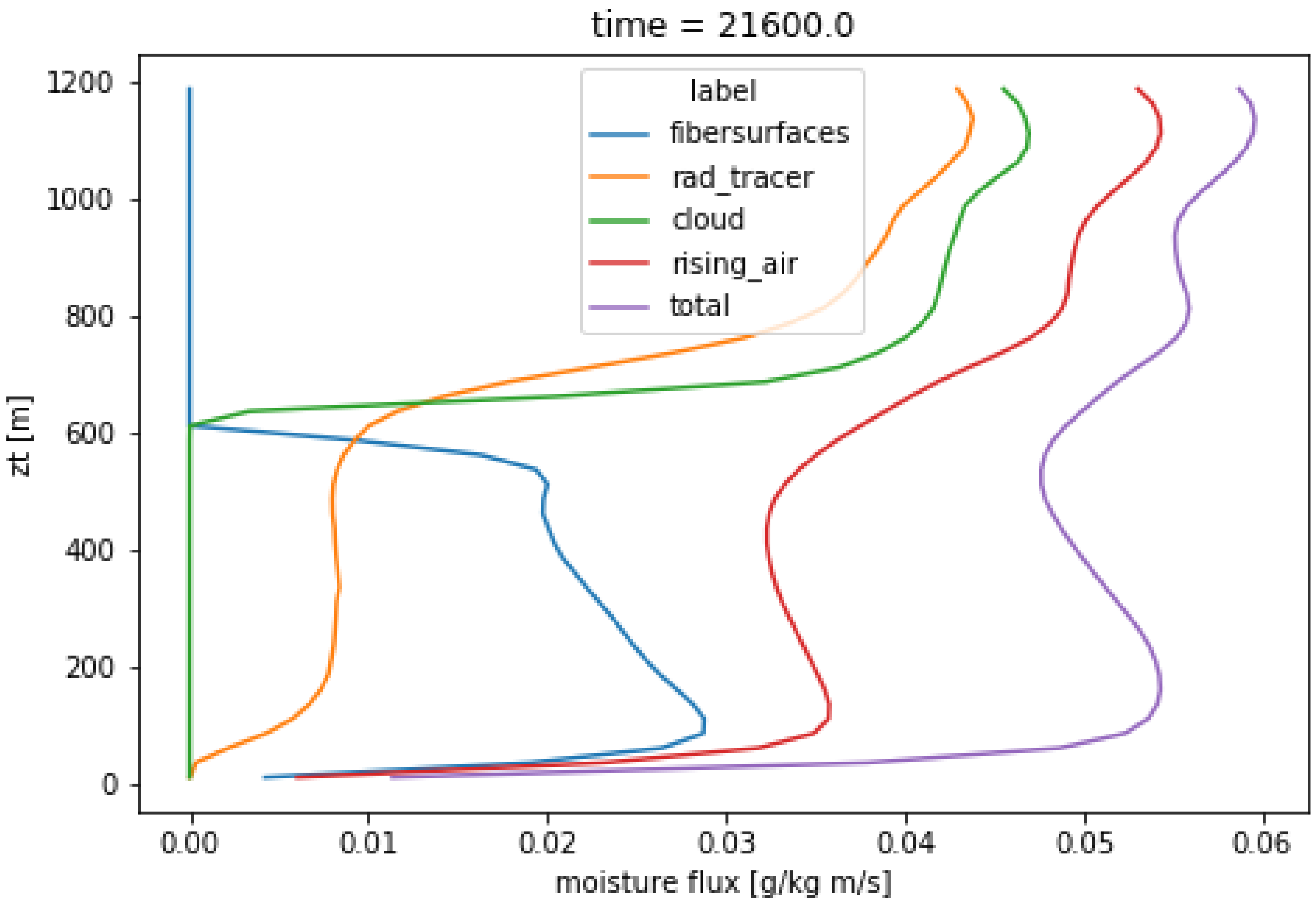


Yes! Φ~30°

- Although objects in non-sheared environment appear titled no correlation with orientation
- Shear tilts objects in direction of shear

- Tilt and orientation calculated from slope of center-of-mass in every height inside object

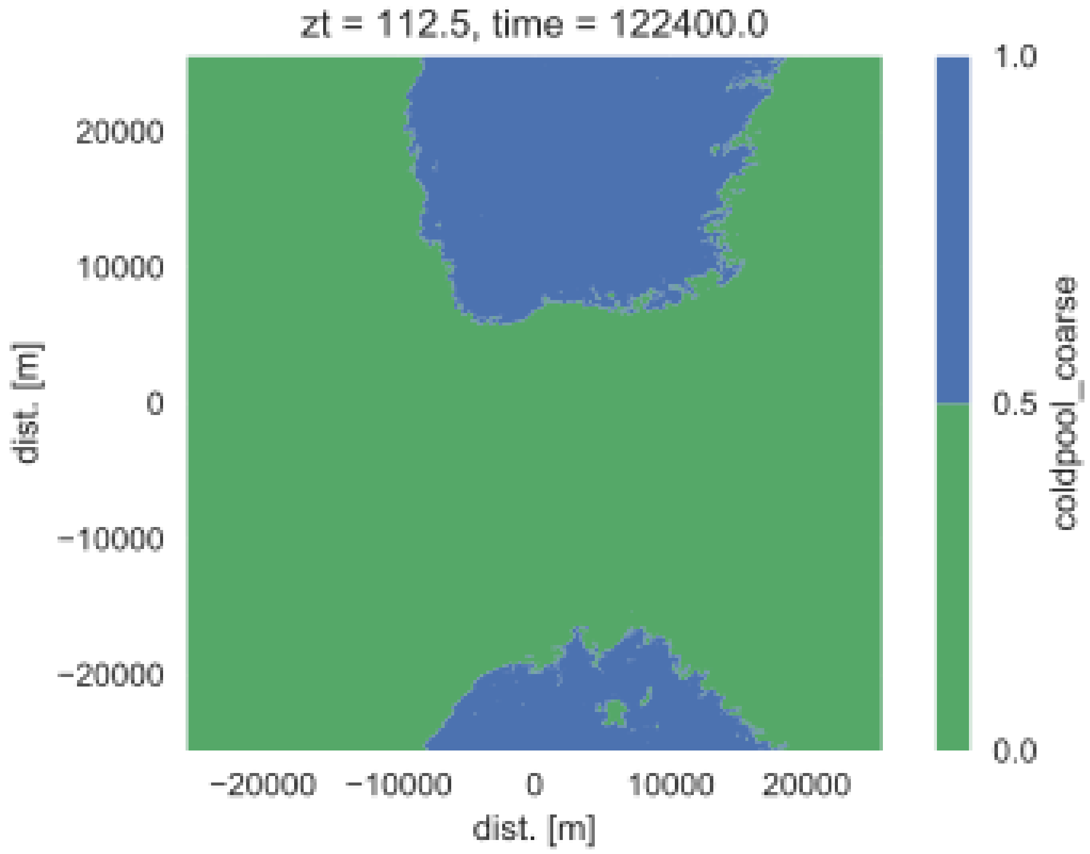
Decomposition of moisture flux



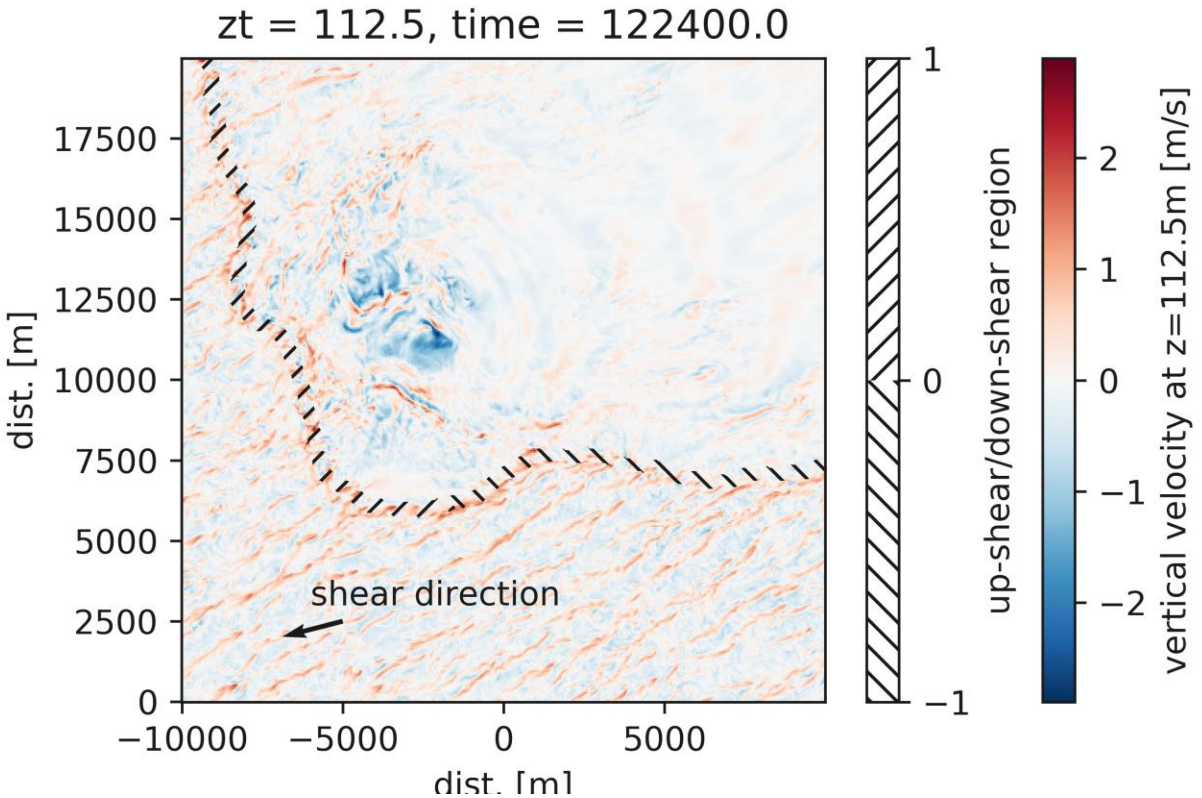
- Radioactive tracer flux near-constant with height

- Flux from region selected by fibersurfaces much larger than rad tracer – includes local transport

Example:
coldpool influence on boundary layer structures



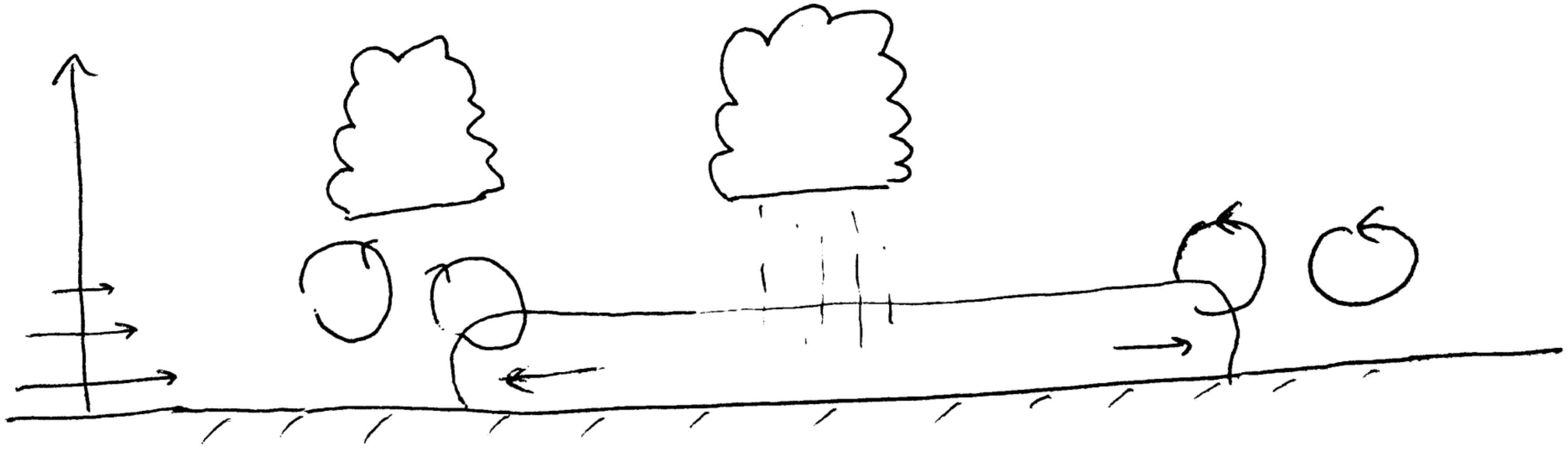
Using density anomaly ($\theta_v' < -0.1K$) to define coldpool region



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

RKW-theory (precipitating clouds)

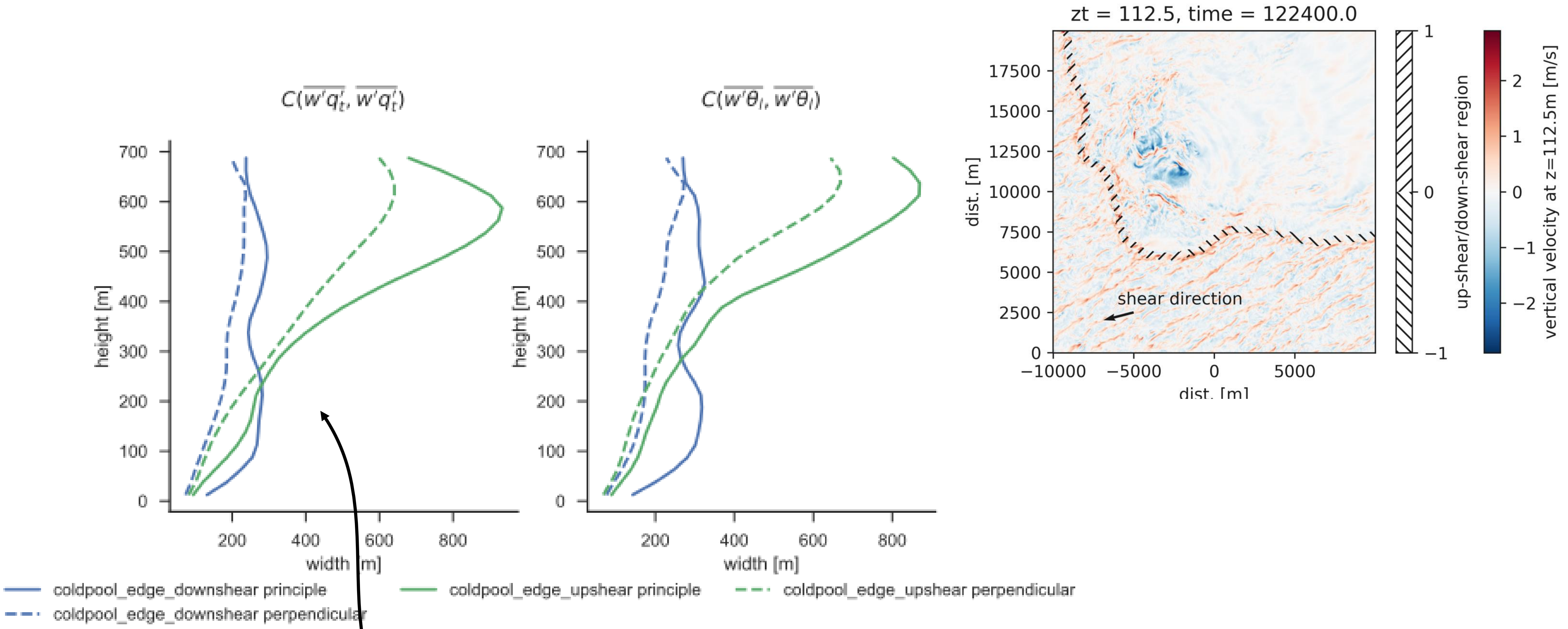
Rotunno, Klemp & Weisman 1980s



- 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)

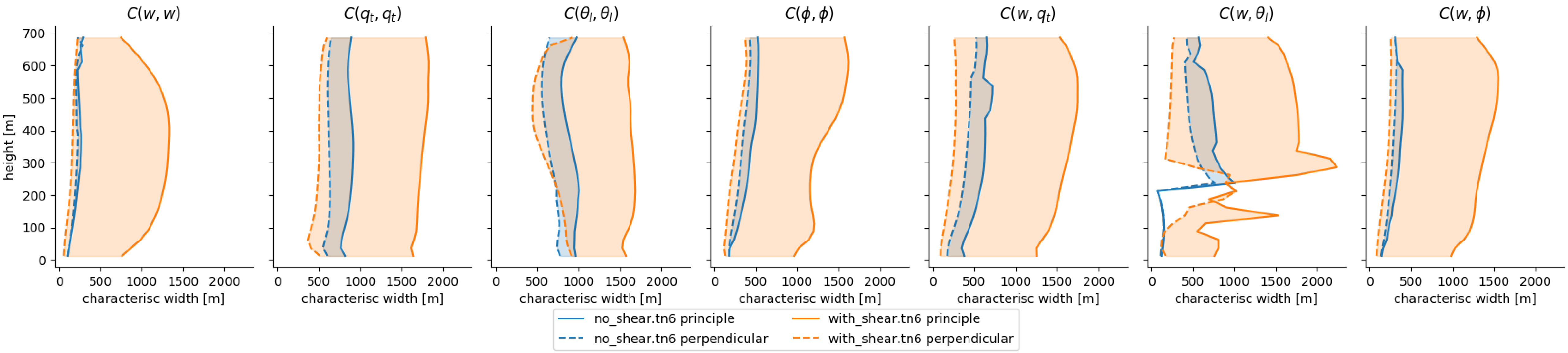
Coherence length of BL structures

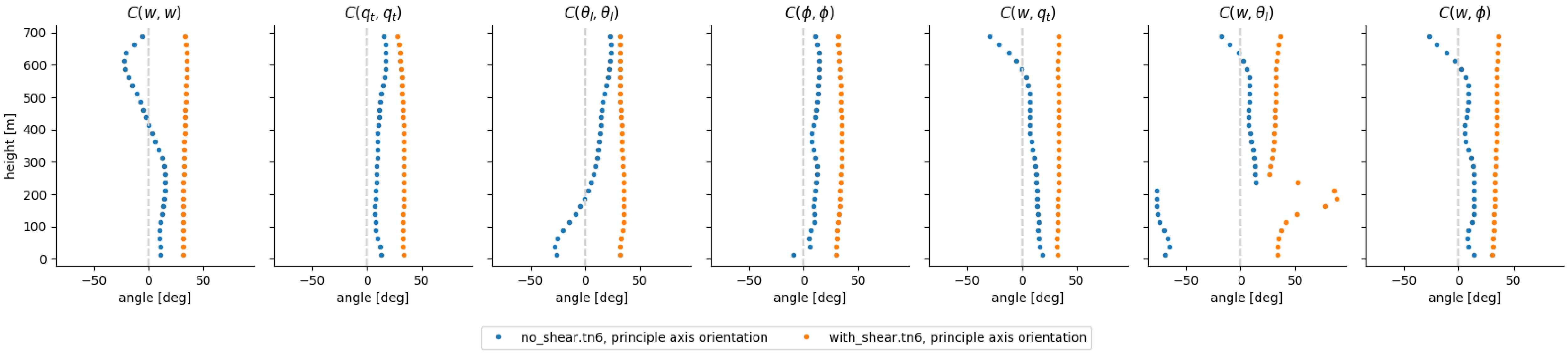
Upshear and downshear coldpool edge



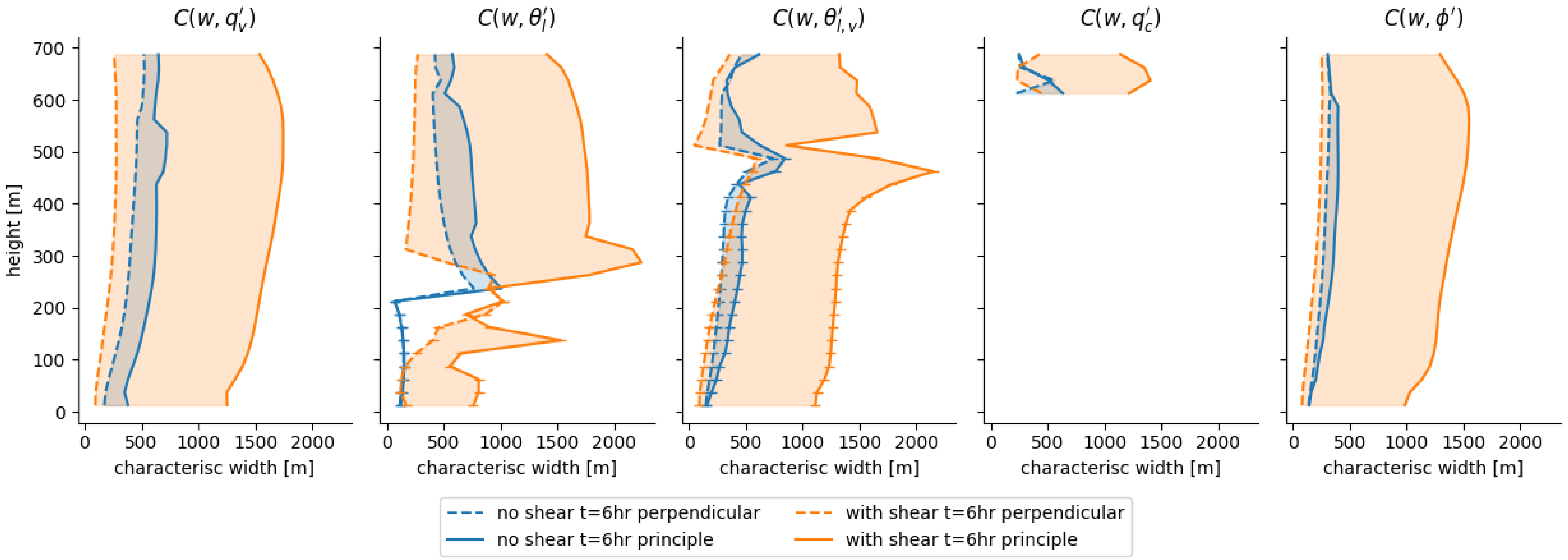
Flux-carrying structures appear larger on up-shear side

Cumulant scales for rad tracer



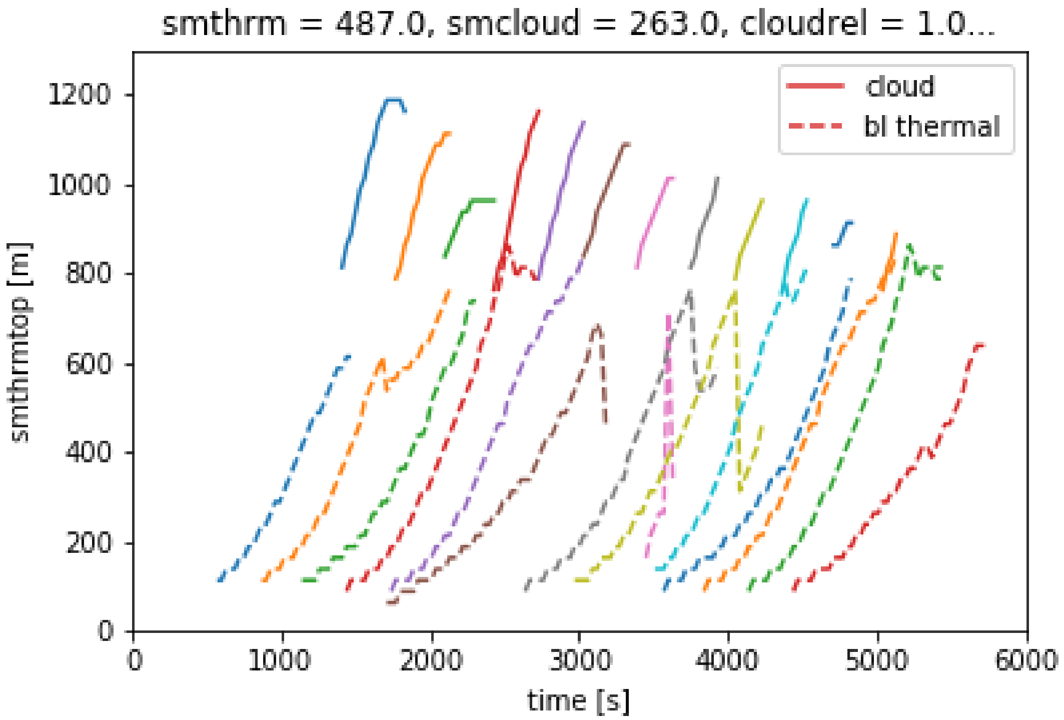


Cumulant scales for fluxes



(we can also track them…)

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

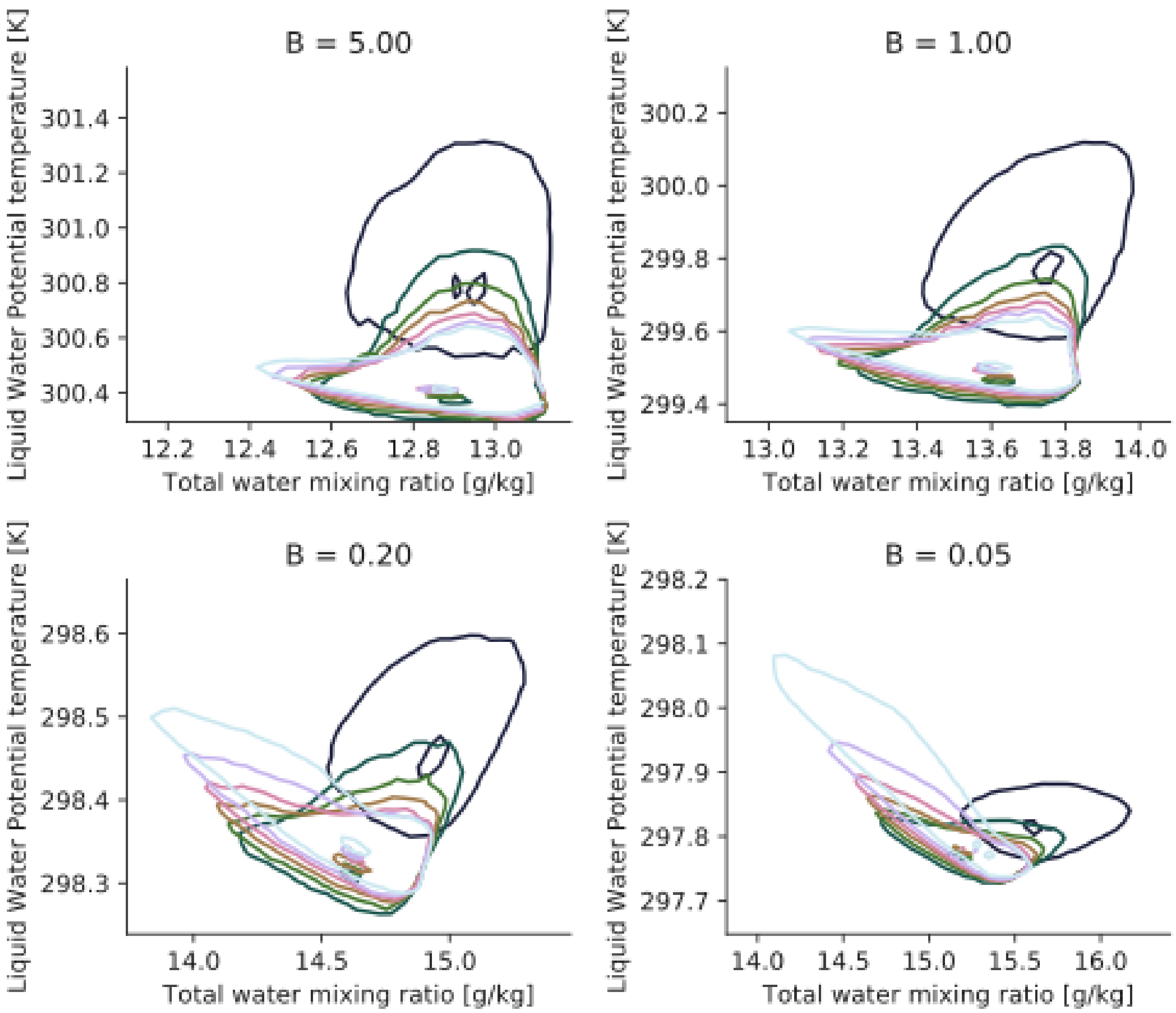


Height of top of individual clouds and thermals that each cloud was triggered by

- 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?



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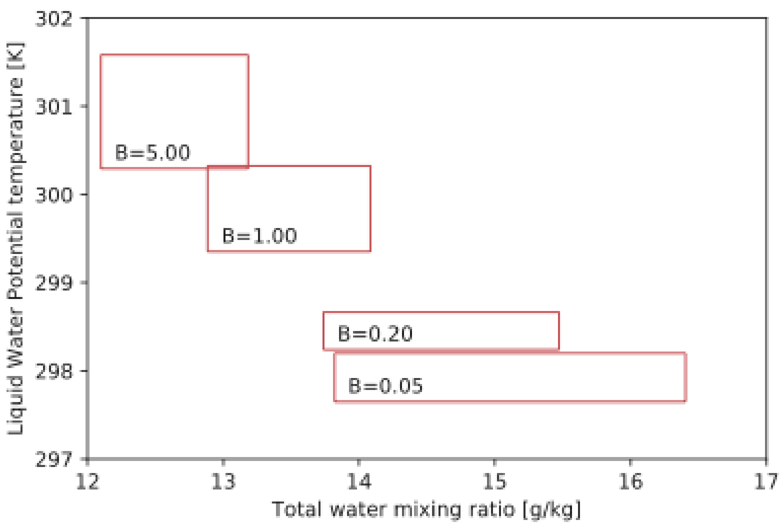
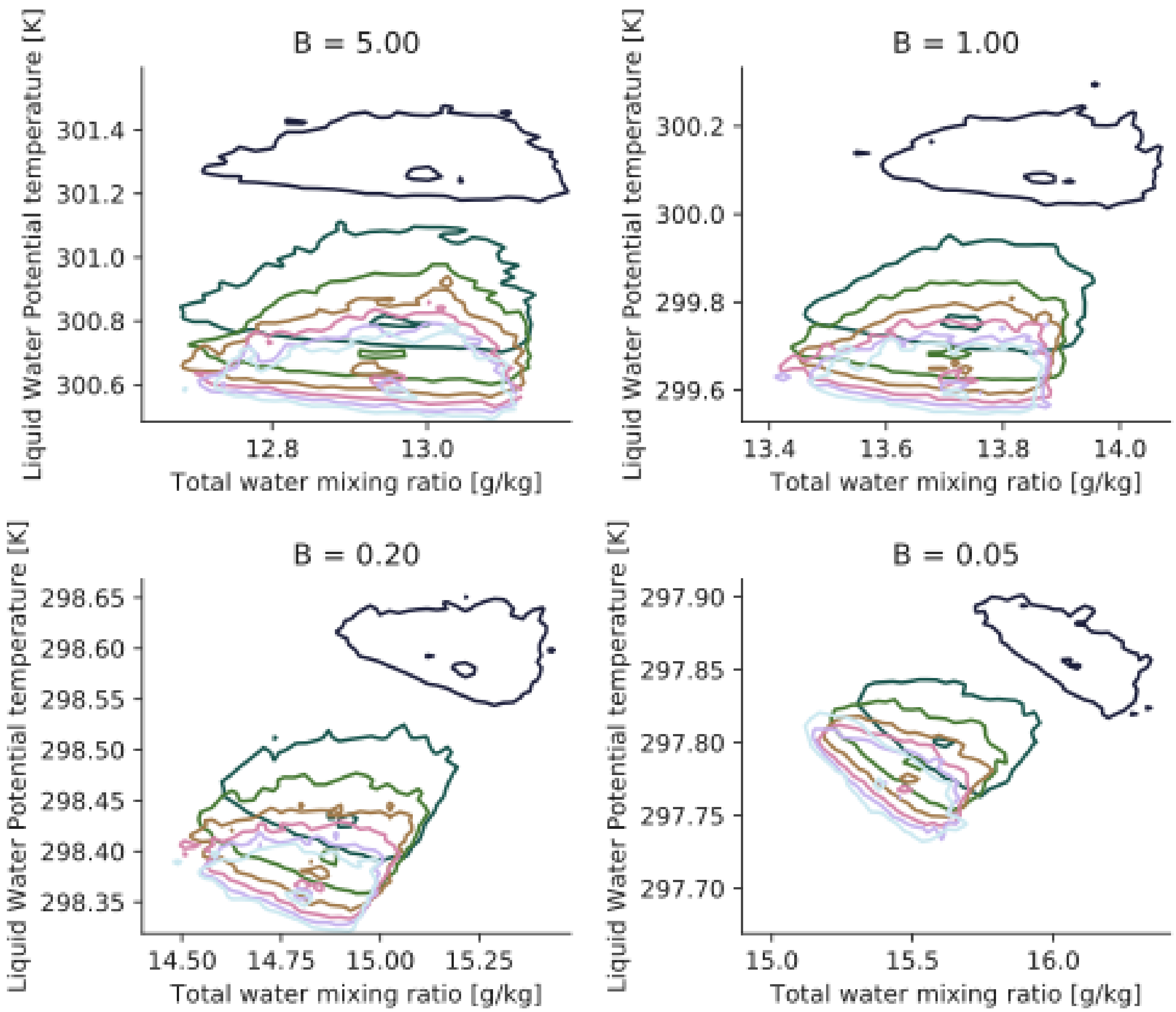


- As Bowen ratio is increased change in mean of distribution has less change in moisture (because less moisture is released from surface)

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



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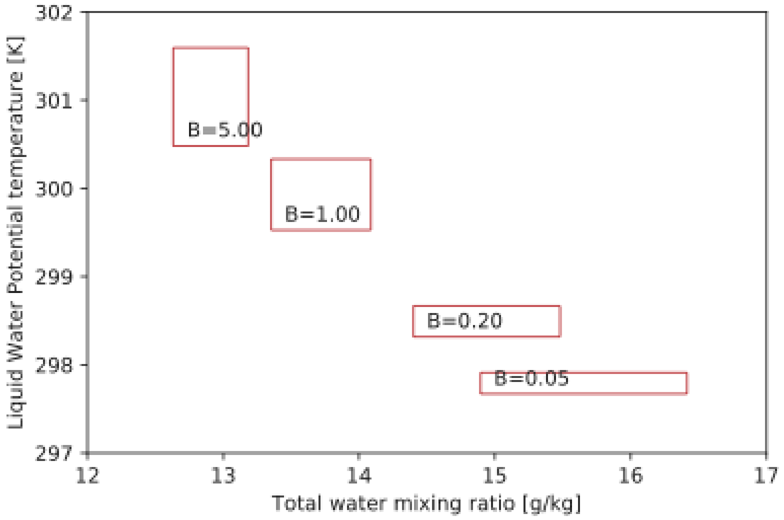

- As Bowen ratio is increased change in mean of distribution has less change in moisture (because less moisture is released from surface)
- All distributions show similar shape displaced with height as air is mixed with boundary layer