Object-oriented identification of coherent structures: A multi-case analysis of boundary-layer Large-Eddy Simulations

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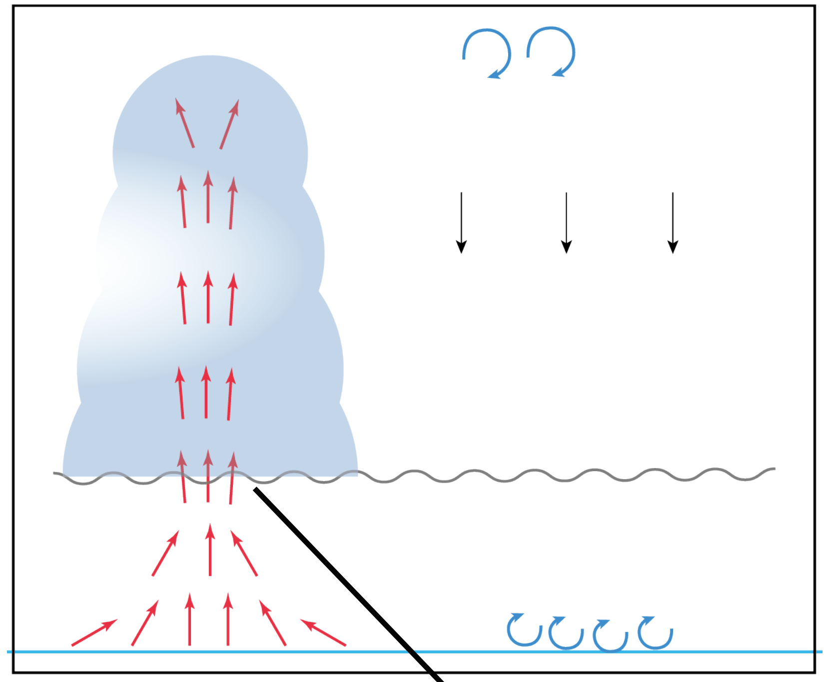
Context

resolved *parameterized*

$$\frac{\partial \overline{\phi}}{\partial t} = -\overline{v} \cdot \nabla \overline{\phi} - \overline{\omega} \frac{\partial \overline{\phi}}{\partial z} - \frac{1}{\overline{\rho}} \frac{\partial}{\partial z} (\overline{\rho} \cdot \overline{\omega' \phi'}) + \alpha(c - e) + Q_{rad}$$

Turbulent and convective vertical transport

GCM Grid box



Investigating **coherent structures** in Large Eddy Simulations for better understanding of PBL motions

We use the <u>MESO-NH model</u>

Closure assumptions

turbulence

$$\overline{\omega' \phi'} = -K \frac{\partial \overline{\phi}}{\partial z}$$

convection

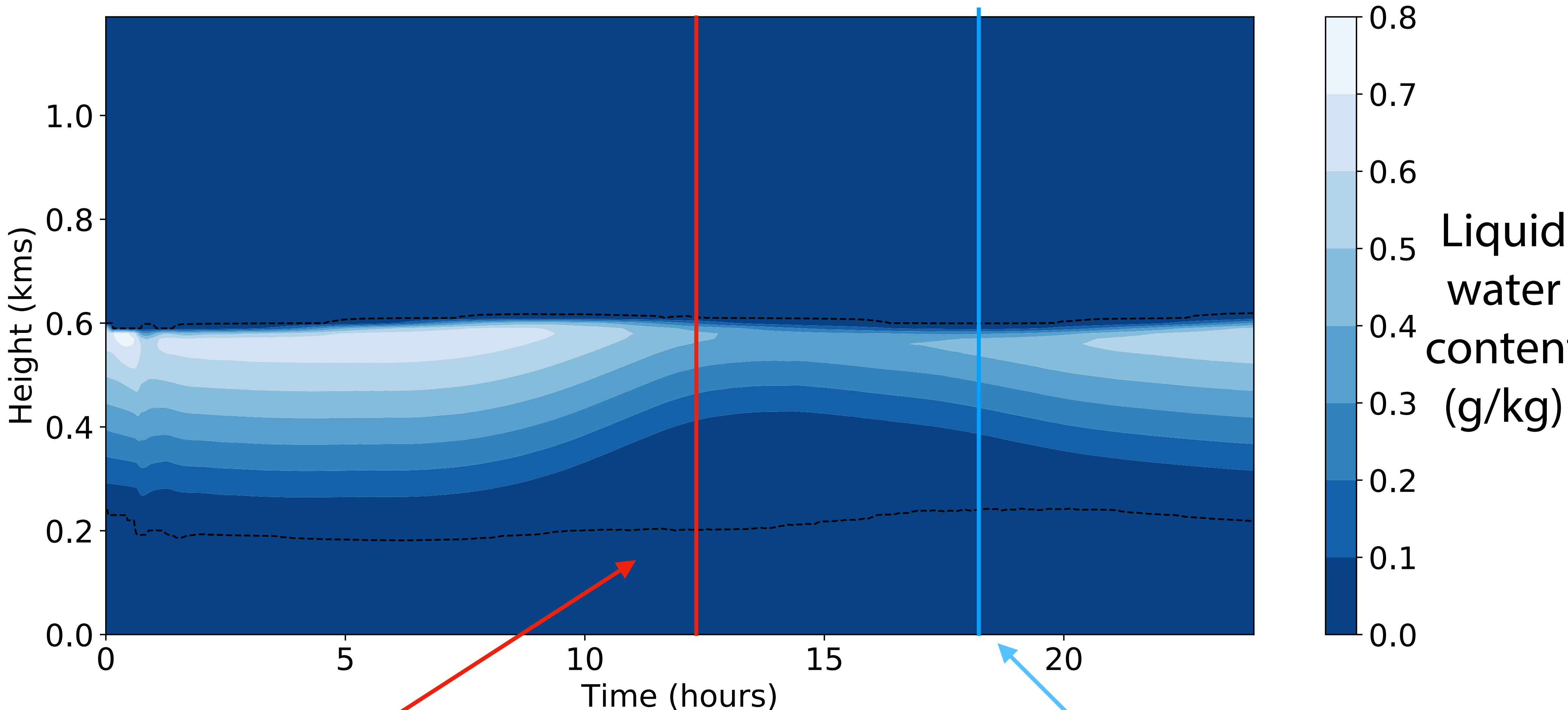
$$\overline{\omega' \phi'} = \sigma \omega_c (\phi_c - \phi_e)$$

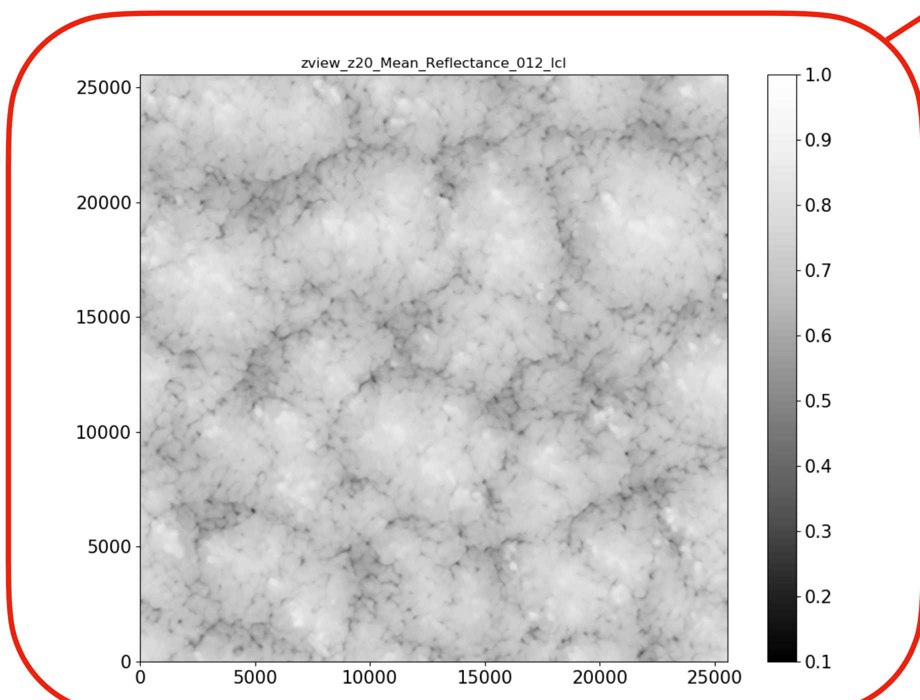
Errors in representing boundary-layer clouds significantly influence cloud feedbacks, the hydrological sensitivity, regional climate projections…

The FIRE diurnal cycle simulation by MESO-NH

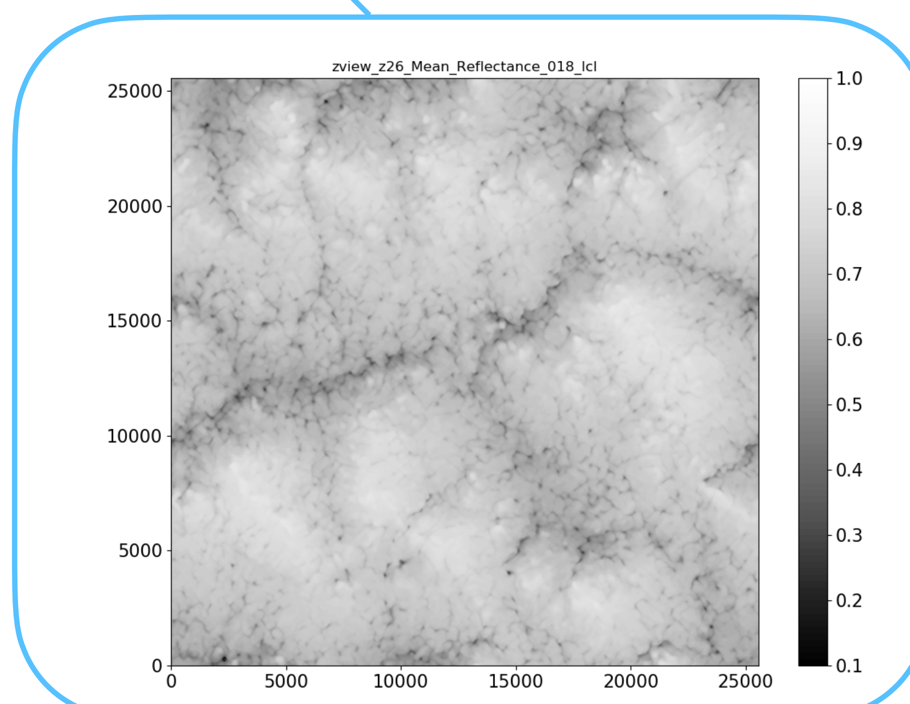
25.6x25.6 km^2
($\Delta x = \Delta y = 50$m, $\Delta z = 10$m)
512 x 512 x 120 grid points
T = 1 day with interactive surface fluxes

2-moment warm microphysics





Reflectance (offline calc.)

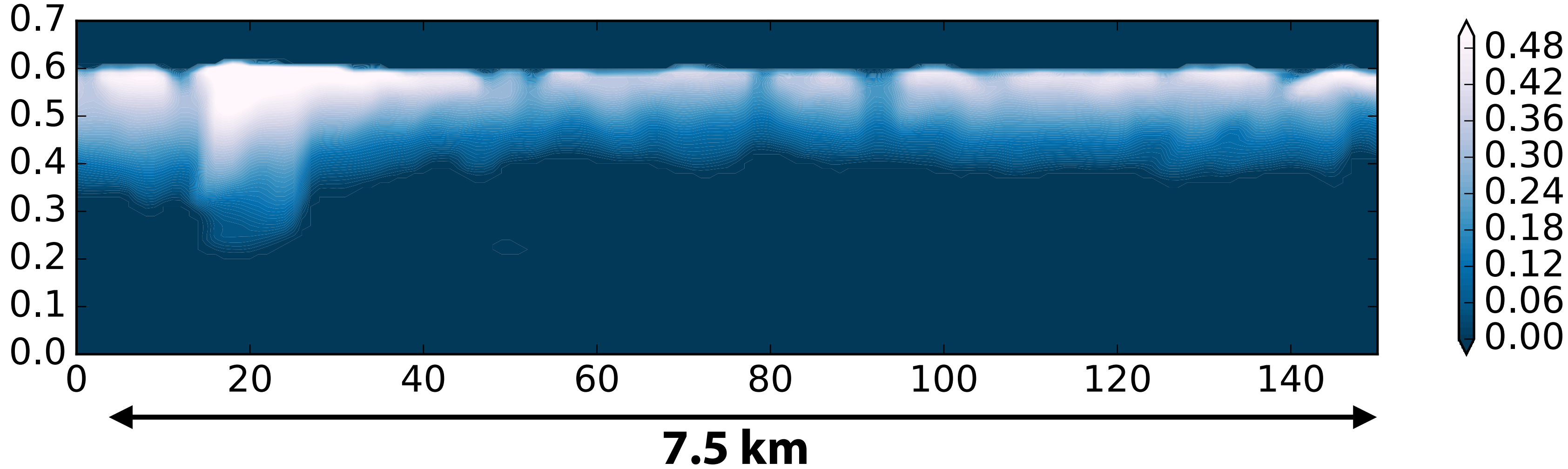


Mesoscale organisation, significant diurnal cycle

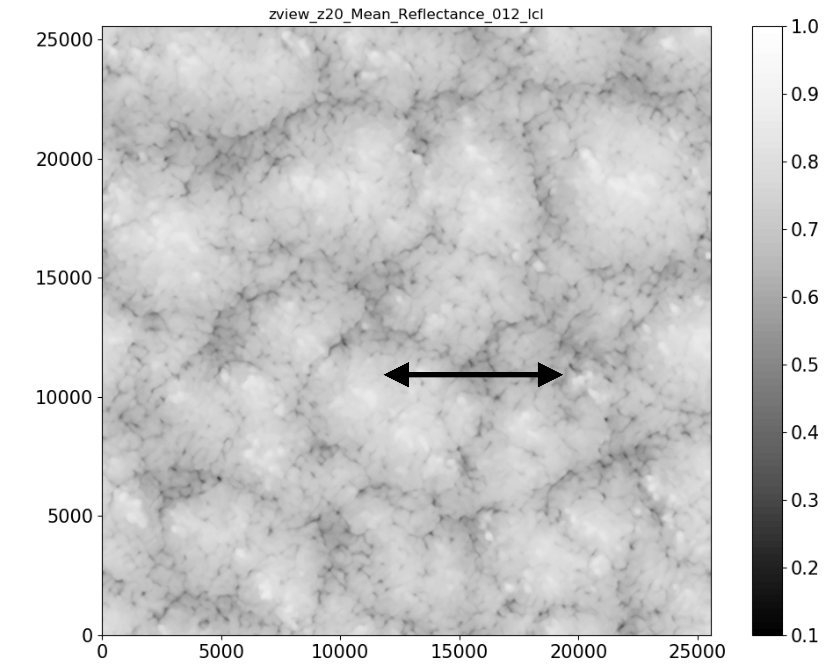
Vertical cross section at t=12h

altitude (km)

Liquid water (g/kg)

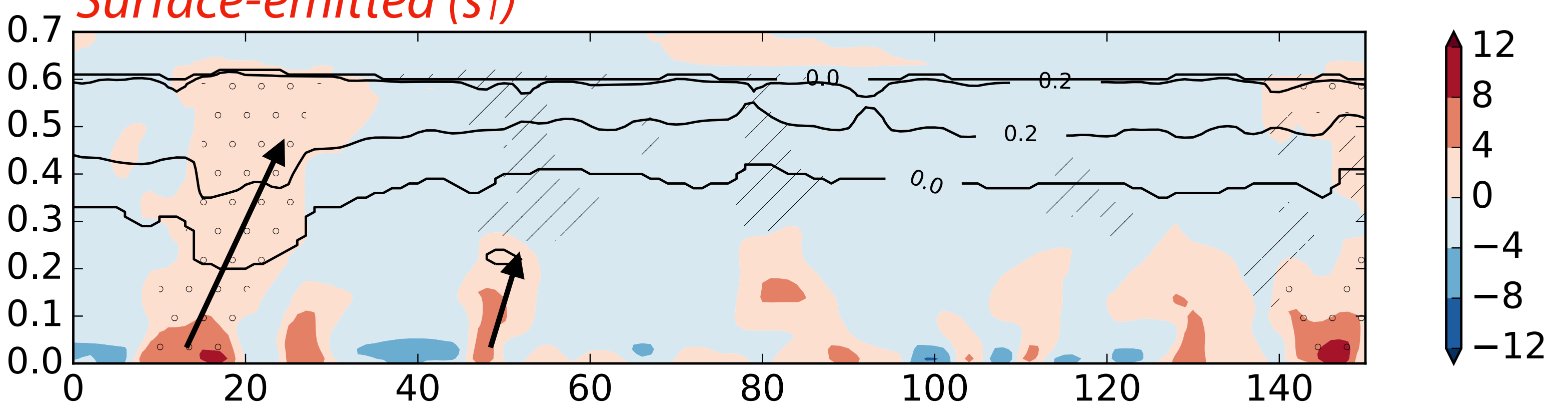


Reflectance

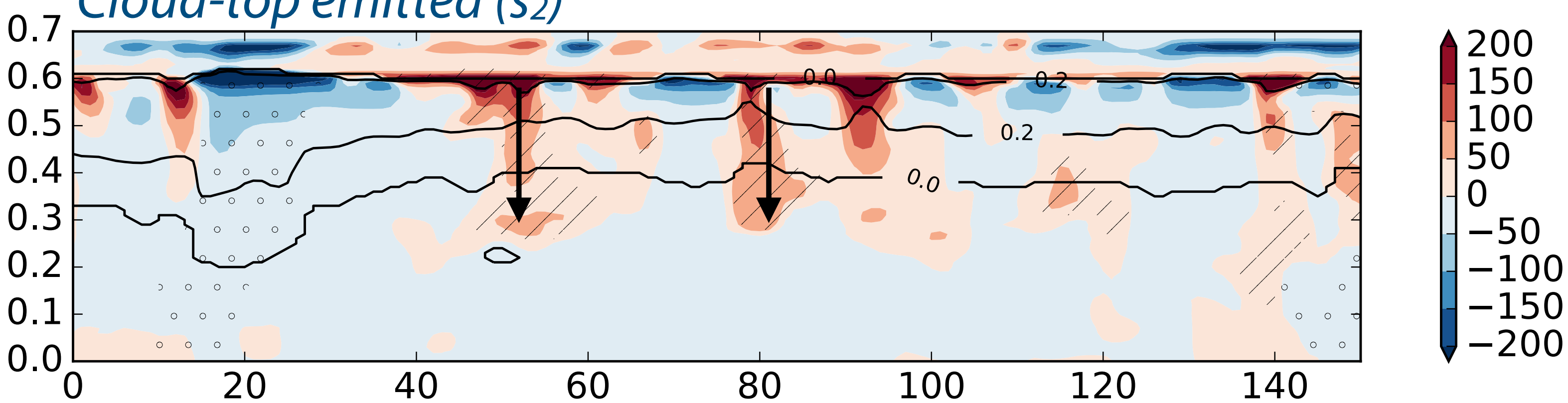


Anomalies of tracer concentration

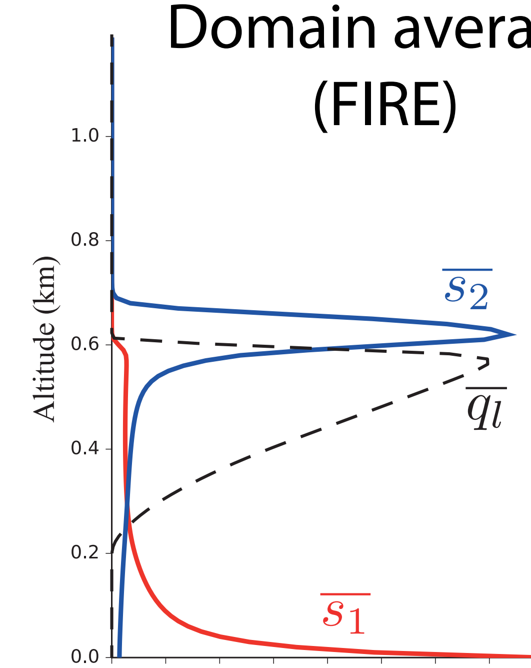
Surface-emitted (s_1)



Cloud-top emitted (s_2)



Domain average (FIRE)



Are these structures coherent in space?

Object-oriented sampling

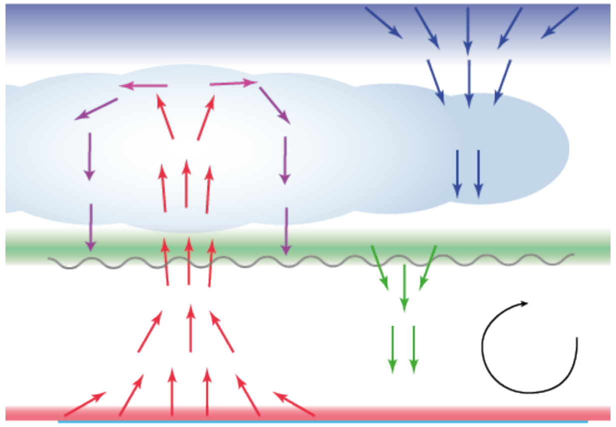
coherent turbulent structures = parts of the flow that have logical interconnections and form a unified whole

Collaborative project: https://gitlab.com/tropics/objects

- *Definition*:

1. Ensemble of grid boxes satisfying the **conditional sampling CS = {*s'(x,y,z)*>*m**σ_s(*z*)}** based on *Couvreux et. al (10)* (with s'(x,y,z) anomalies of tracer concentrations)
2. *Object* = Contiguous cells of positive CS (sharing face, edge, corner)
3. *Selected object* = Object with volume larger than **V_{min}**

- *Advantages:*
  - **3D geometrical coherence**
  - Individual object characterisation
  - No **a priori** assumptions of flow characteristics (ω, q_l)



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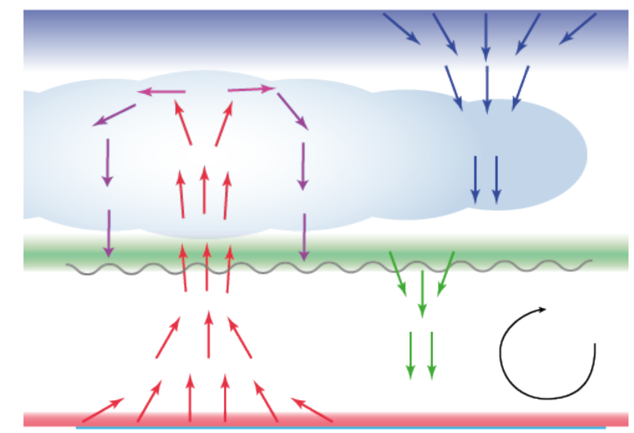

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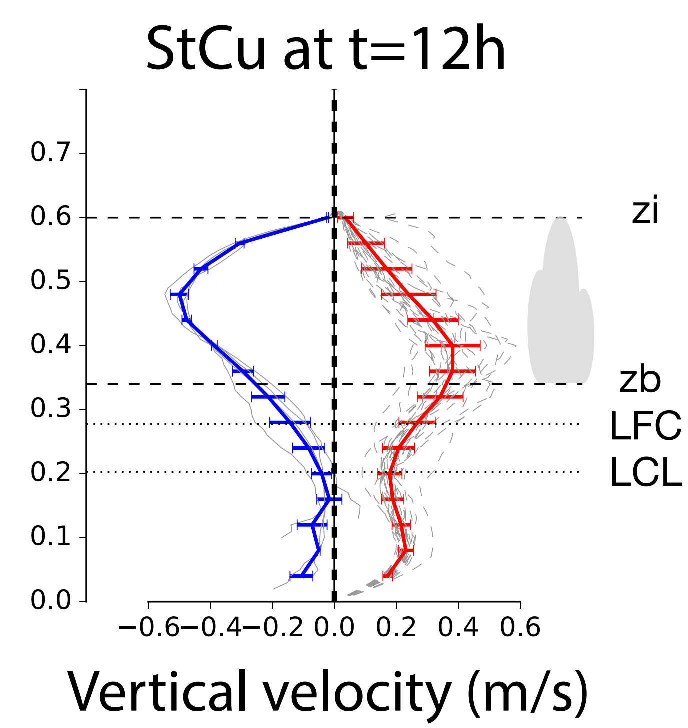
Conclusions of *Brient et. al, 2019 (GRL)* with 2 tracers

In a stratocumulus boundary layer, **coherent downdrafts** contribute to a significant part (40%) of **heat and moisture transport**, while only covering ~10% of the domain volume



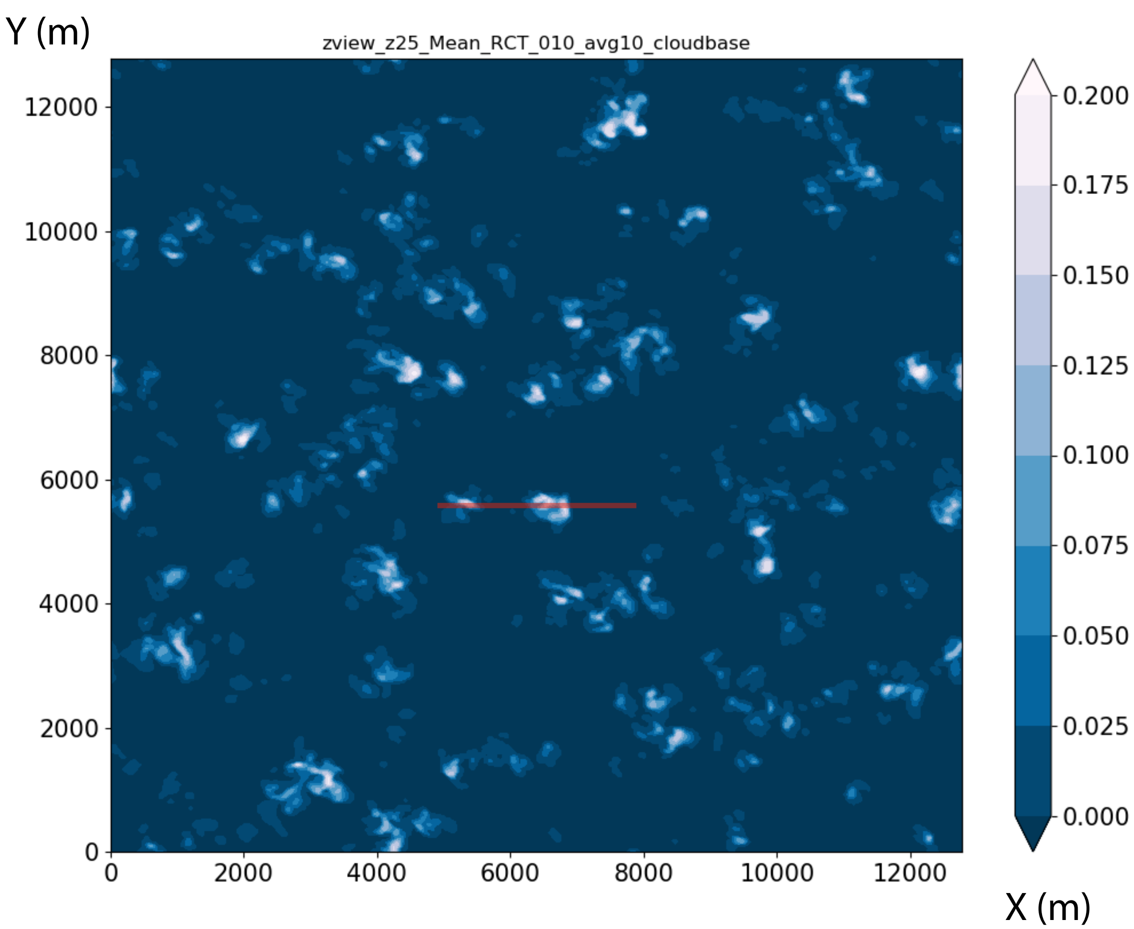
Are coherent structures consistent across atmospheric boundary layers?

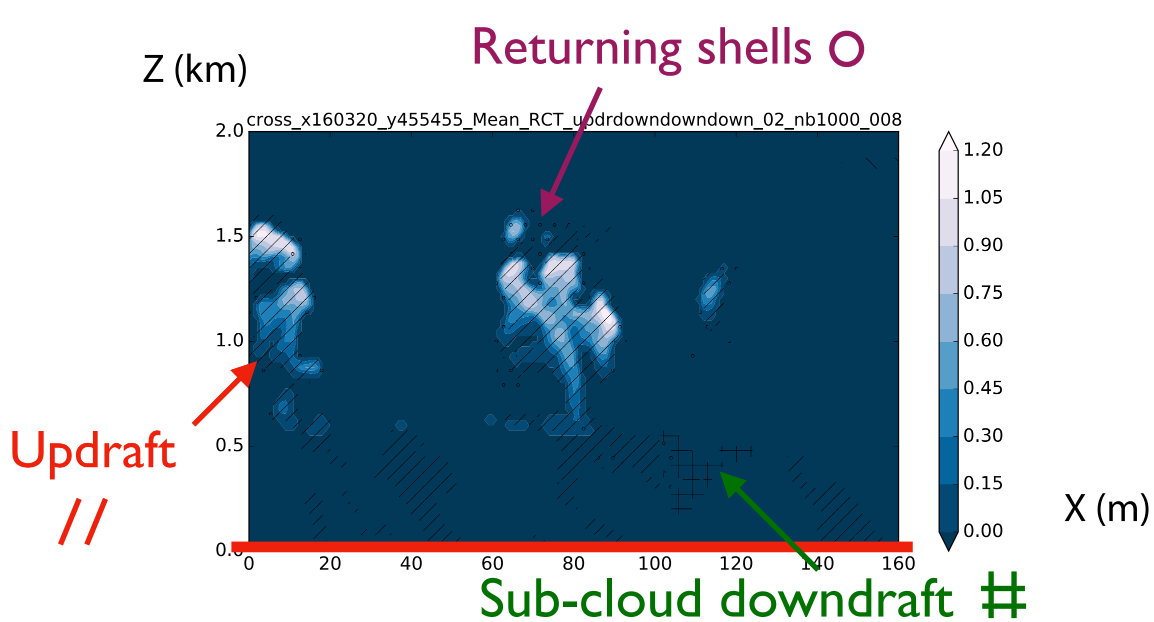
Cumulus boundary layers

BOMEX - t+8h

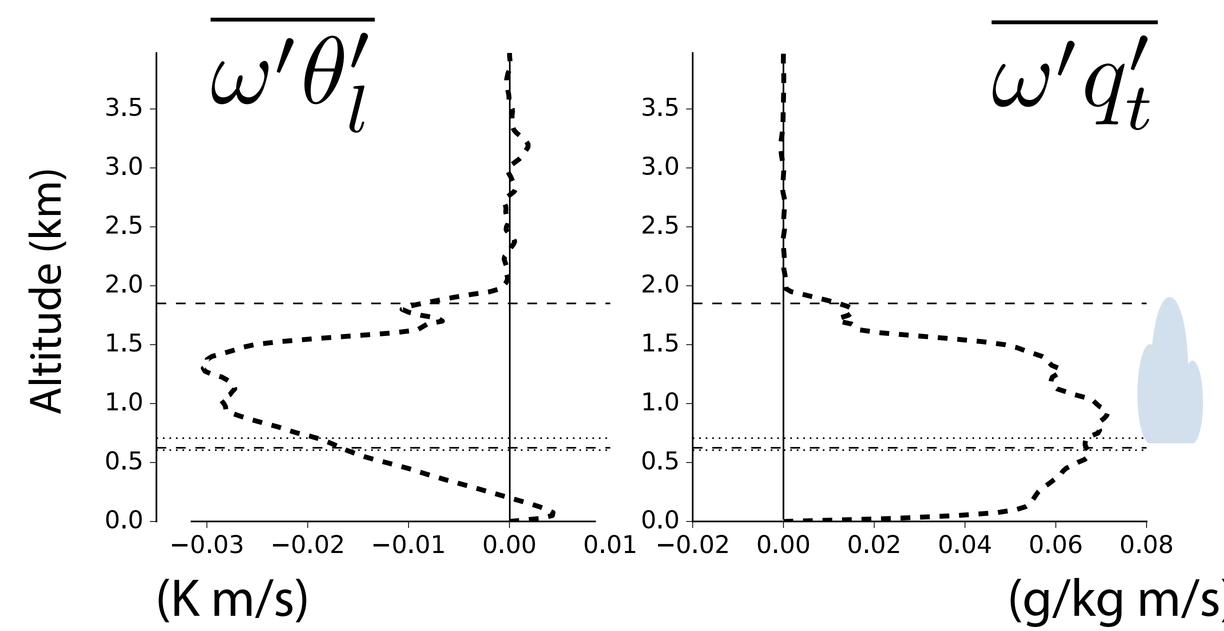
All Structures
Updraft
Entrained downdraft
Sub-cloud downdraft
Returning shells

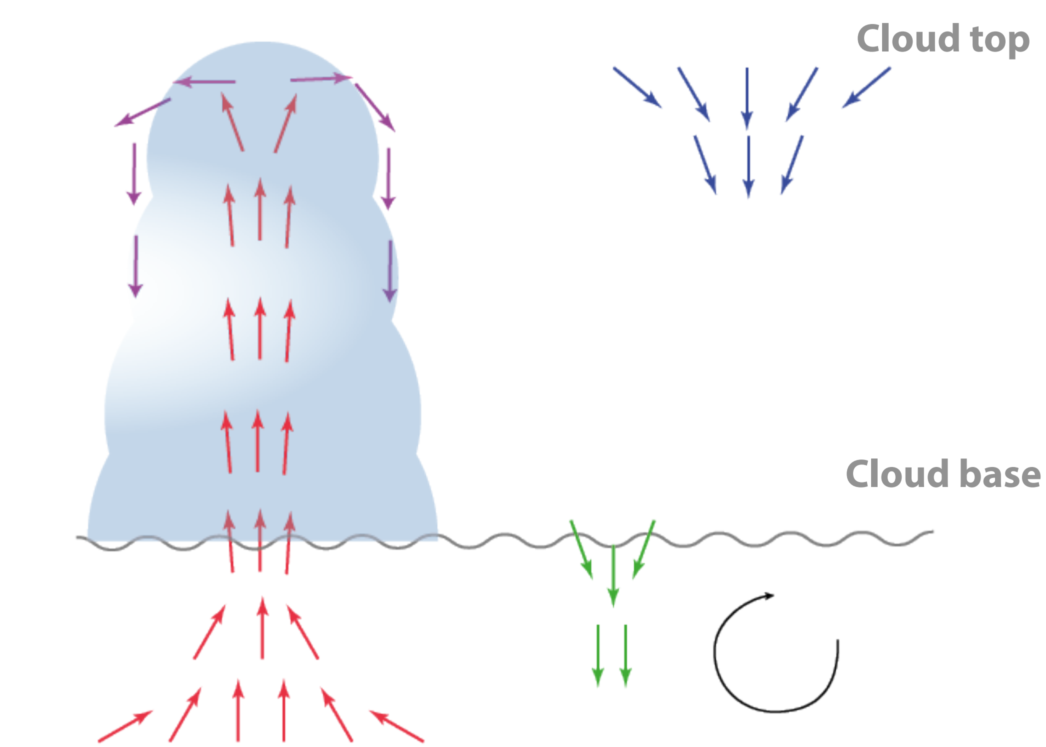
Liquid water content (g/kg)





Domain-mean resolved fluxes -----





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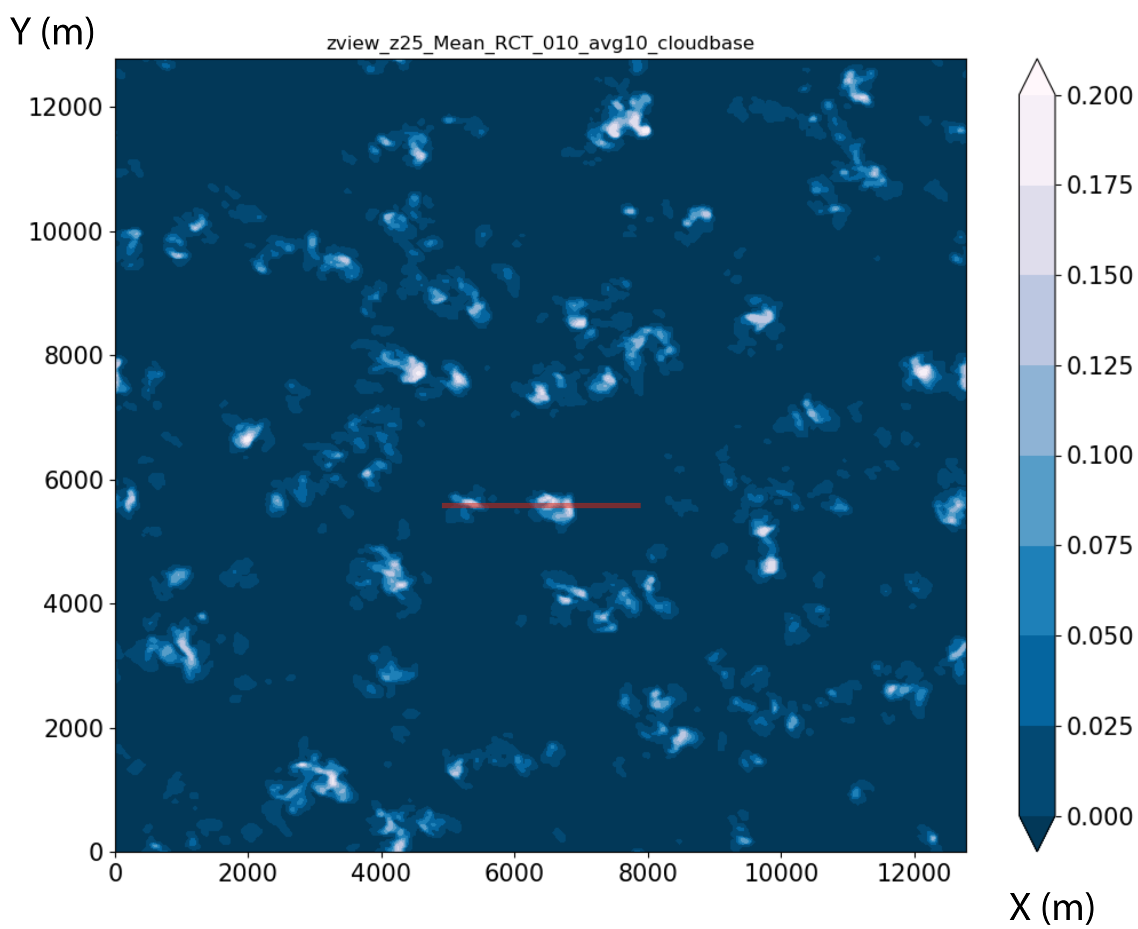
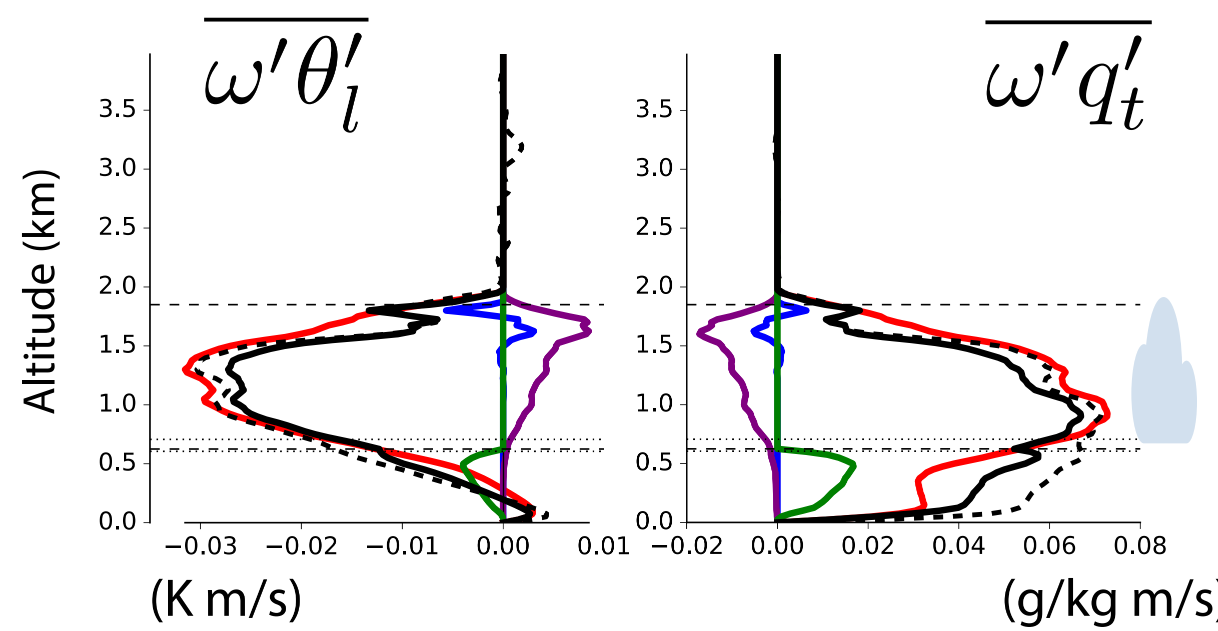
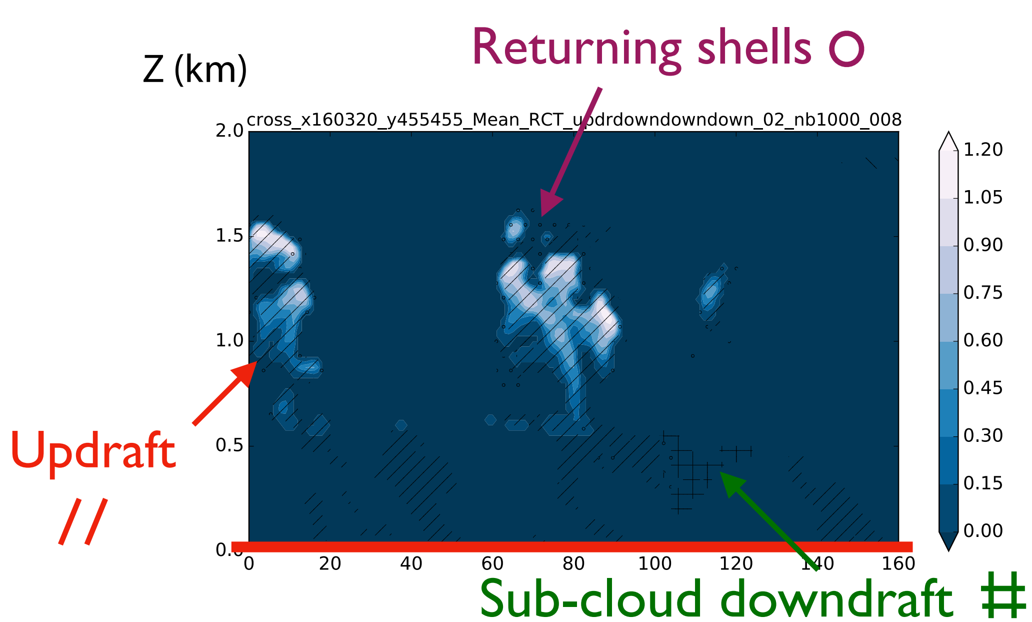


Domain-mean volume:

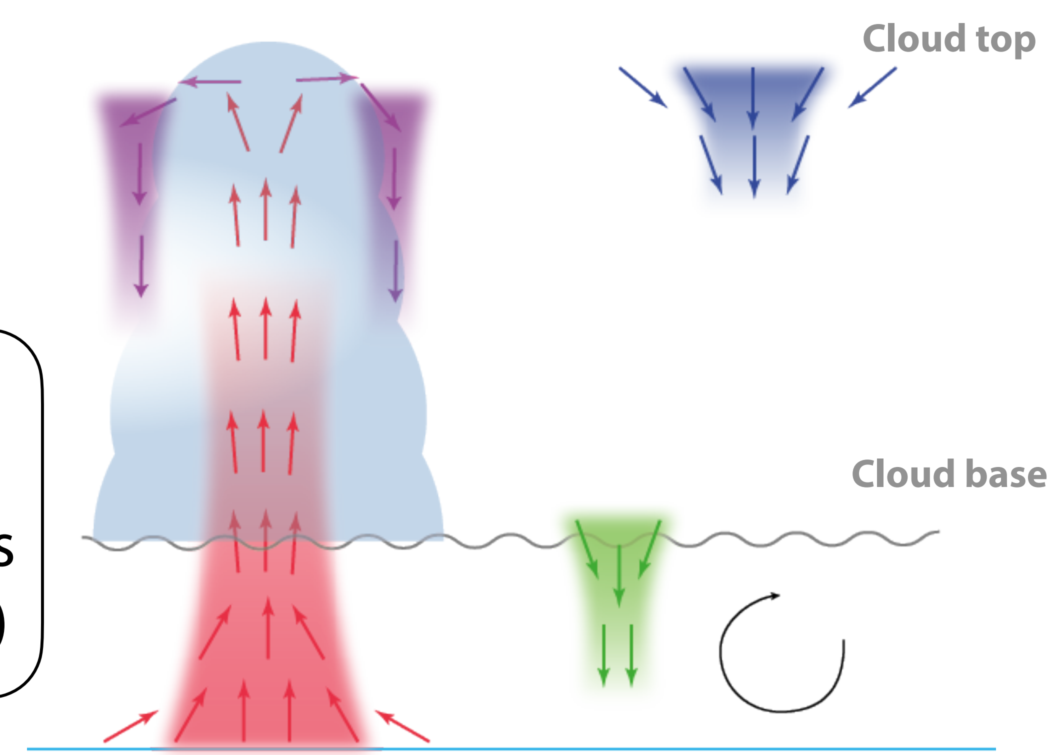
2%
6%
2%
3%

Domain-mean resolved fluxes -----





Objects contribute to **90/85%** of total heat/moisture fluxes (for **13%** of volume)

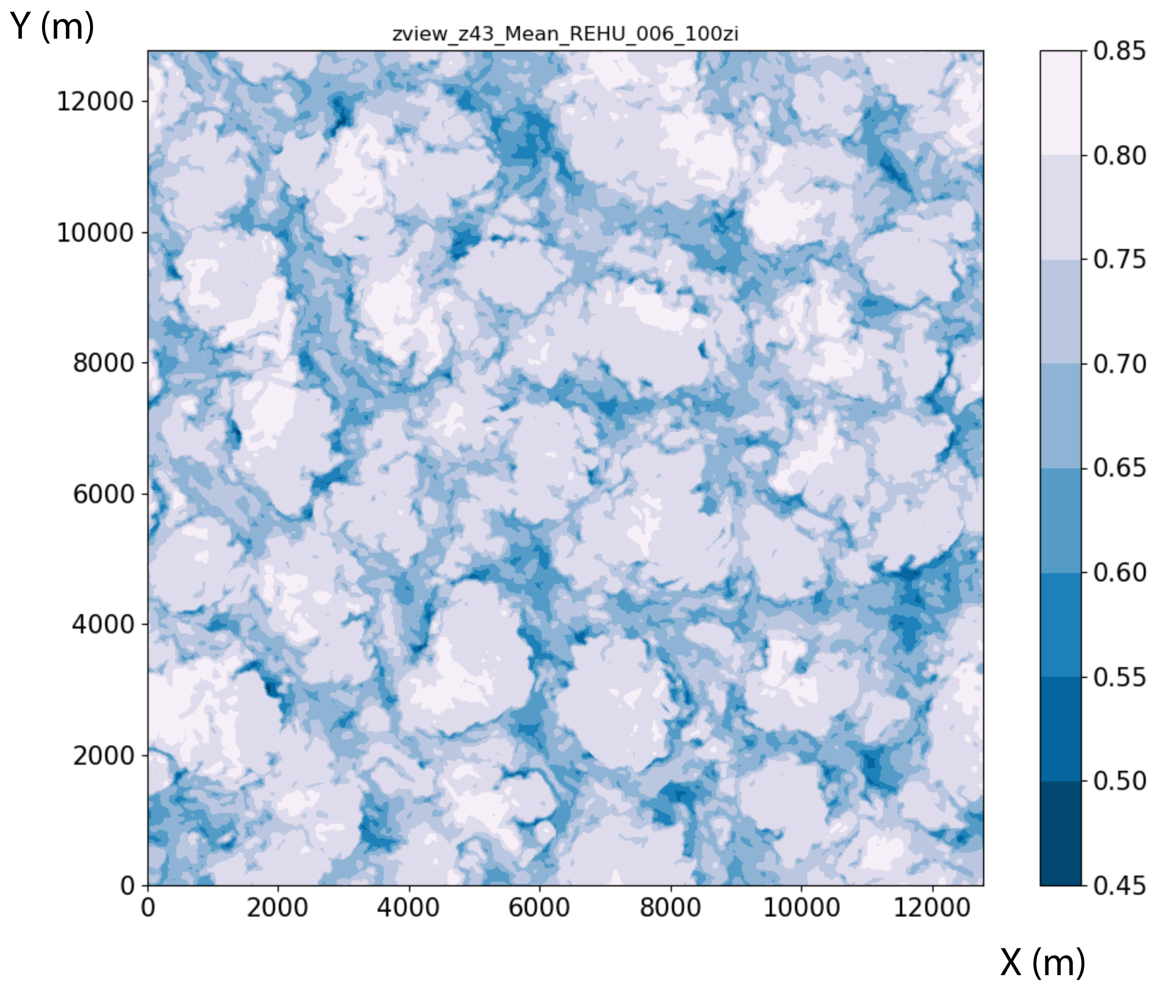


Convective clear-sky boundary layers

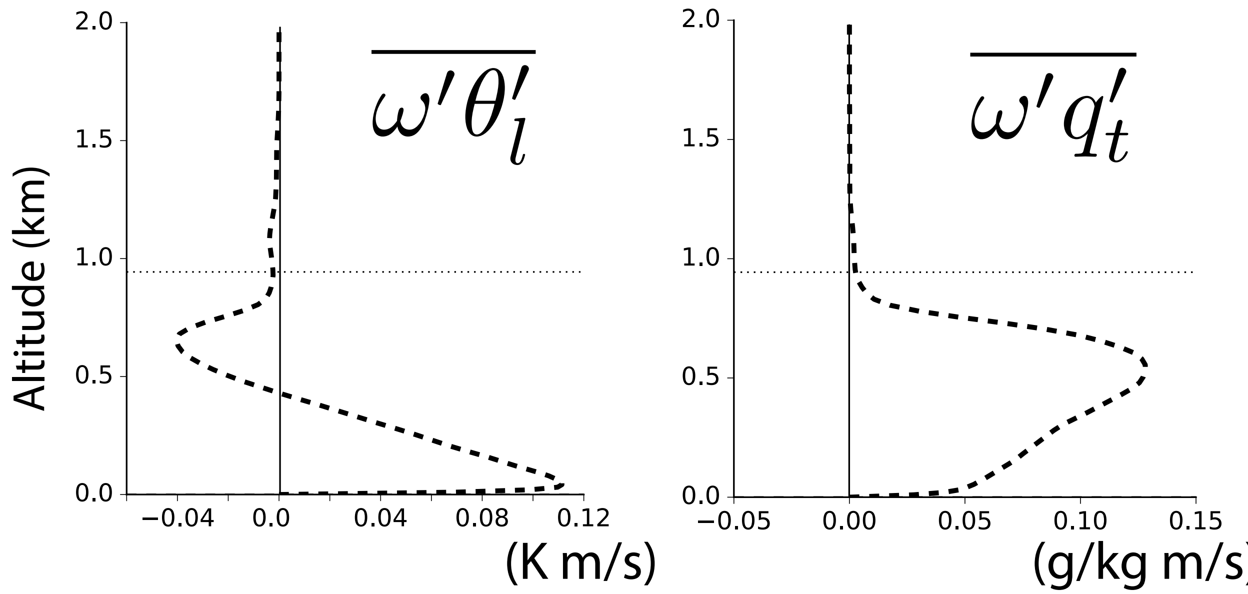
All Structures
Updraft
Entrained downdraft
Returning shells

IHOP t+6h

Relative humidity at the inversion (-)



Domain-mean resolved fluxes -----



Convective clear-sky boundary layers

All Structures
Updraft
Entrained downdraft
Returning shells

IHOP t+6h

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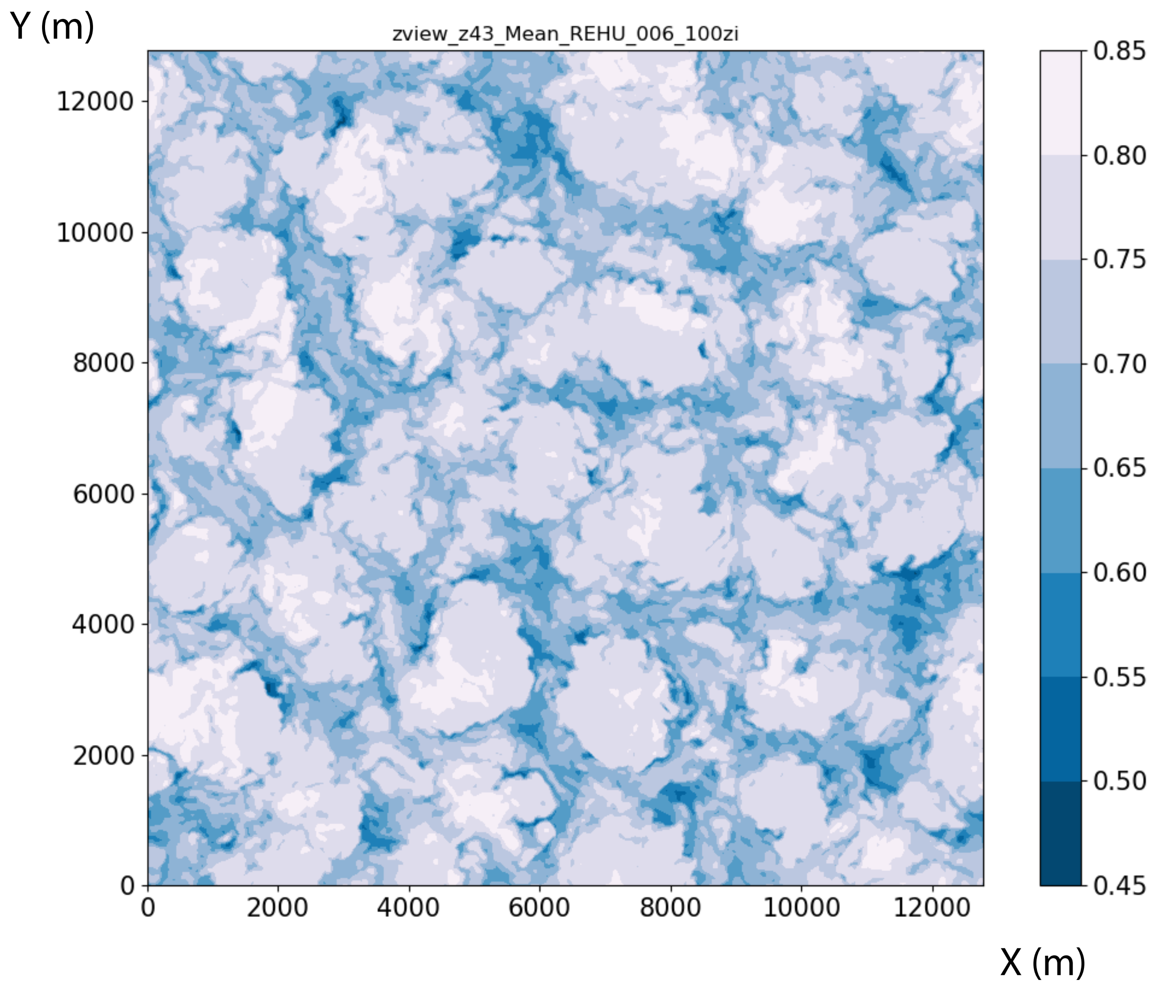
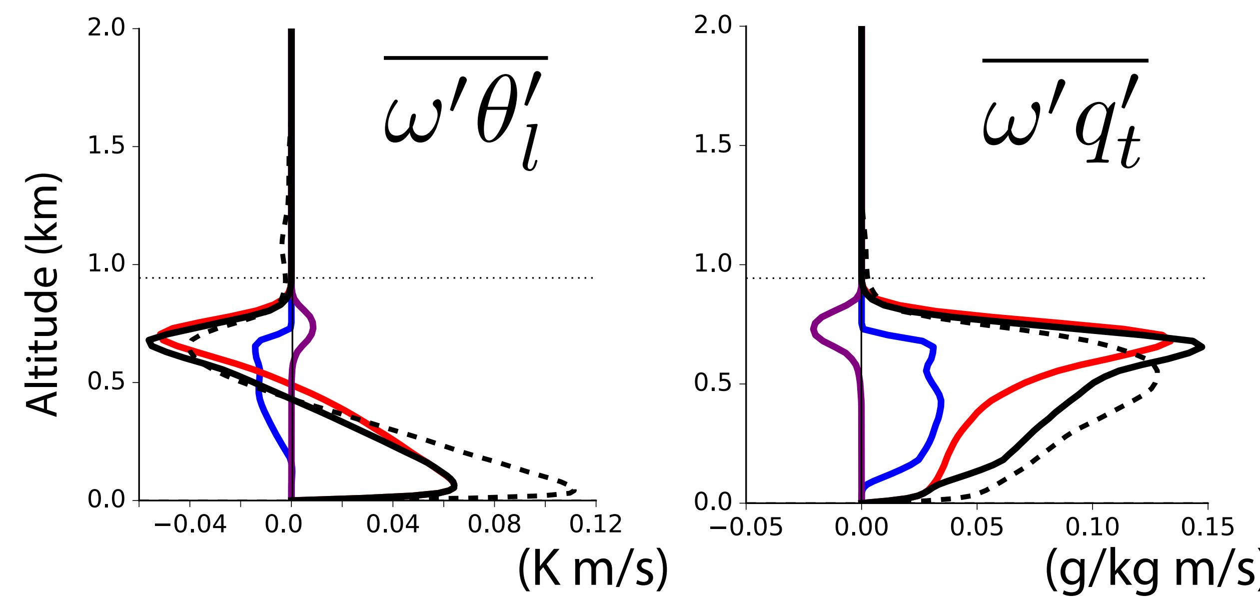
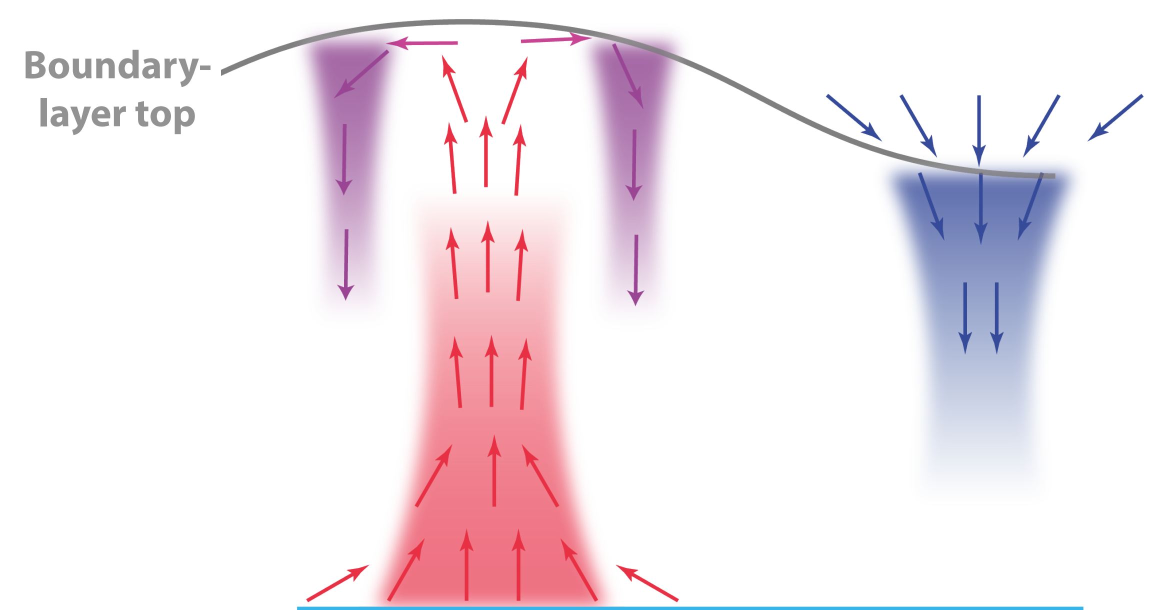


Domain-mean volume:

1%
13%
11%

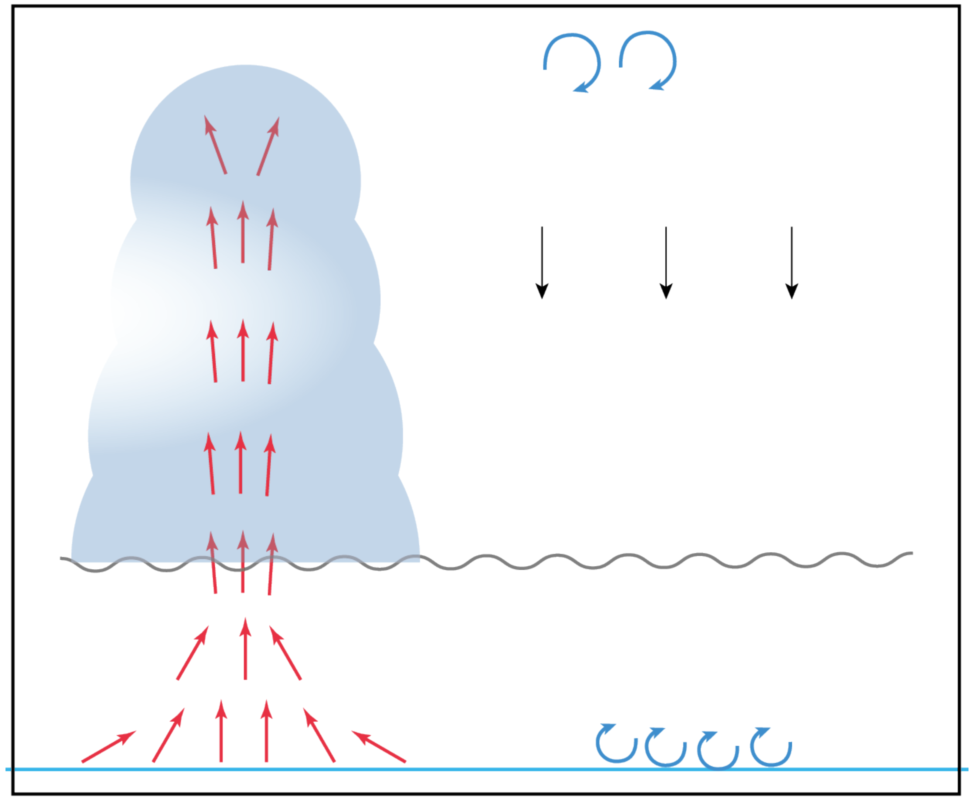
Domain-mean resolved fluxes -----





- **Objects** contribute to **74/86%** of total heat/moisture fluxes (for **25%** of volume)
- **Similarities** with Rayleigh-Benard cells (aspect ratio ~2) with a entraining layer

What does it mean for parameterization?



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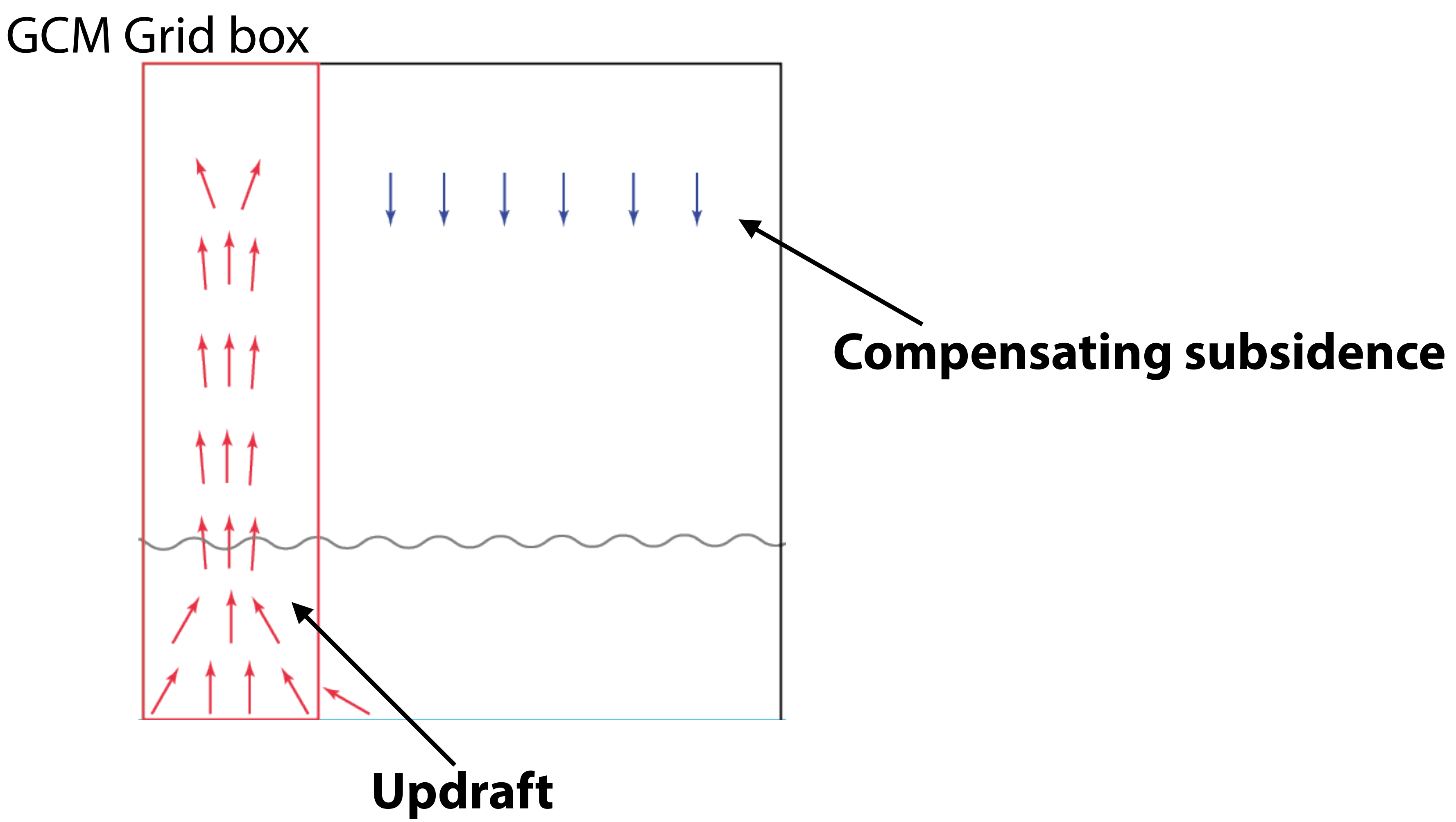
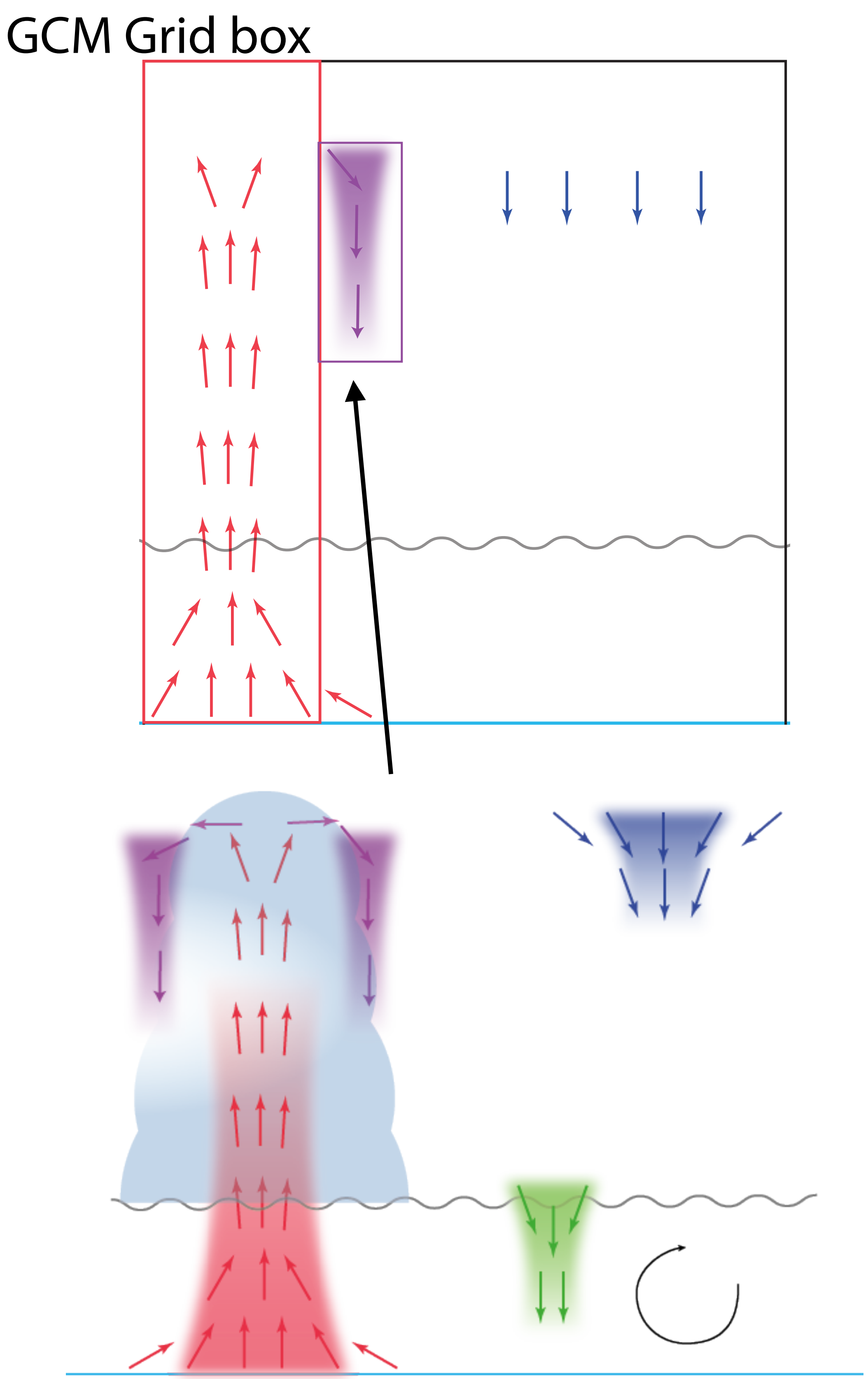


Aspect ratio = updraft size / grid size

What does it mean for parameterization?



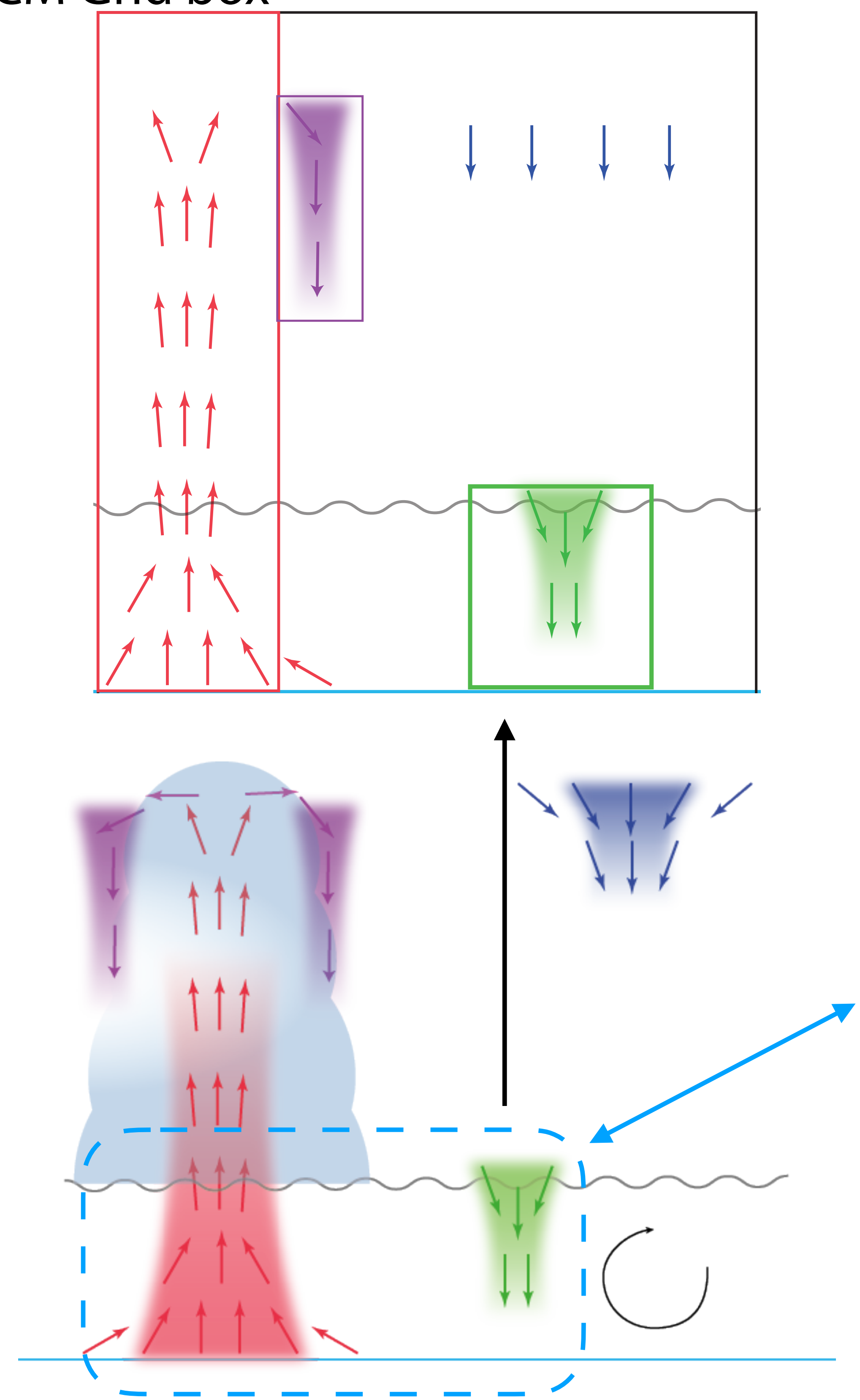
Coherent structures

Subsiding shells contribute to transport of heat/moisture in the cloud layer. This process might already be included by a updraft parameterisation

Do subsiding shells influence the sub-cloud energy budget by bringing <u>moist and cold air</u> back below the cloud base?

What does it mean for parameterization?

GCM Grid box



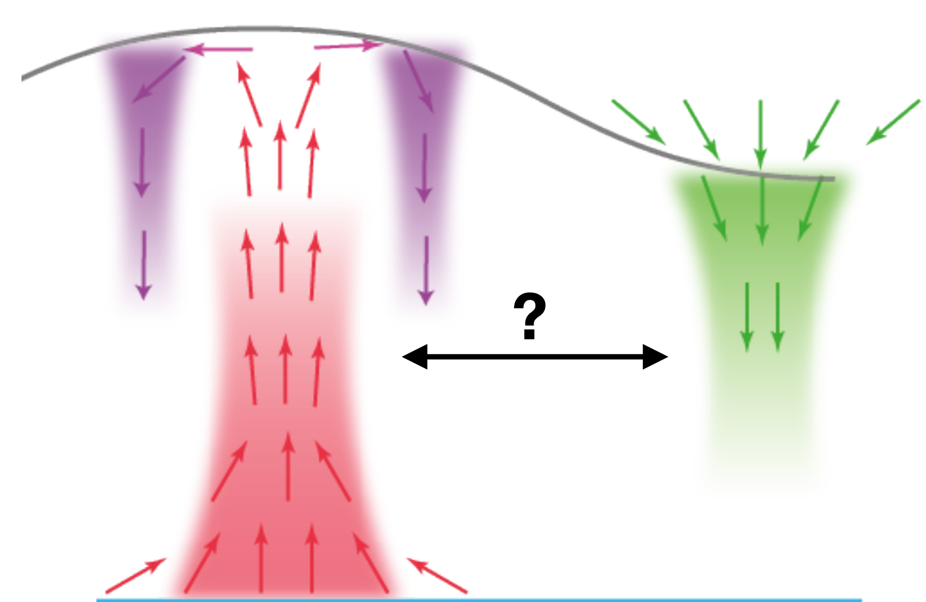
Coherent structures

Sub-cloud downdrafts contribute to around **20% of transport** of heat and moisture in the sub-cloud layer

Sub-cloud downdrafts entrain dry and warm air from the free troposphere to the sub-cloud layer (Importance for sub-cloud energy budget)

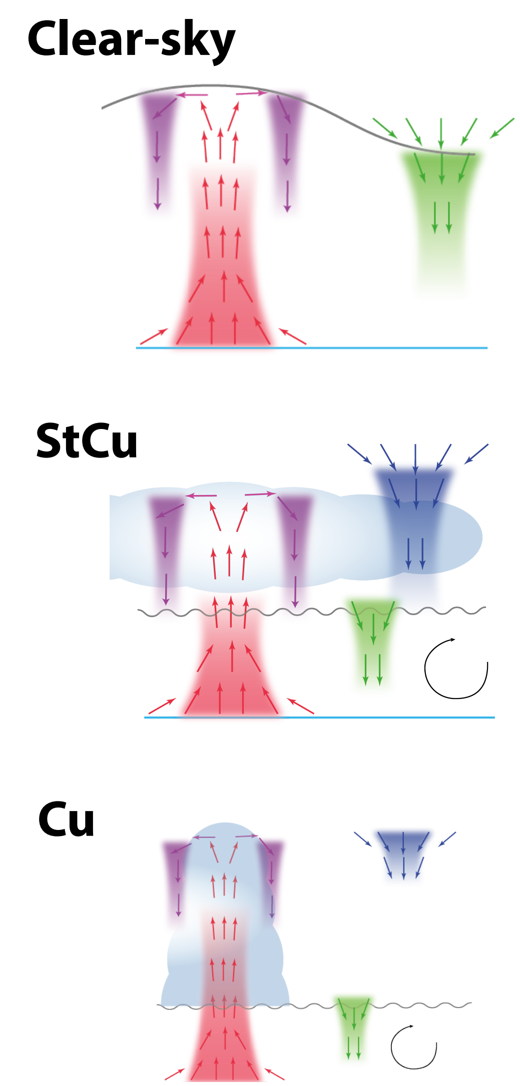
Should the sub-cloud layer be represented through a convective **clear-sky** overturning circulation?

Convective Clear Sky (IHOP)



Conclusions

Identifying coherent structures in LES provides an ideal framework to analyse the **boundary-layer dynamics**



Coherent structures contribute to 70-90% of resolved fluxes

Updrafts contribute the most to heat and moisture transport

Downdrafts contribute significantly to transport only in StCu

Well-mixed downdrafts exist below the cloud base and ressemble coherent downdrafts of convective clear-sky situations (IHOP)

Returning shells are close to updrafts but contribute only to ~10% of fluxes

Future work about boundary-layer coherent structures:

- Process-oriented analysis of the meso-scale boundary-layer organisation

  Buoyancy reversal, Rayleigh-Benard cells, pression force, gravity waves

- Building better unified parameterizations for low-clouds

  How should coherent downward motions be represented ?

- Low-cloud morphology feedback

  How will coherent structures change with global warming ?