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

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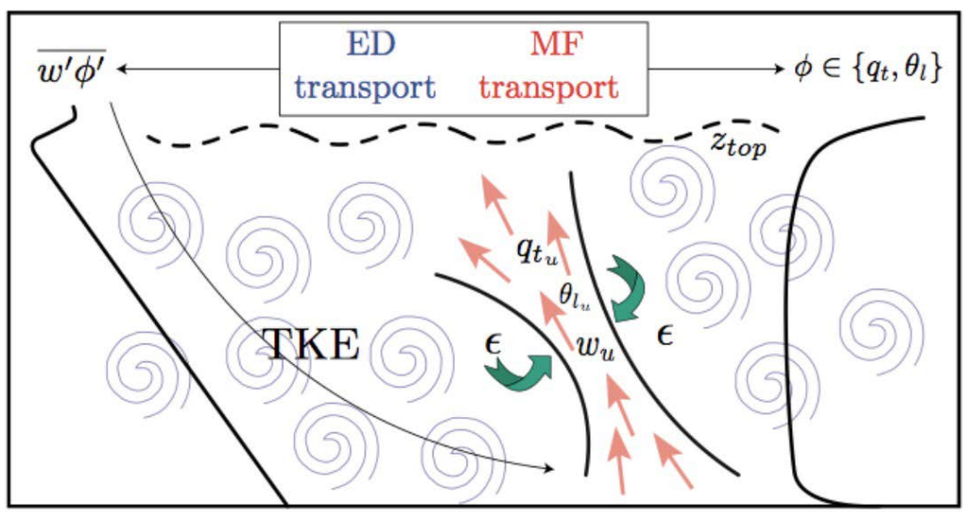
CNRM/Météo-France/CNRS

Representing the boundary layer in climate models

resolved *parameterized*

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

Turbulent and convective vertical transport



Witek et. al 11

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…

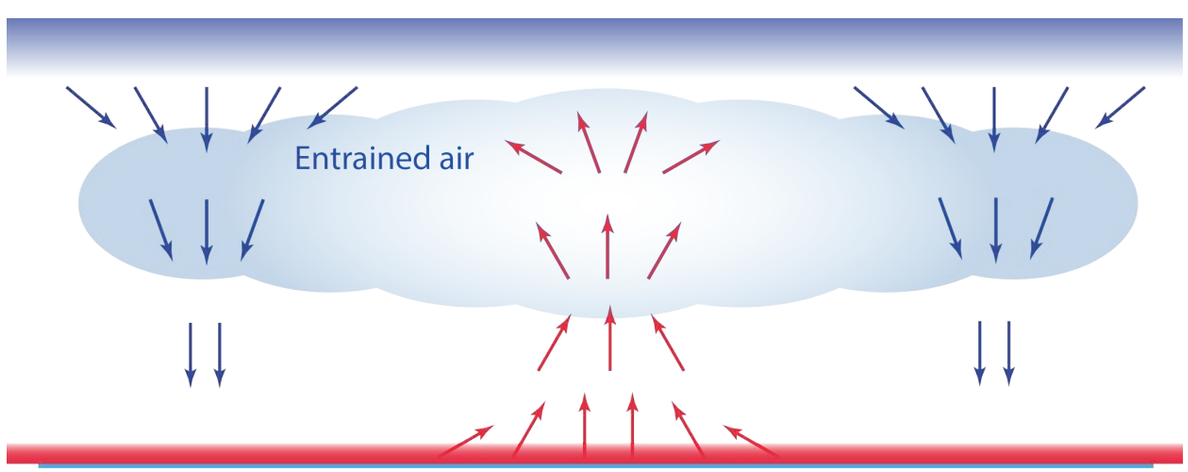
—> Investigating **coherent structures** in Large Eddy Simulations for better understanding of PBL motions (MESO-NH model)

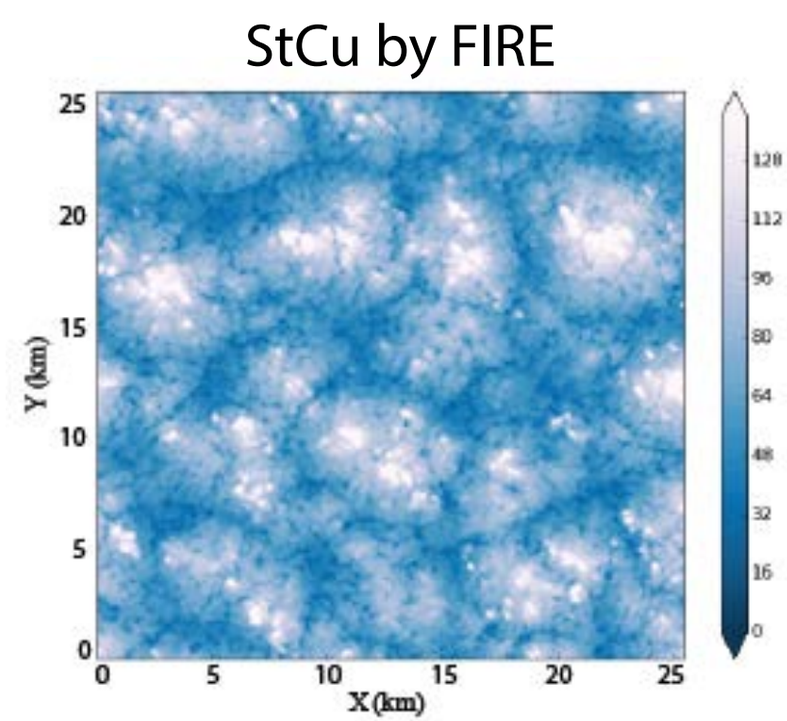
Object-oriented sampling

- *Definition of coherent structures* :

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}

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





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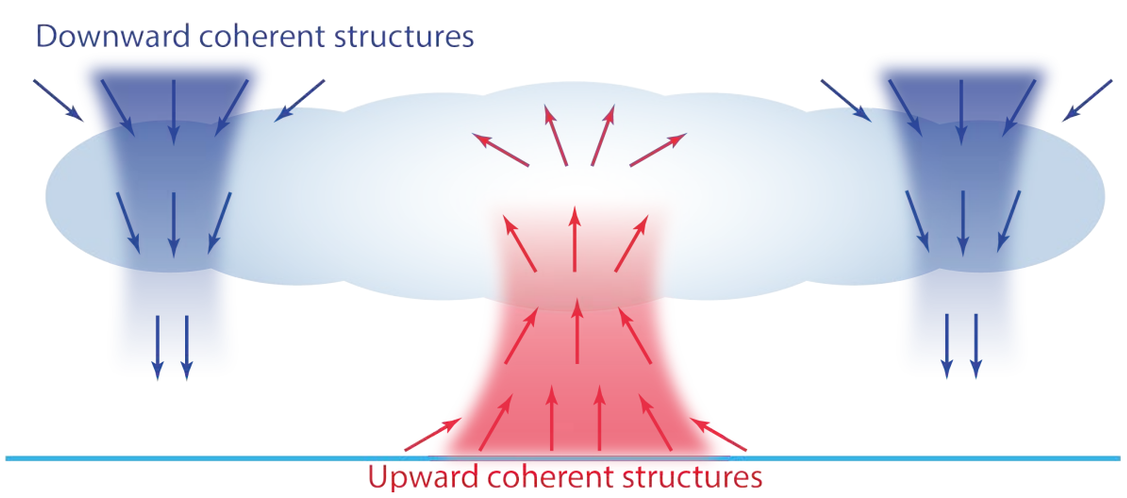
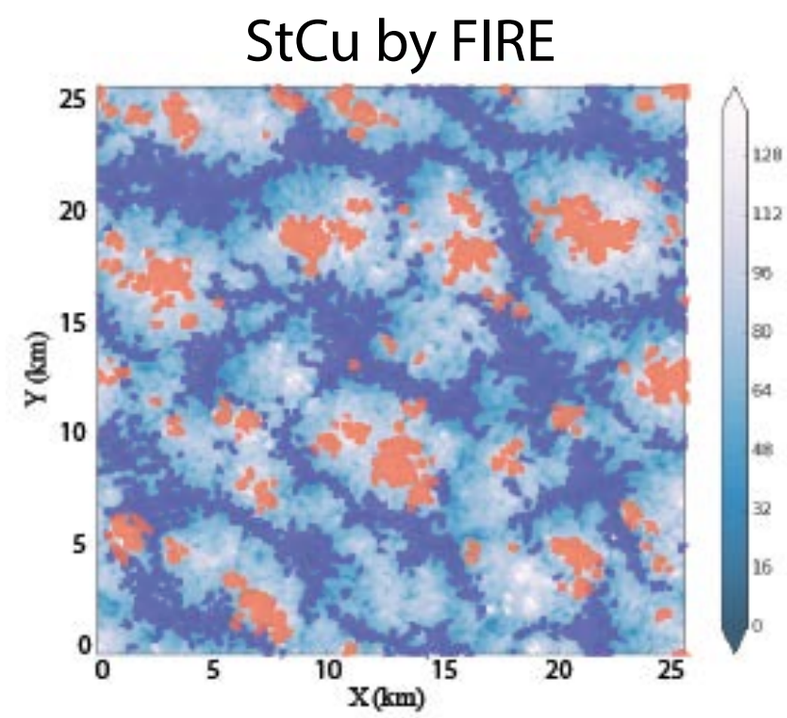
- *Advantages:*
  - **3D geometrical coherence**
  - Individual object characterisation
  - No **a priori** assumptions of flow characteristics (ω, q_l)

- *Main results for StCu*:
  - Objects cover **20%** of the volume, but contribute to **~80%** of moisture and temperature resolved fluxes
  - **Coherent downdrafts** matter !

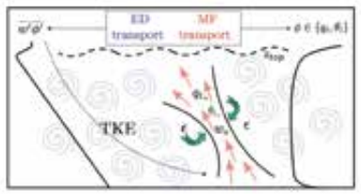
Brient et. al, 19 (GRL)





A diversity of boundary-layer situations

Are coherent structures consistent across boundary layers?

	Clear-sky	Stratus/Fog	Stratocumulus	St-to-Cu	Cumulus
					
Marine					
Continental					

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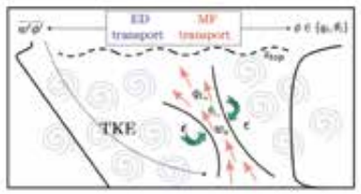
Microphysics Warm Cold	Clear-sky	Stratus/Fog	Stratocumulus	St-to-Cu	Cumulus
					
Marine		*CGILS (s12)*	FIRE DYCOMS	ASTEX *CONSTRAIN*	RICO BOMEX
Continental	IHOP AYOTTE				ARMCu

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	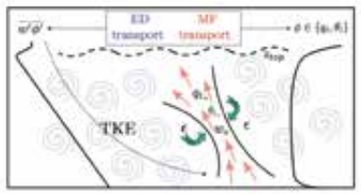				
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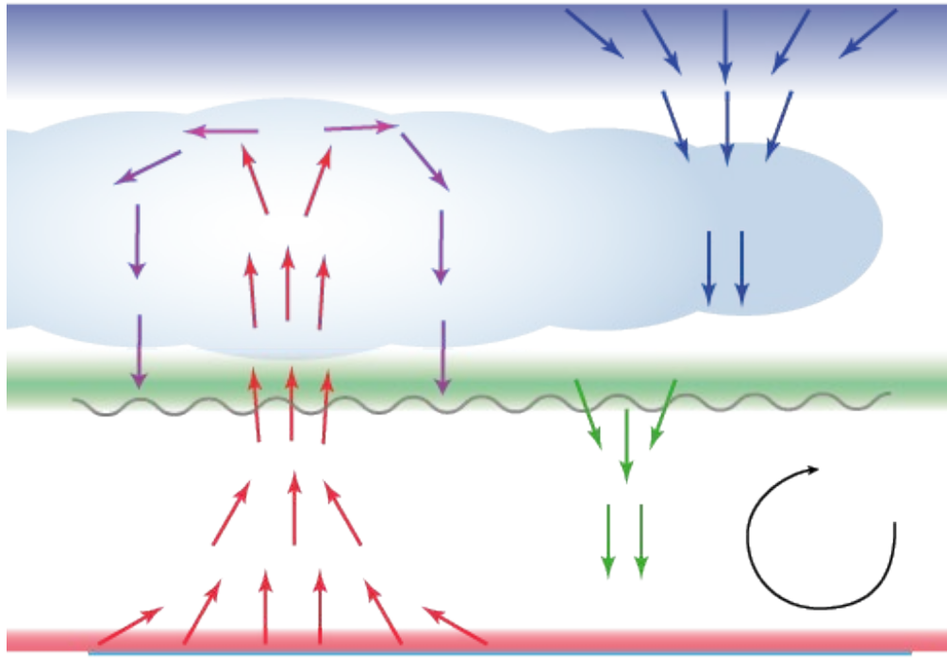
Update since Brient et. al (19):

- A new tracer emitted above the domain-average cloud base —> Tracking structures entrained in the mixed layer
- Updrafts are separated by positive/negative vertical motions —> Returning shells
- Definition of "PBL-top" tracers for clear skies

First layer where:

$$\theta_v(z) > \int_0^z \theta_v(z)dz + 0.25$$



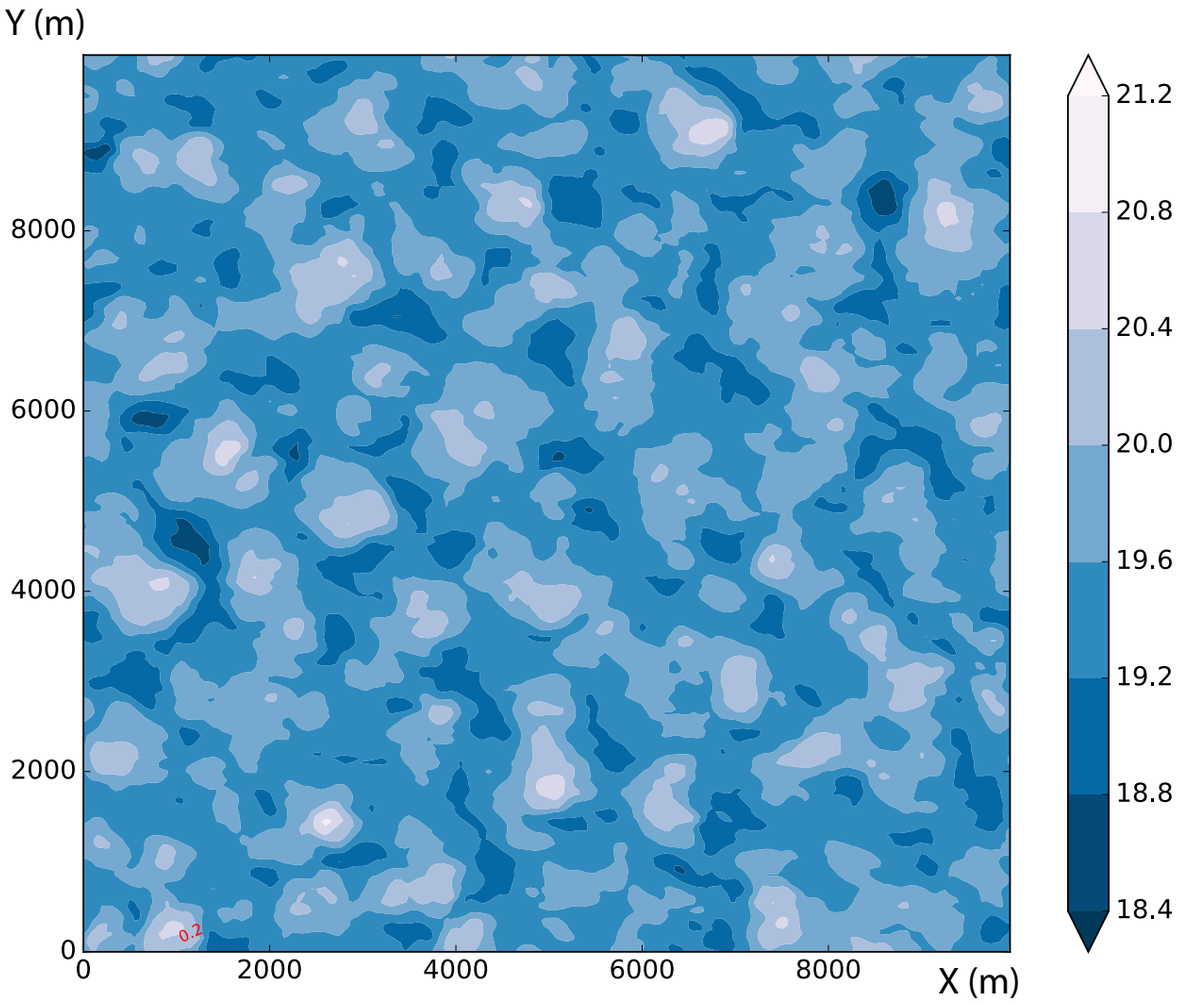
Characteristics of boundary layers

All Structures
Updraft
Entrained downdraft

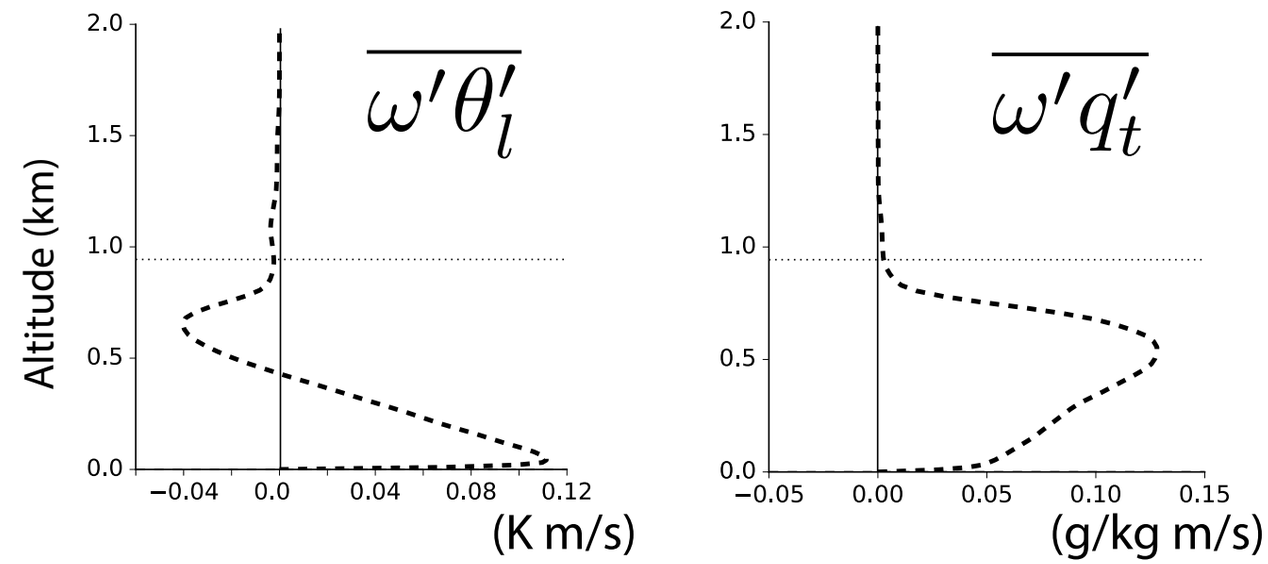
Returning shells

Convective Clear Sky (IHOP)

Mean Precipitable Water (mm/day)



Domain-mean resolved fluxes -----



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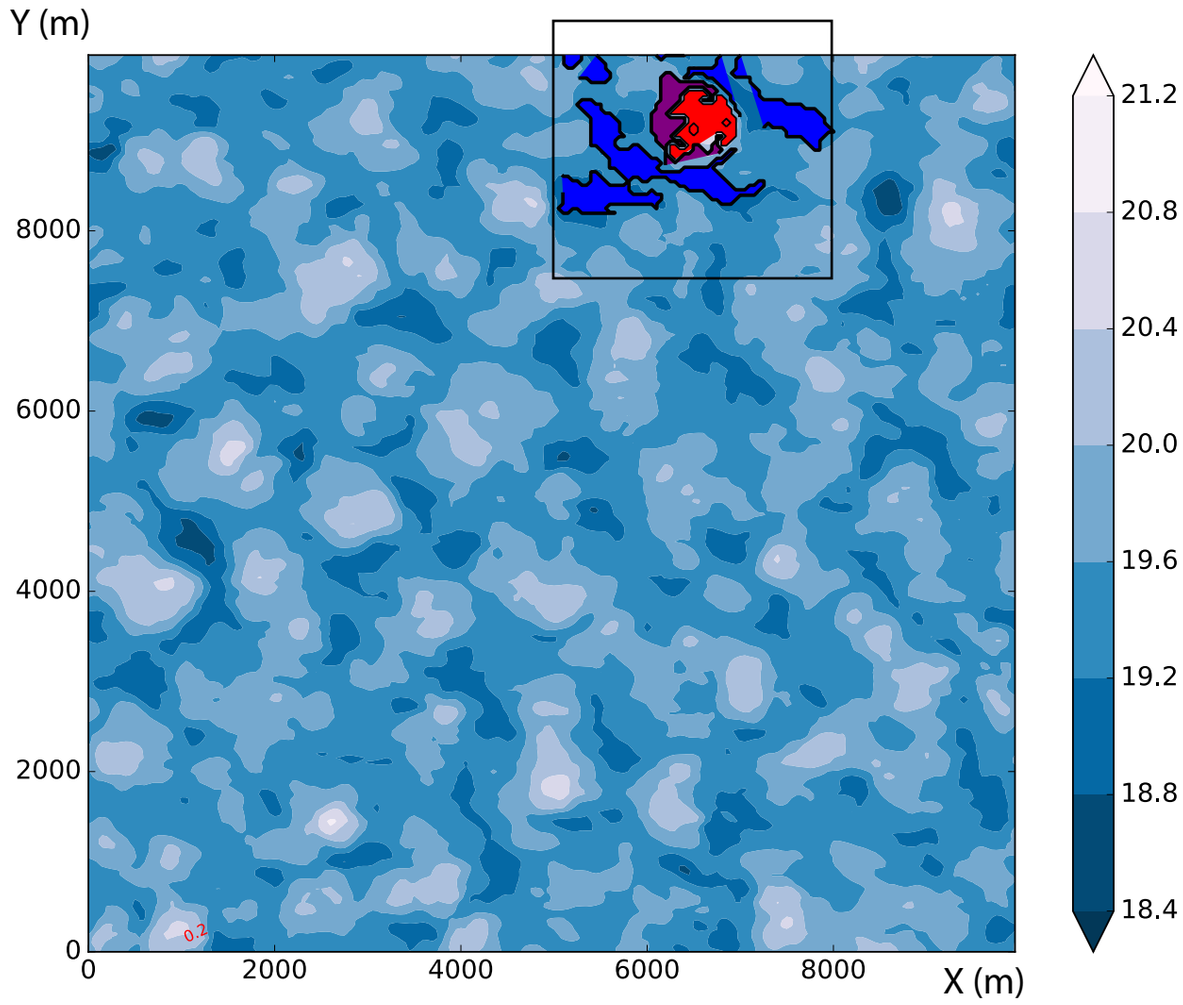

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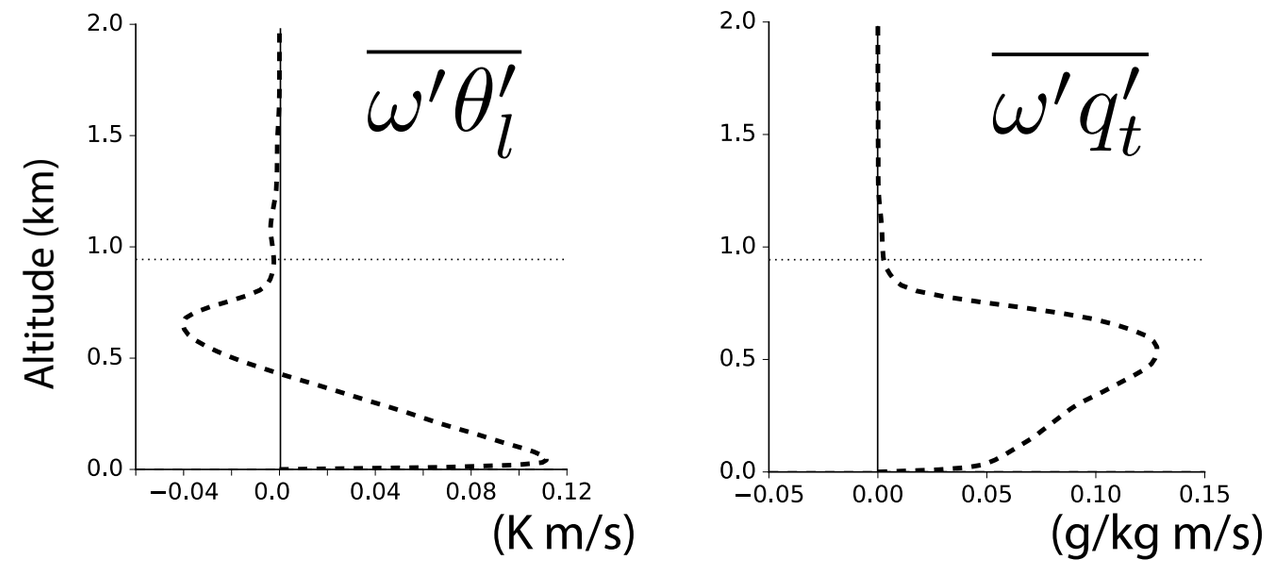

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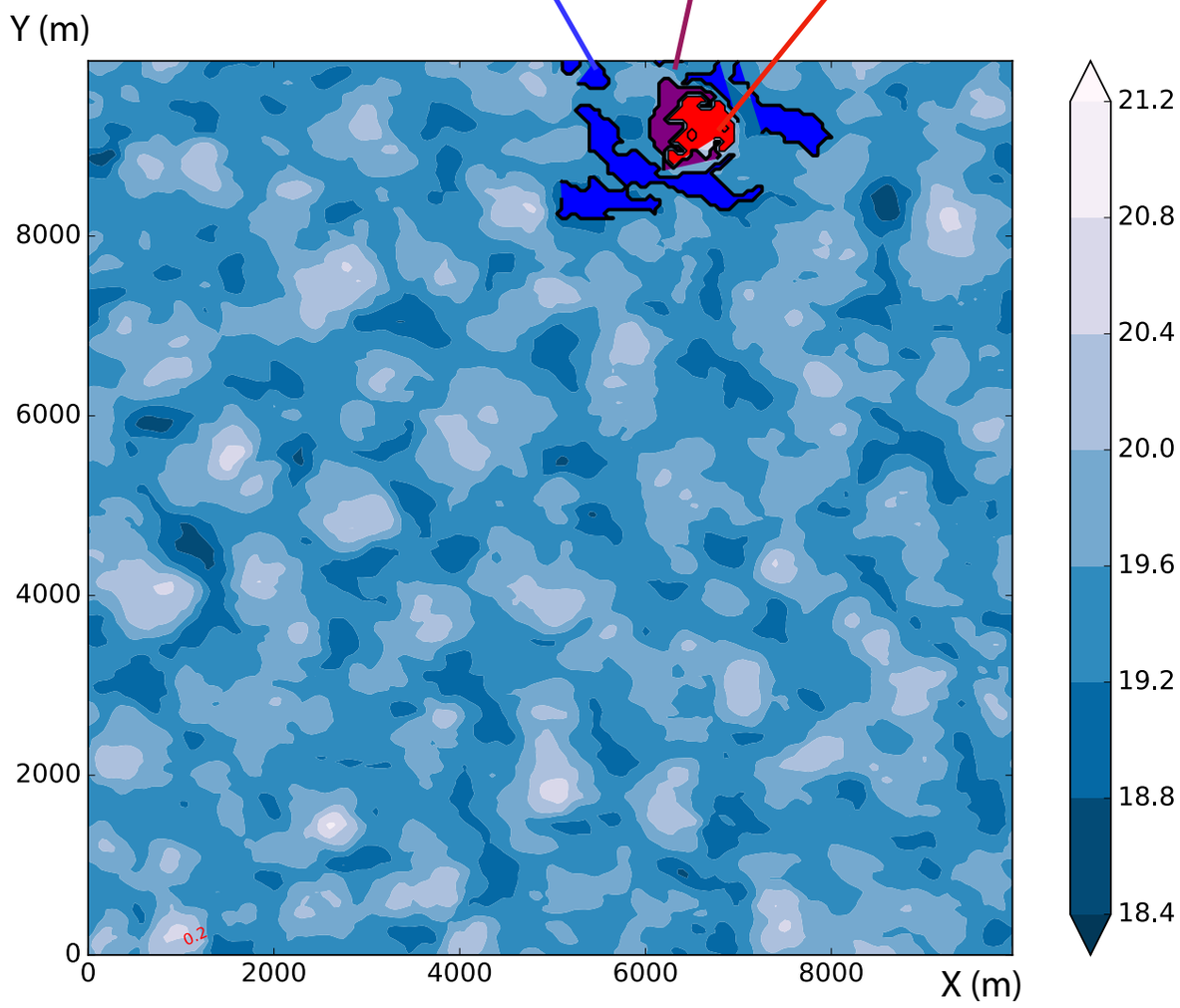
Convective Clear Sky (IHOP)

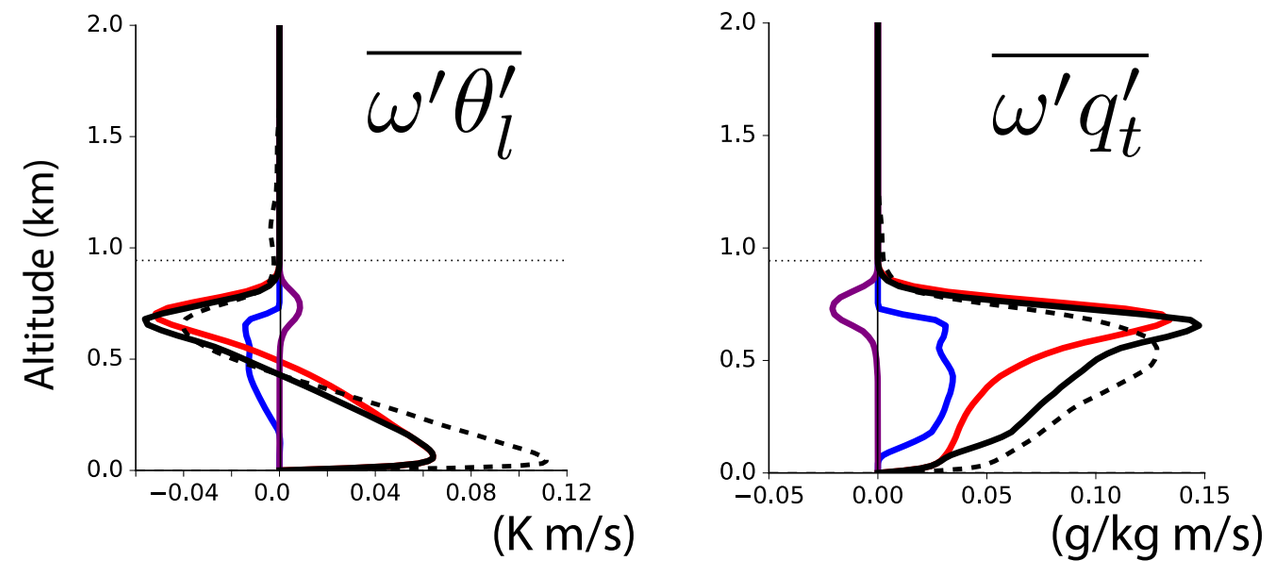
Domain-mean volume

11% 1% 13%

Mean Precipitable Water (mm/day)



Domain-mean resolved fluxes -----



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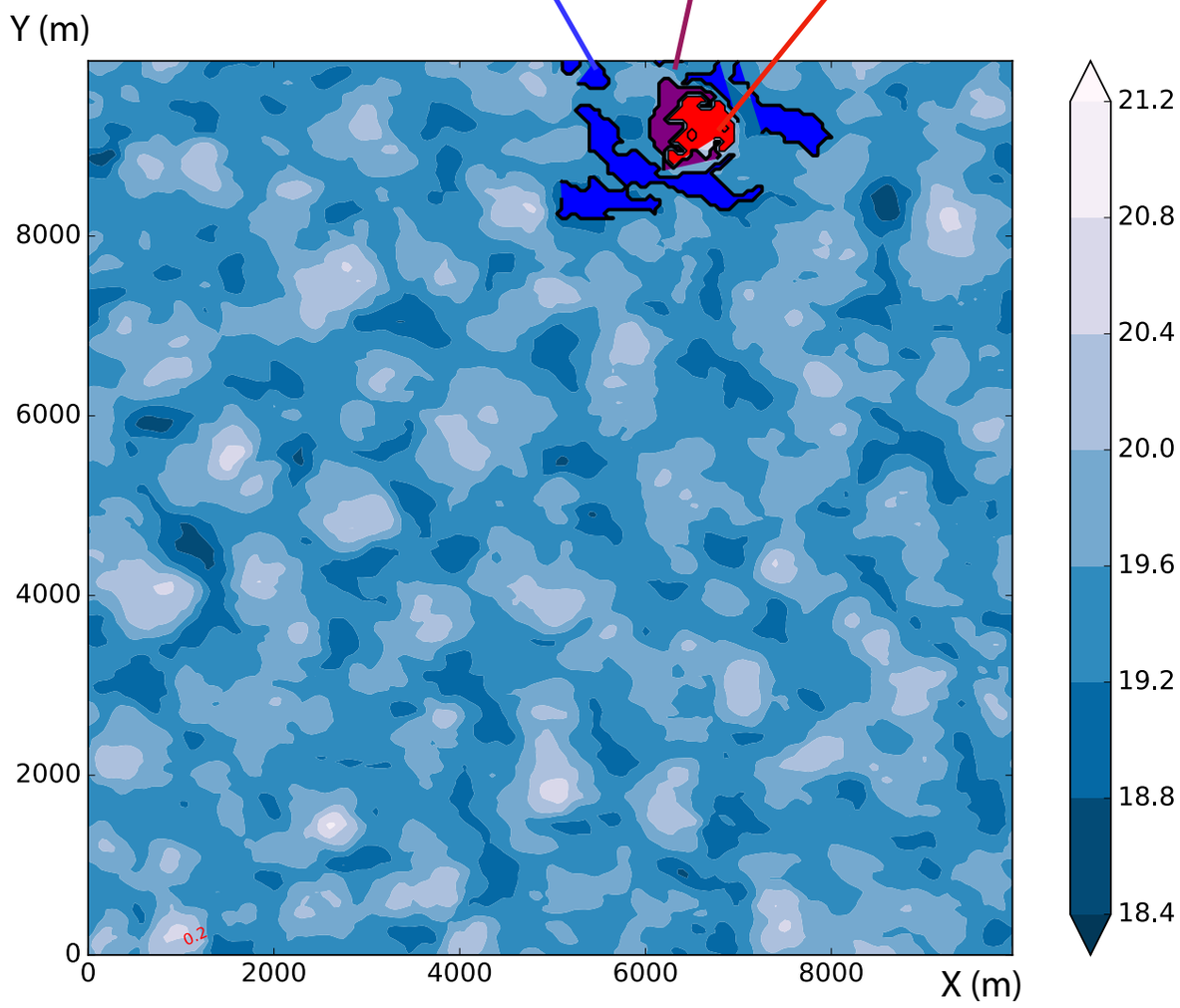
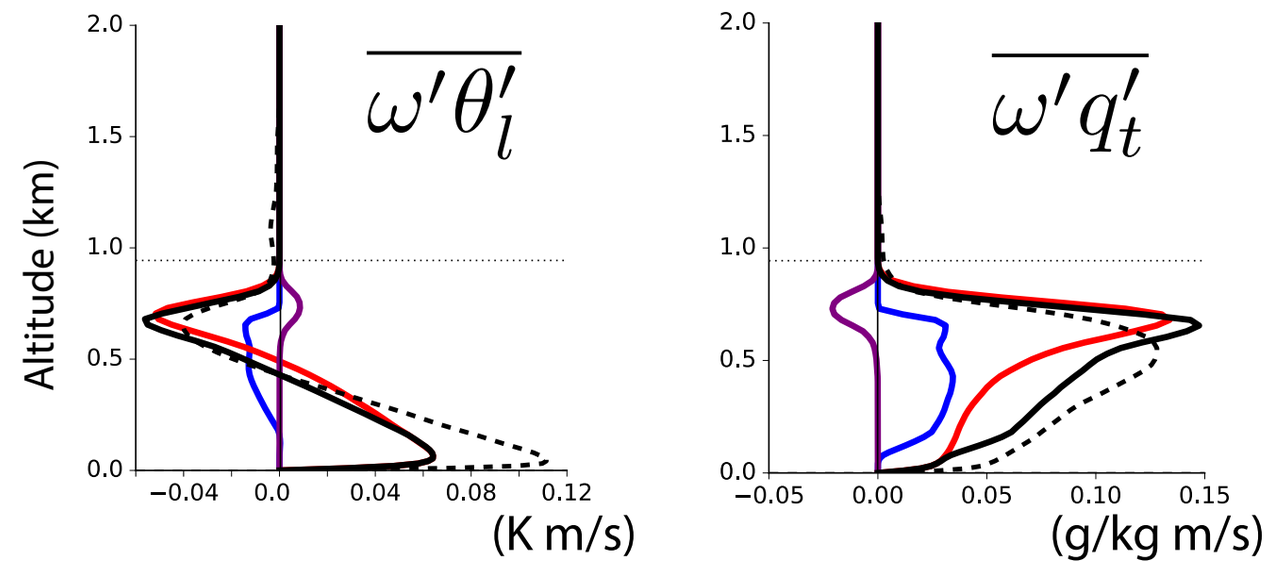
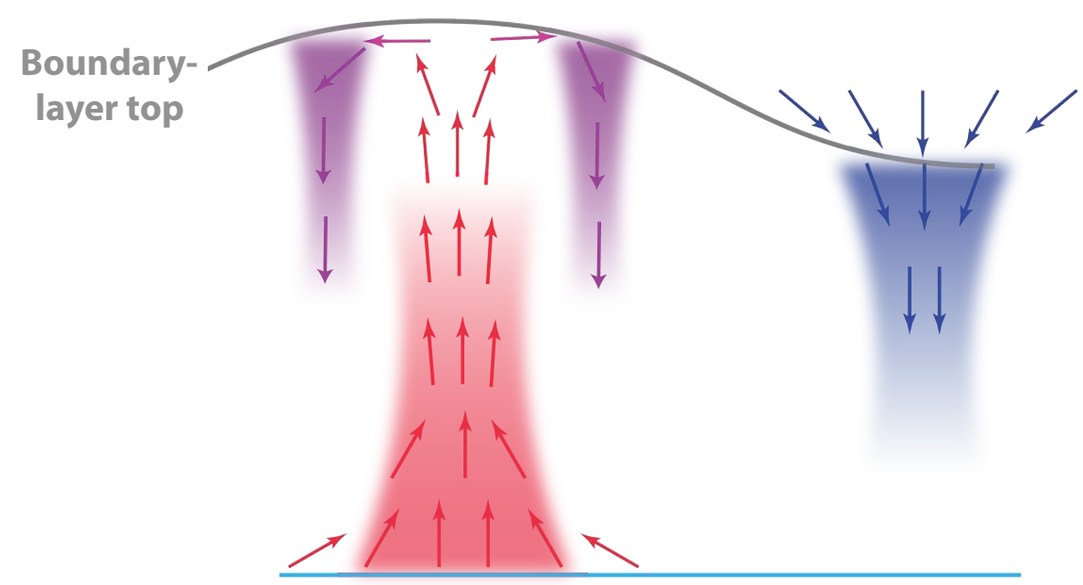


Domain-mean resolved fluxes -----





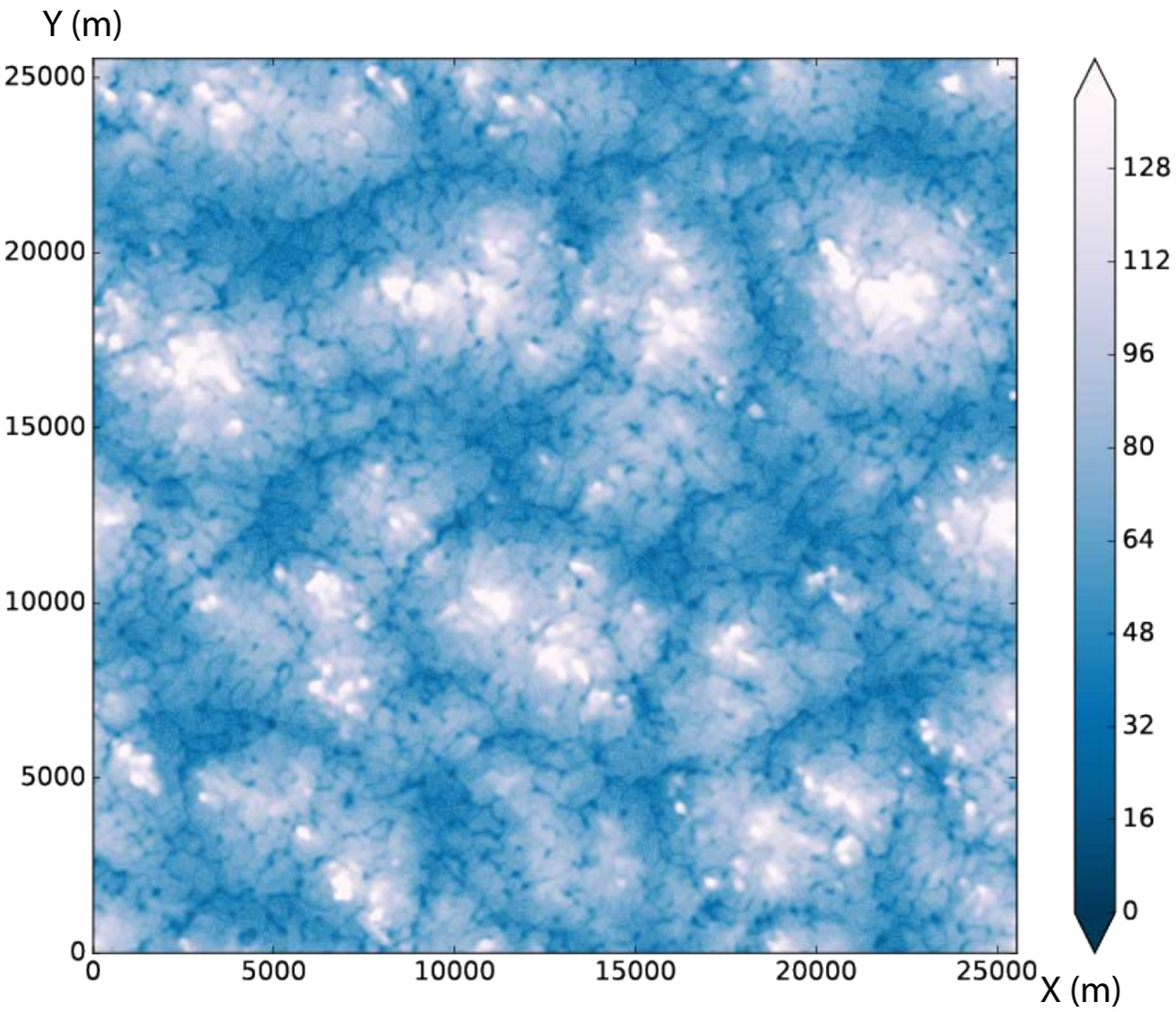
- **Objects** contribute to **74/86%** of total heat/moisture fluxes (for **25%** of volume)

Characteristics of boundary layers

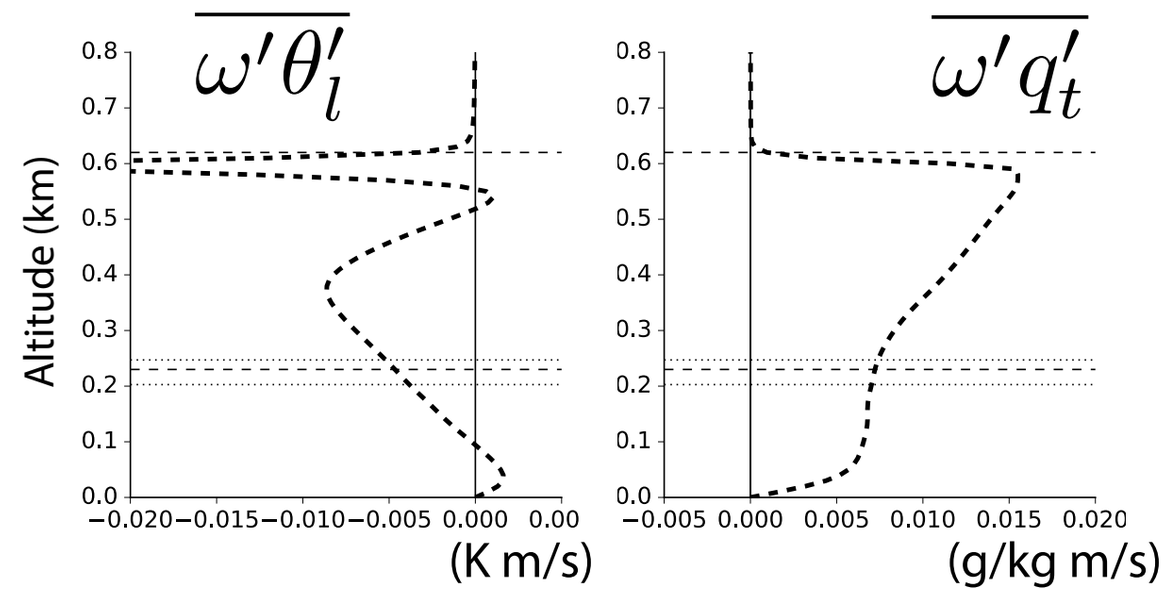
All Structures
Updraft
Entrained downdraft
Sub-cloud downdraft
Returning shells

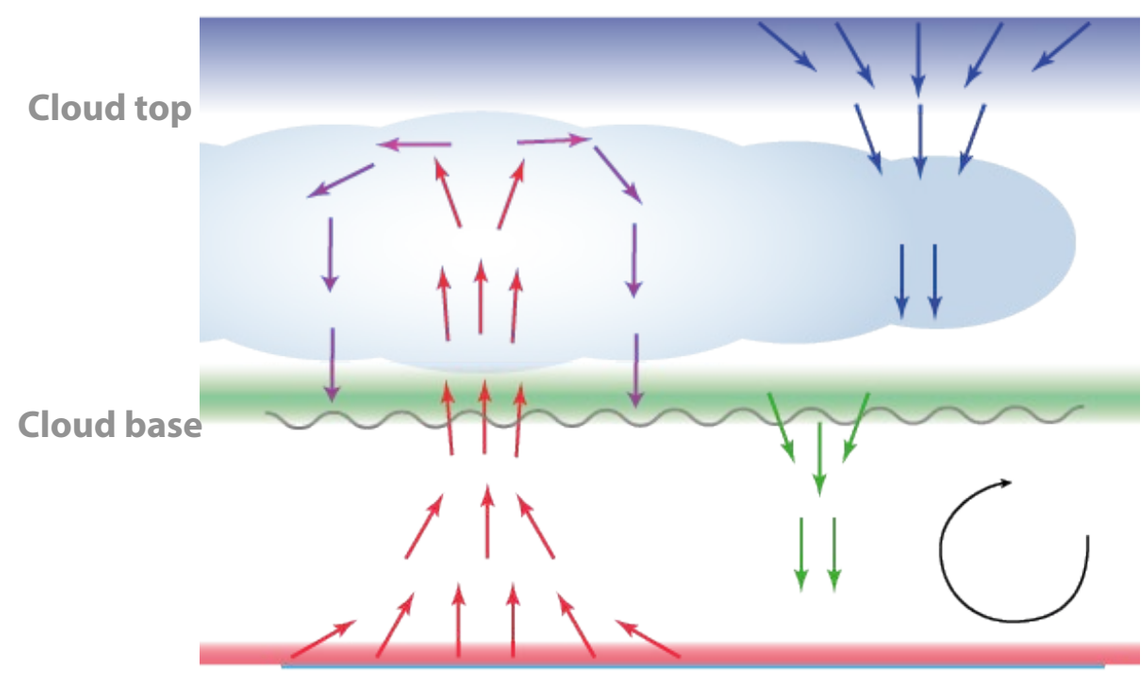
Stratocumulus (FIRE)

Liquid Water Content (g/m2)



Domain-mean resolved fluxes -----





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Returning shells

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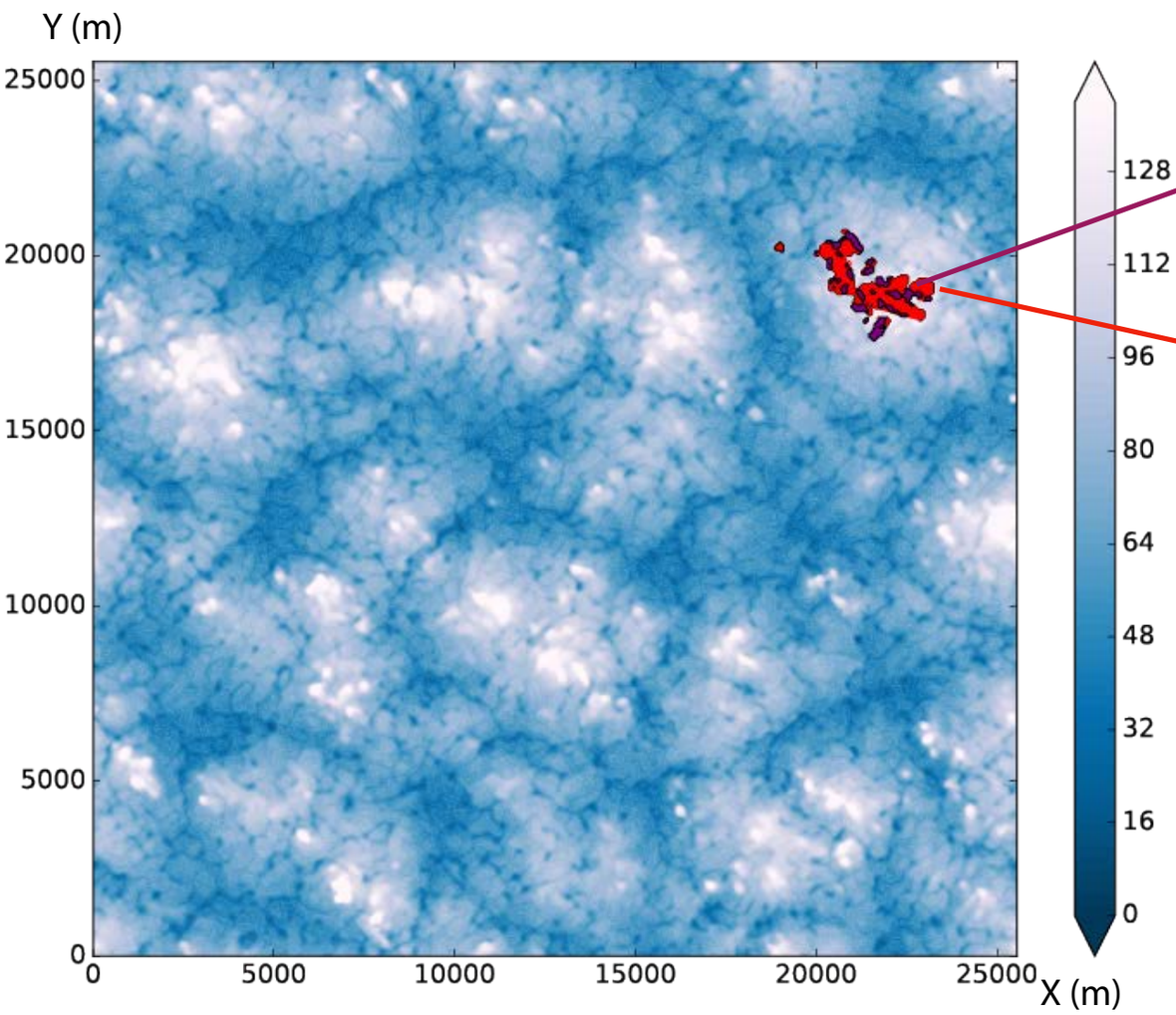
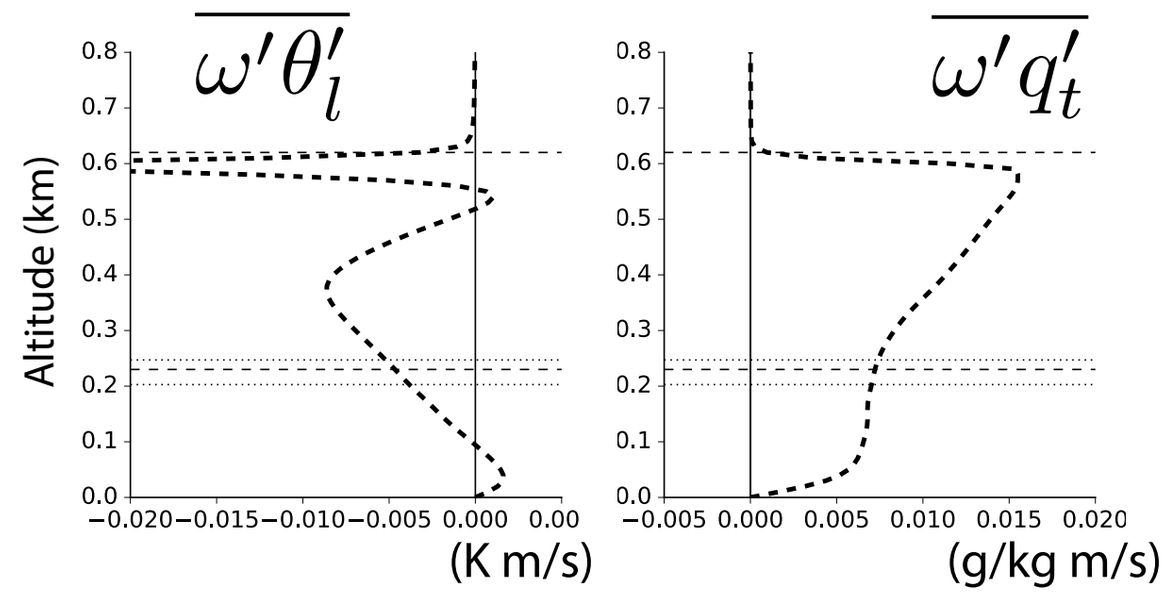


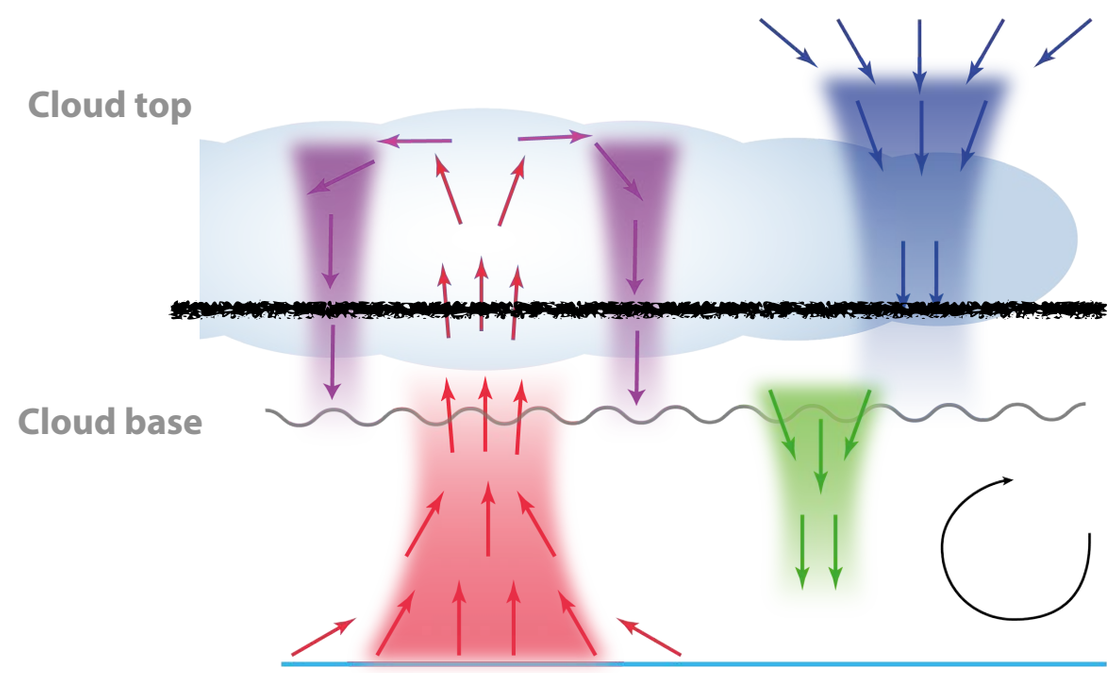
Domain-mean volume:

1%

7%

Domain-mean resolved fluxes -----





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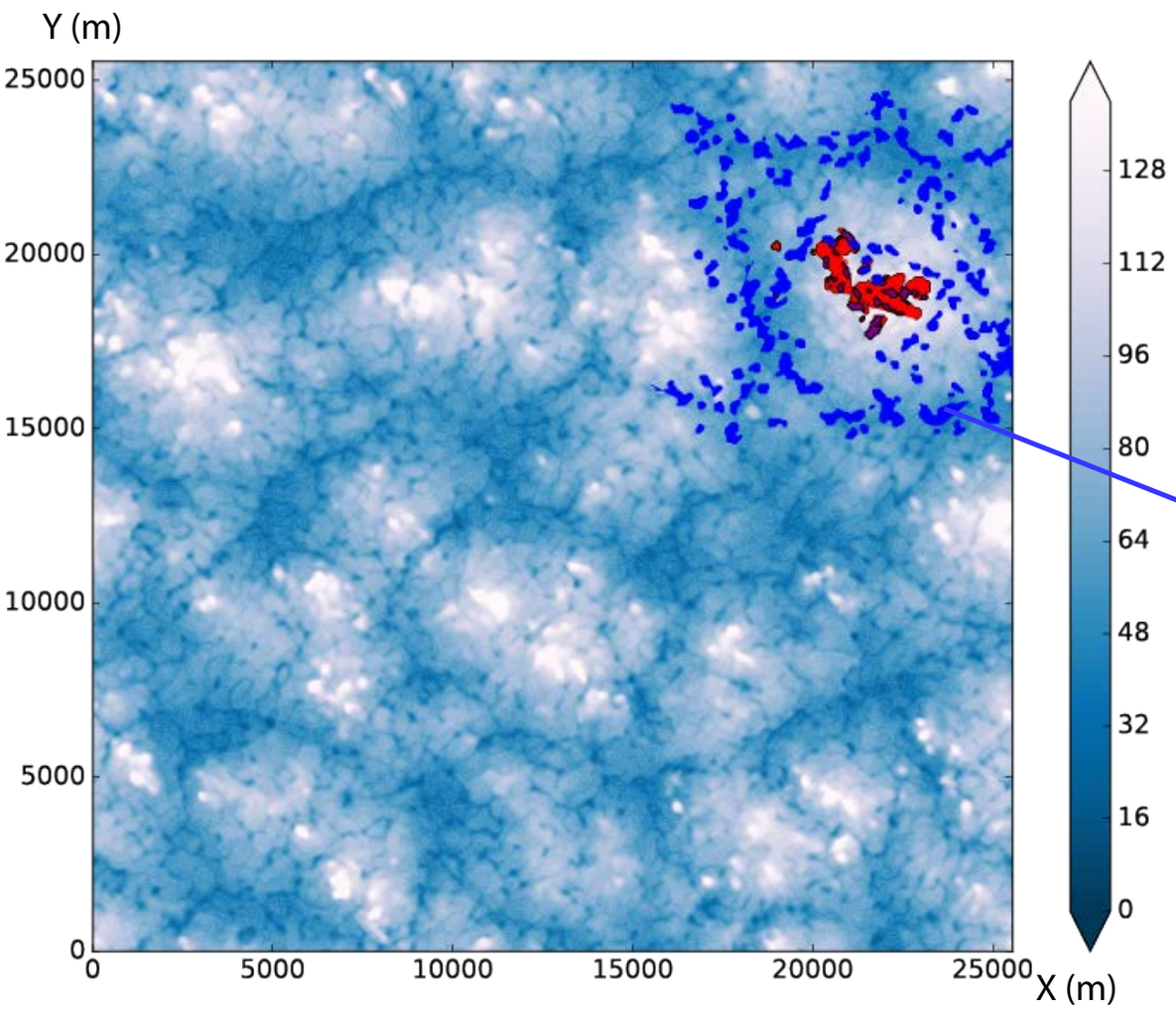
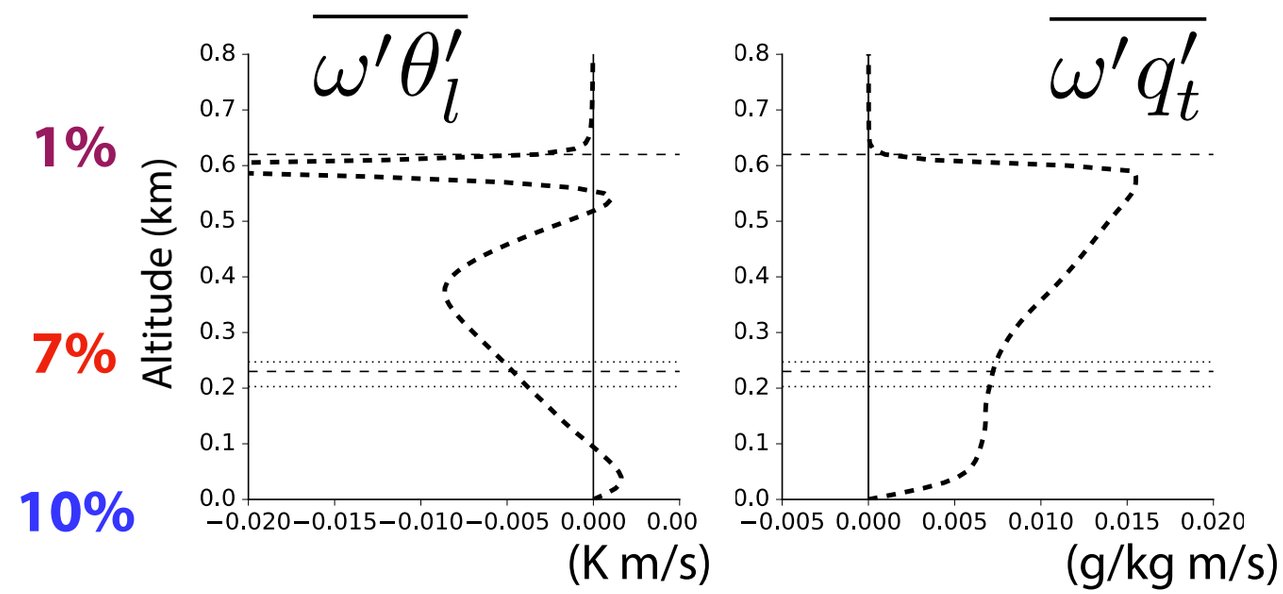
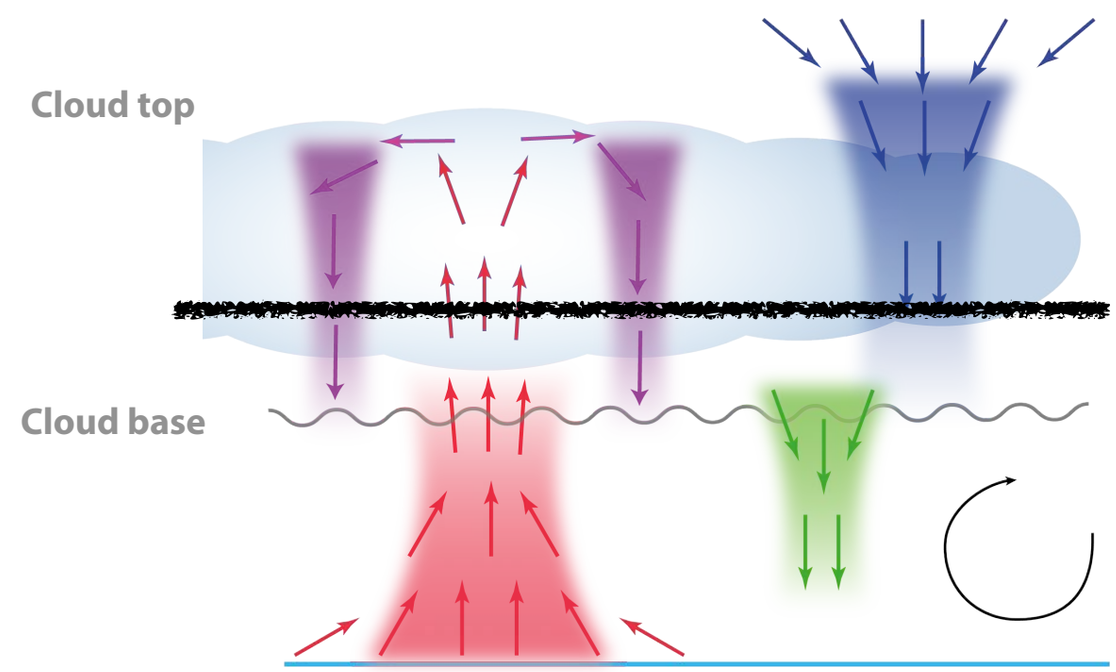


Domain-mean volume:

Domain-mean resolved fluxes -----





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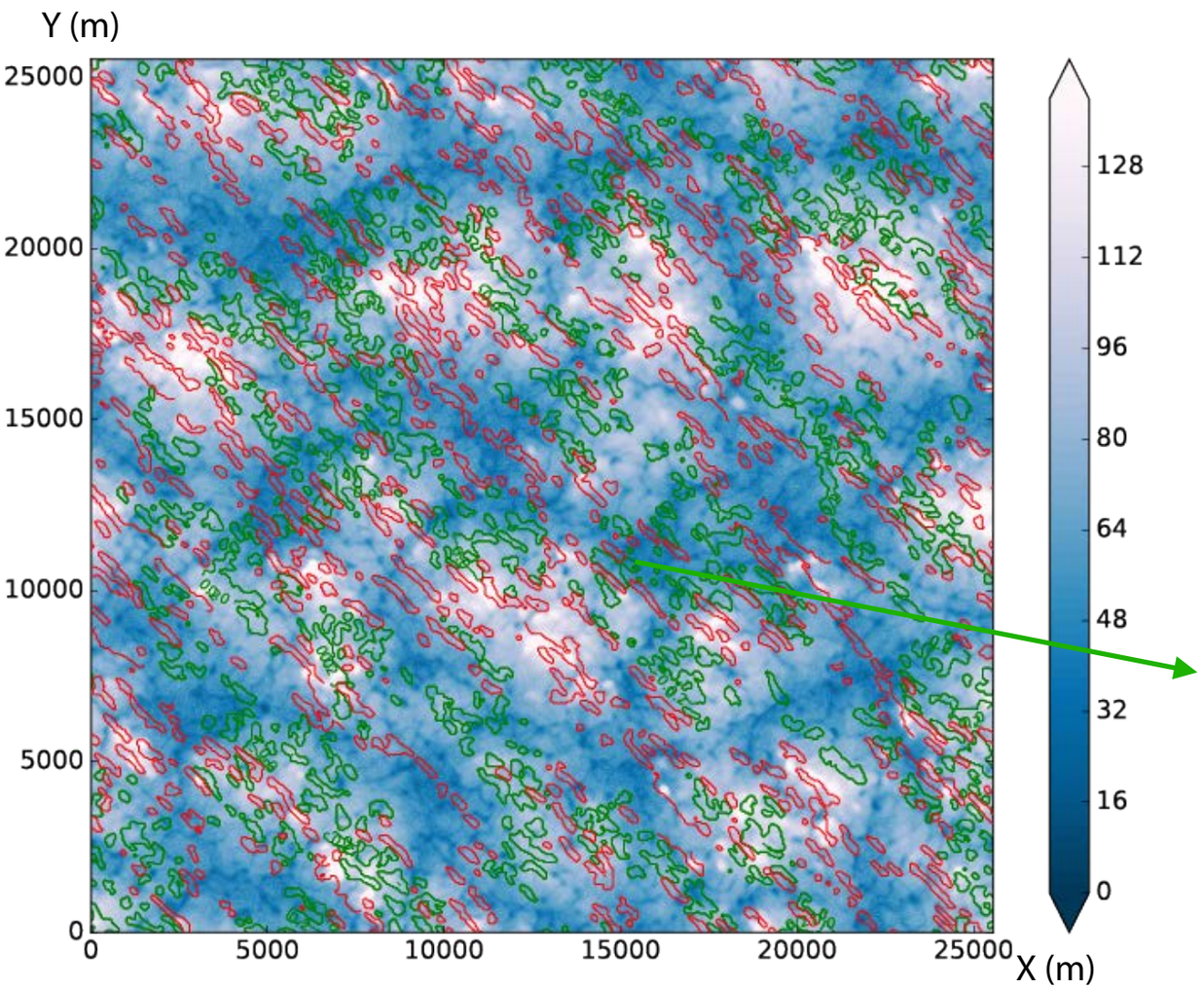
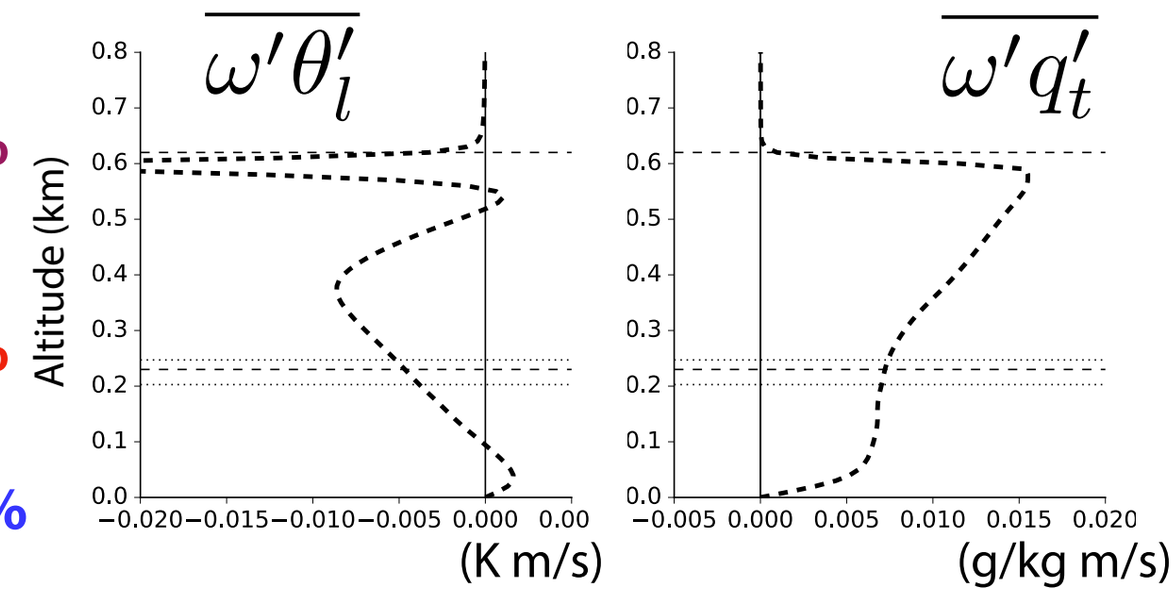
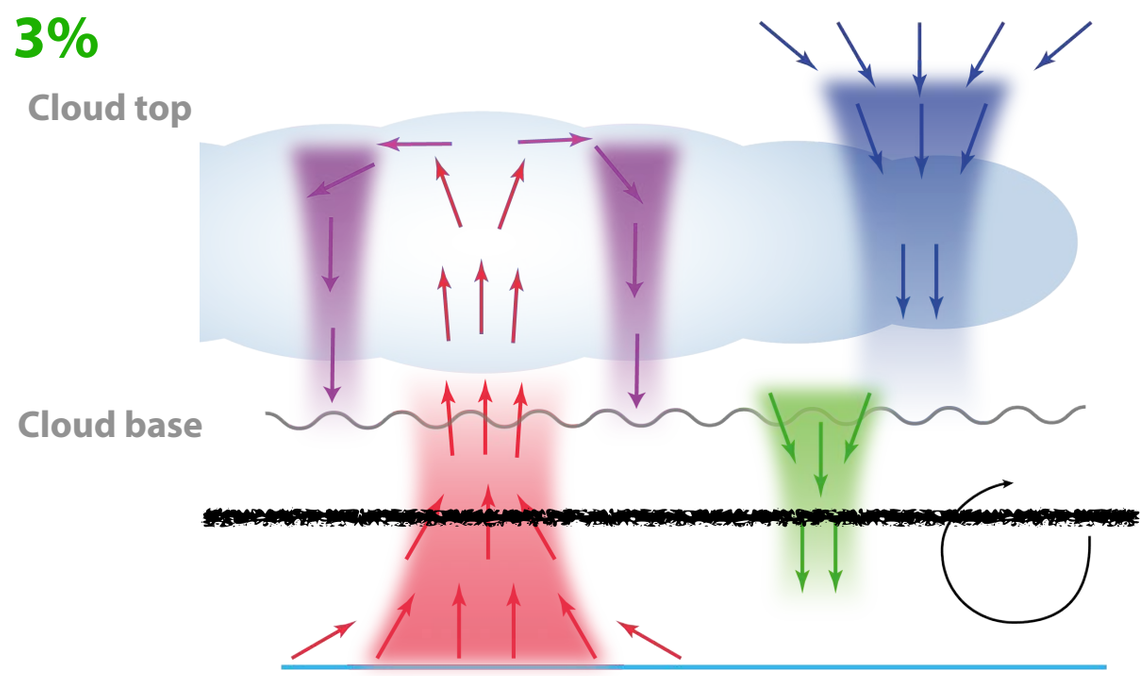


Domain-mean volume:

1%
7%
10%
3%

Domain-mean resolved fluxes -----





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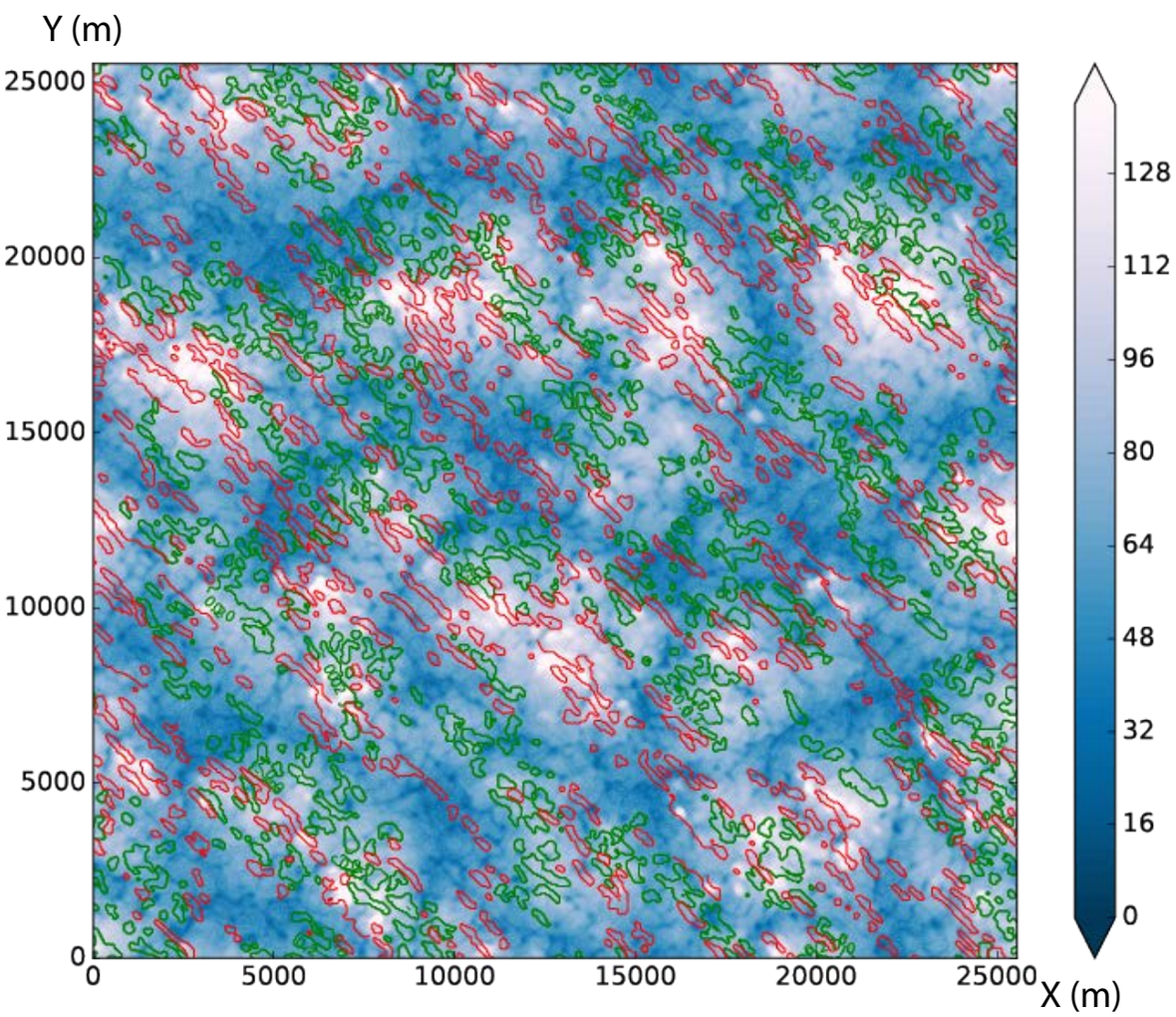
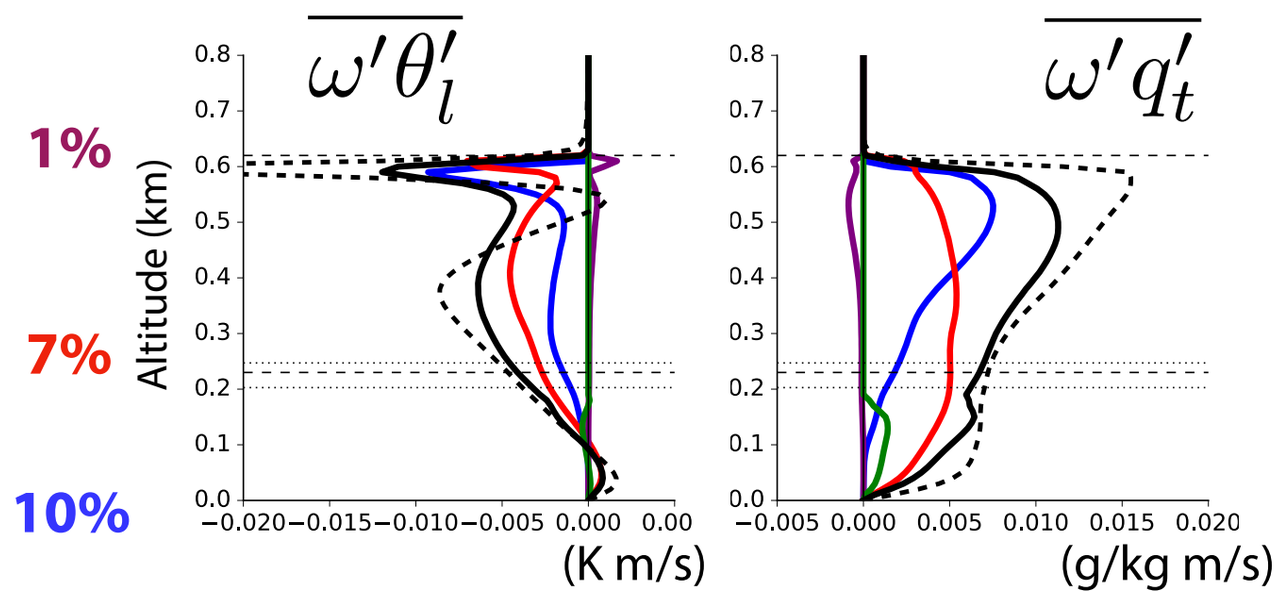
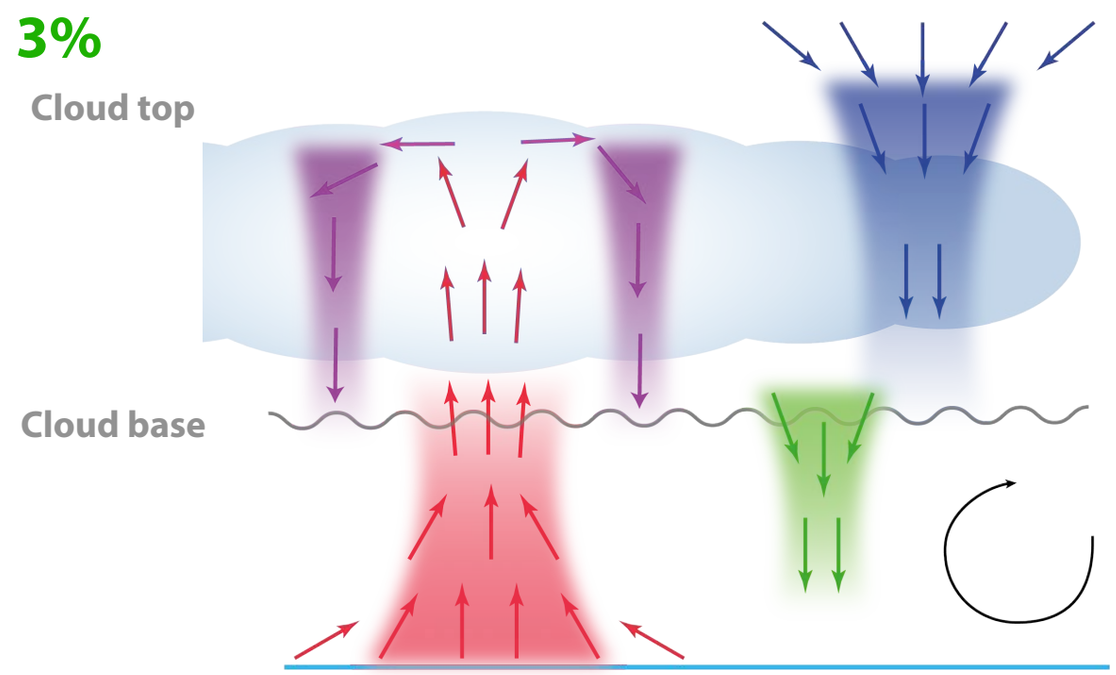


Domain-mean volume:

Domain-mean resolved fluxes -----





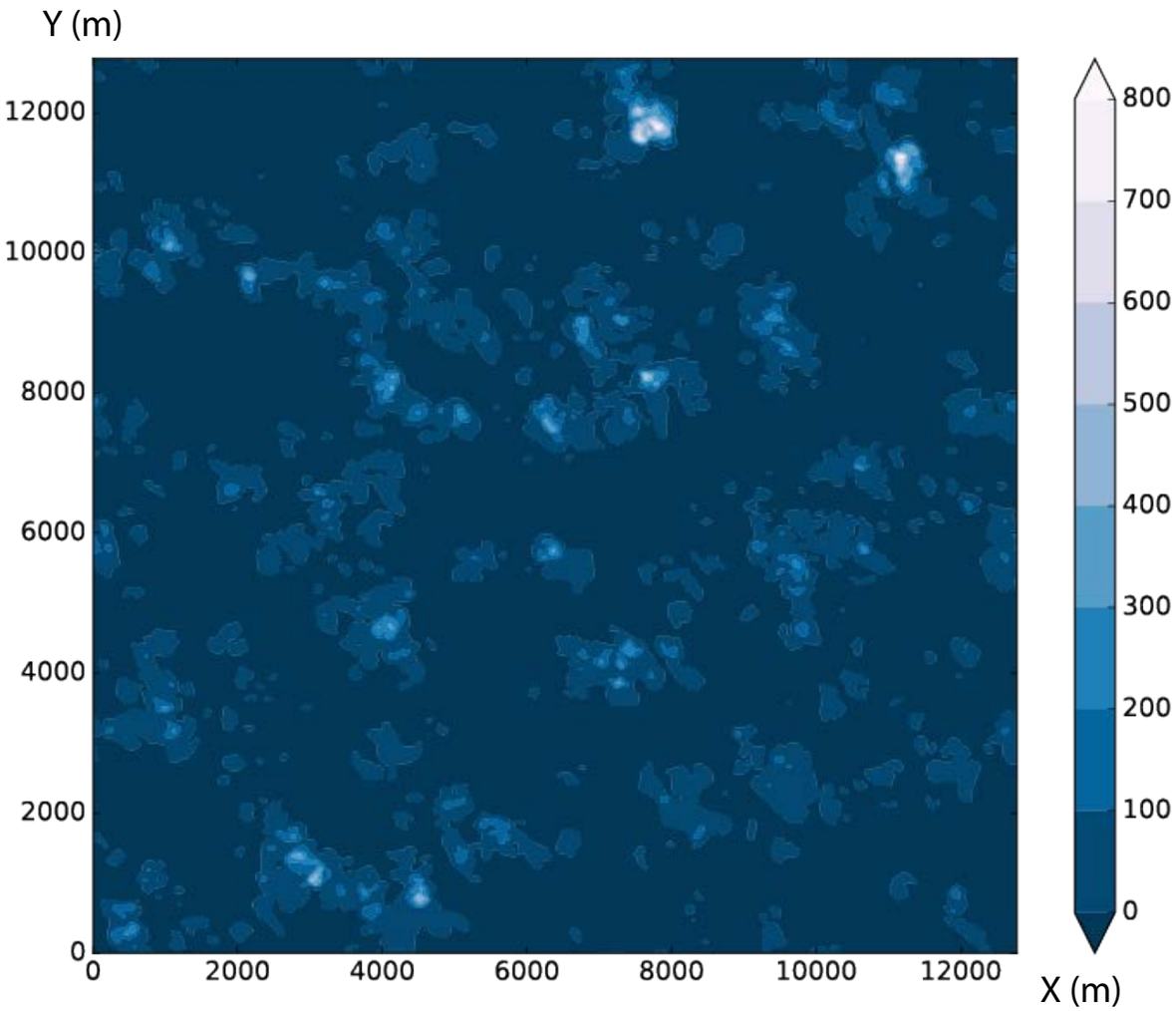
- Objects contribute to **88/82%** of total heat/moisture fluxes (for **21%** of volume)

Characteristics of boundary layers

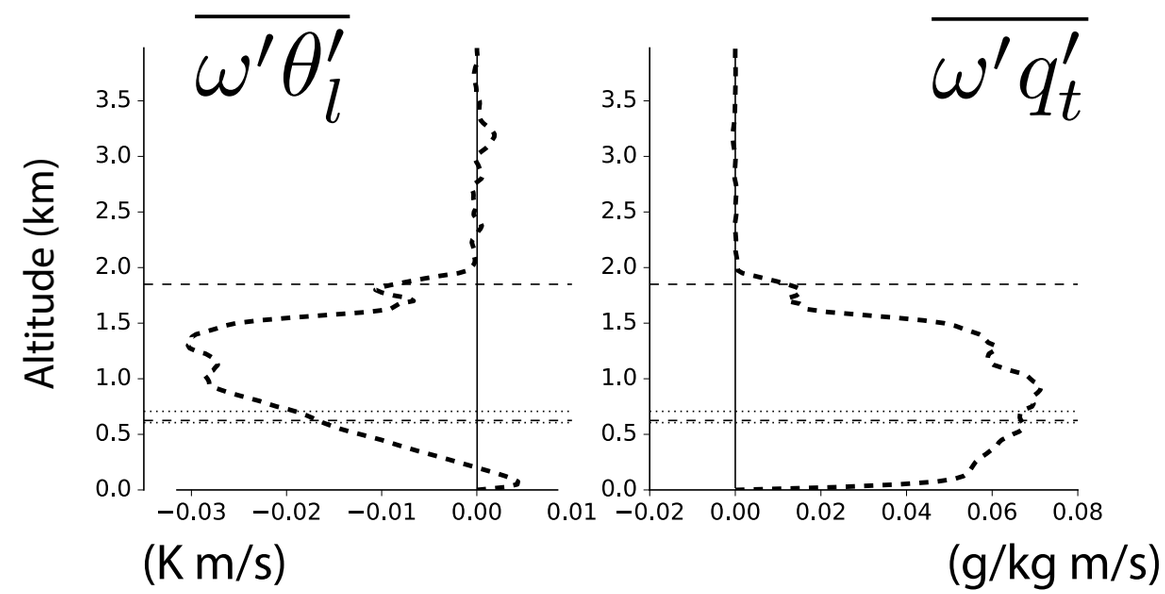
Cumulus (BOMEX)

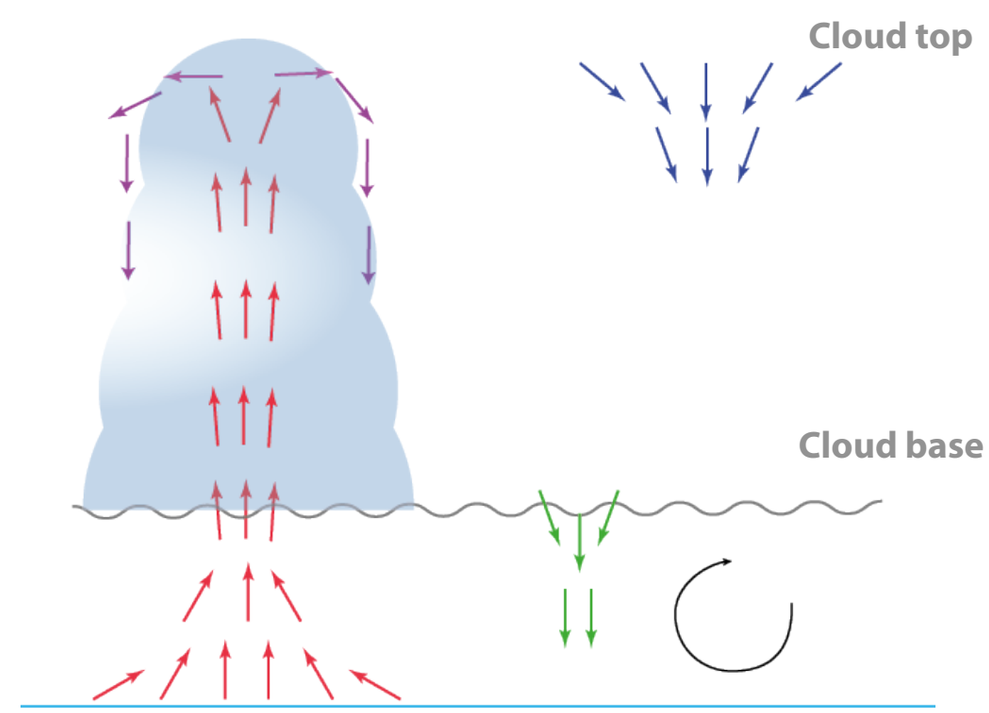
All Structures
Updraft
Entrained downdraft
Sub-cloud downdraft
Returning shells

Liquid Water Content (g/m2)



Domain-mean resolved fluxes -----





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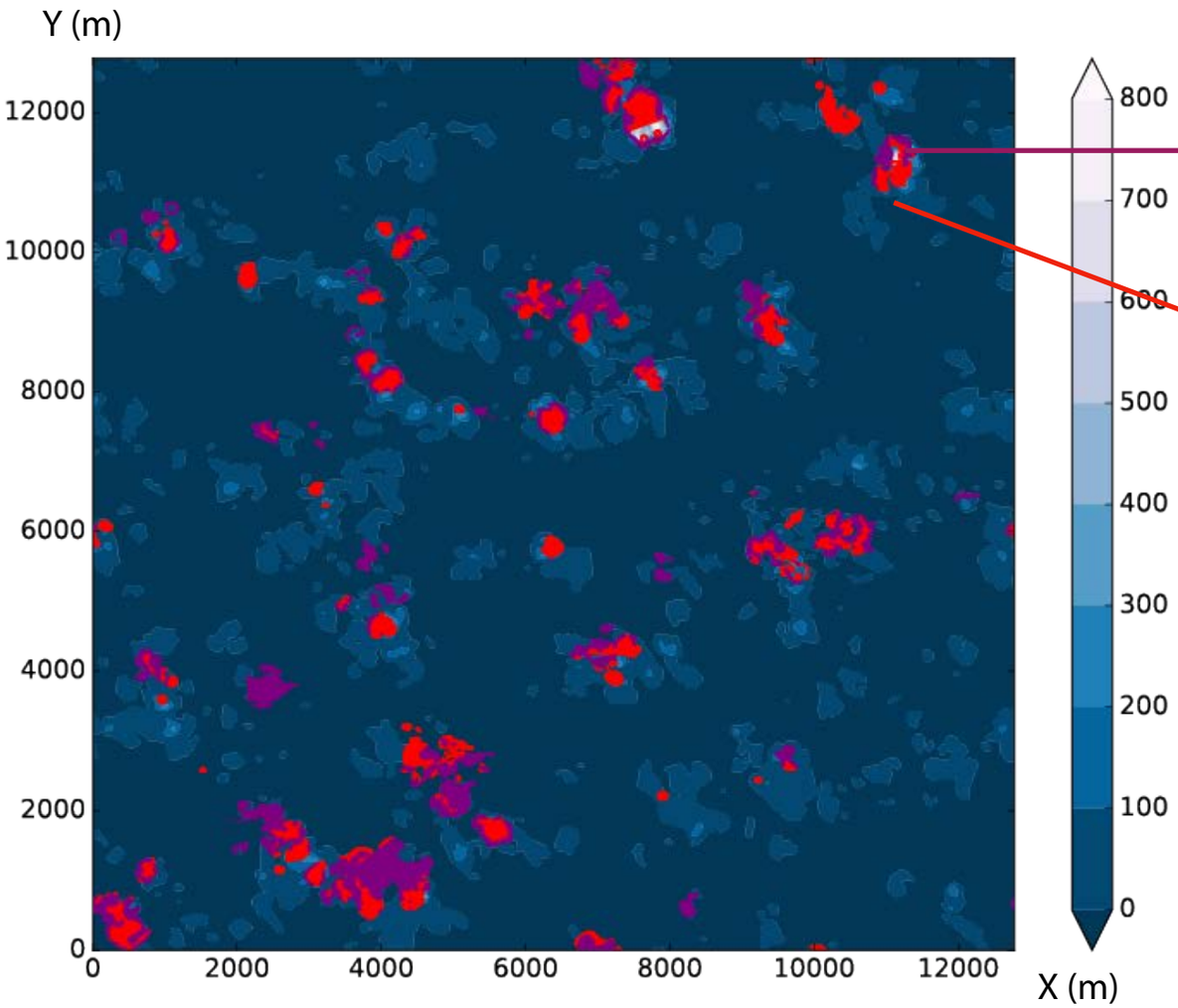
Cumulus (BOMEX)

Liquid Water Content (g/m2)

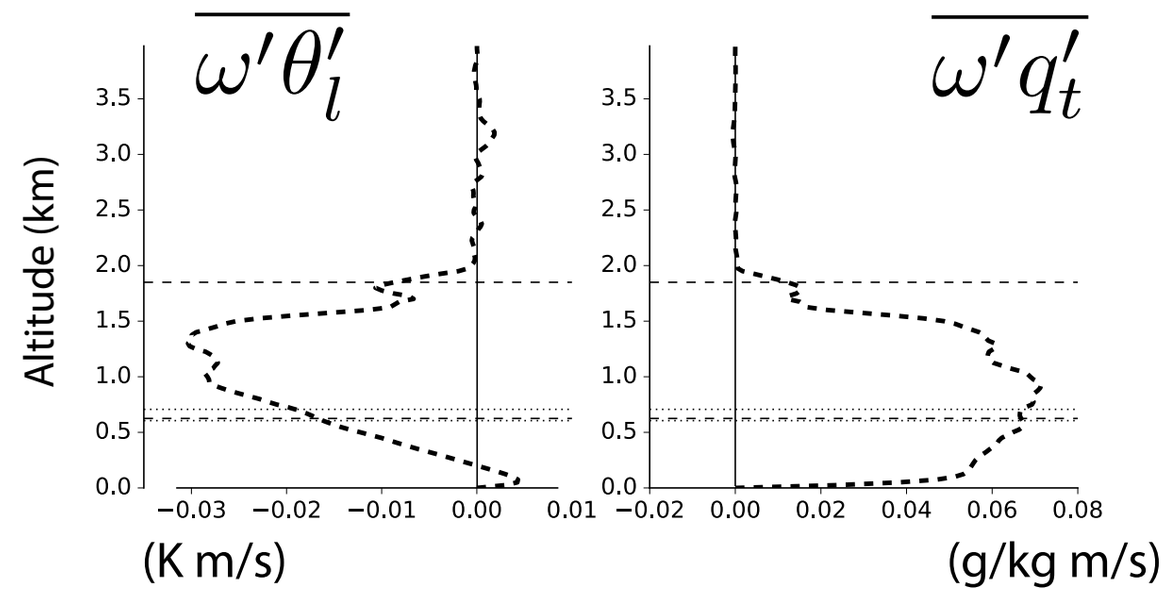


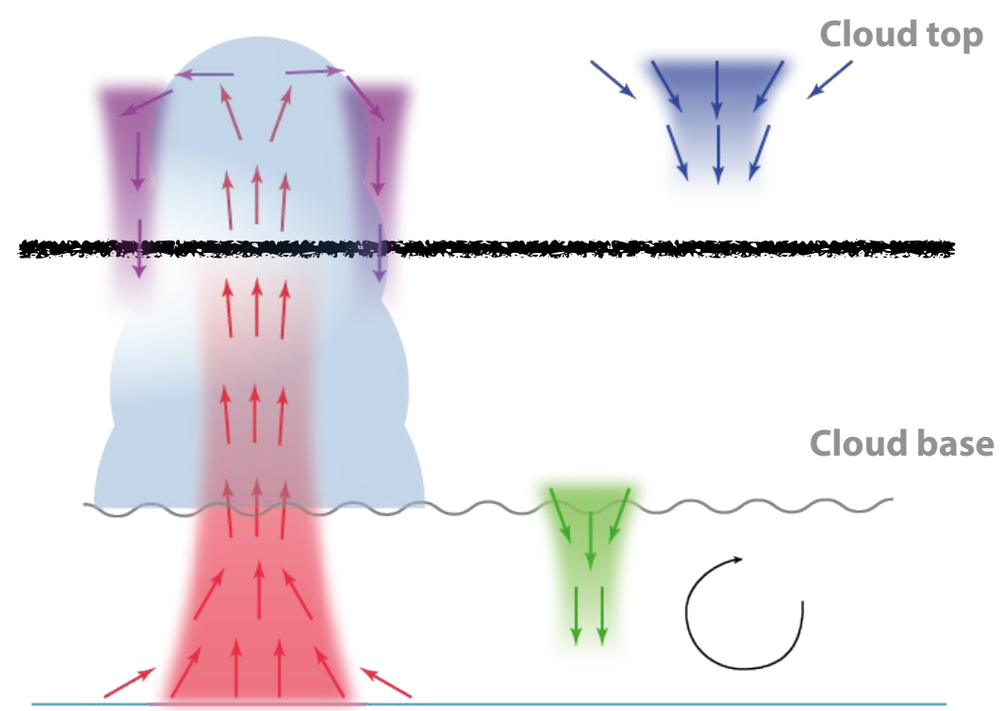
Domain-mean volume:

2%

6%

Domain-mean resolved fluxes -----





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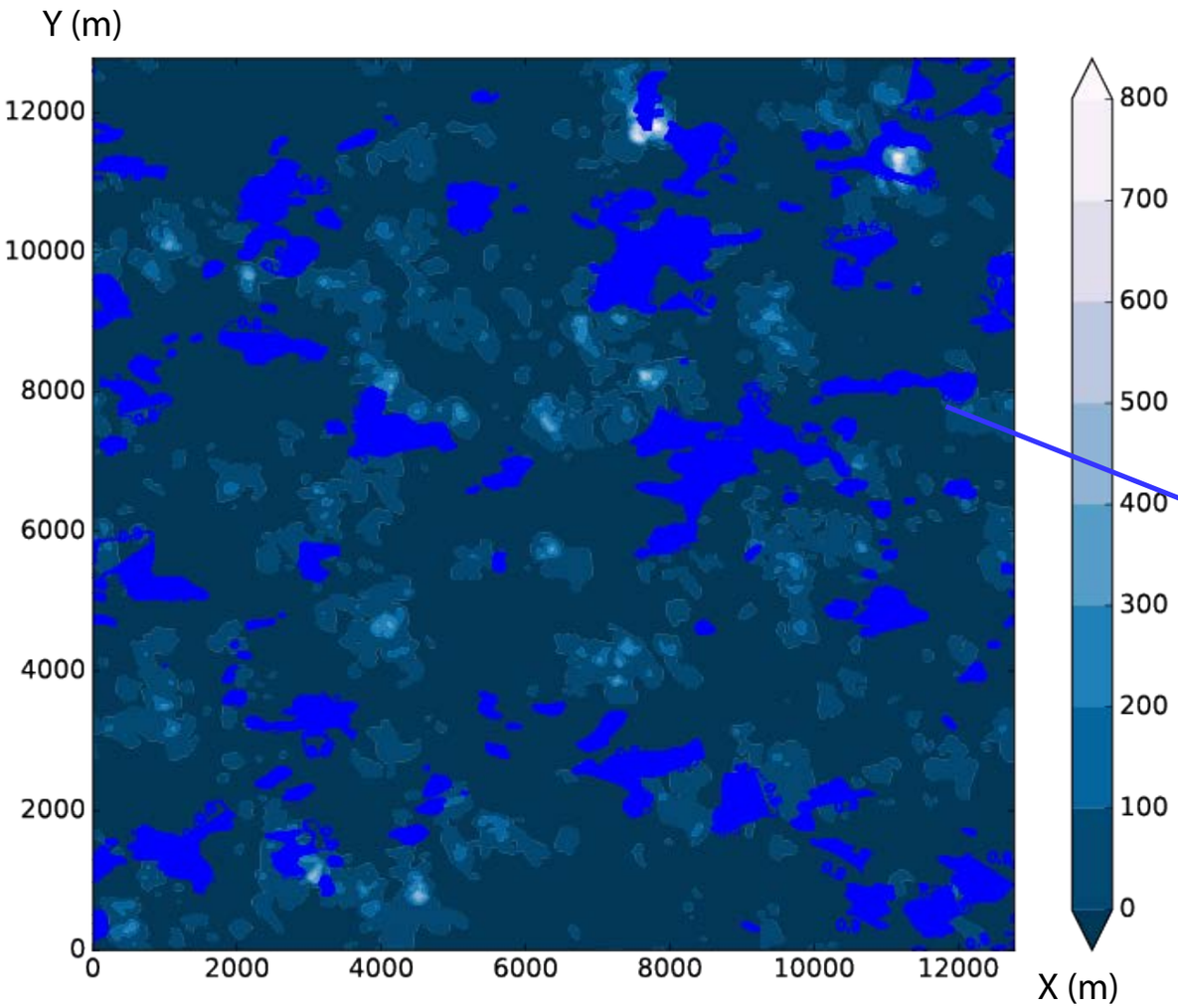

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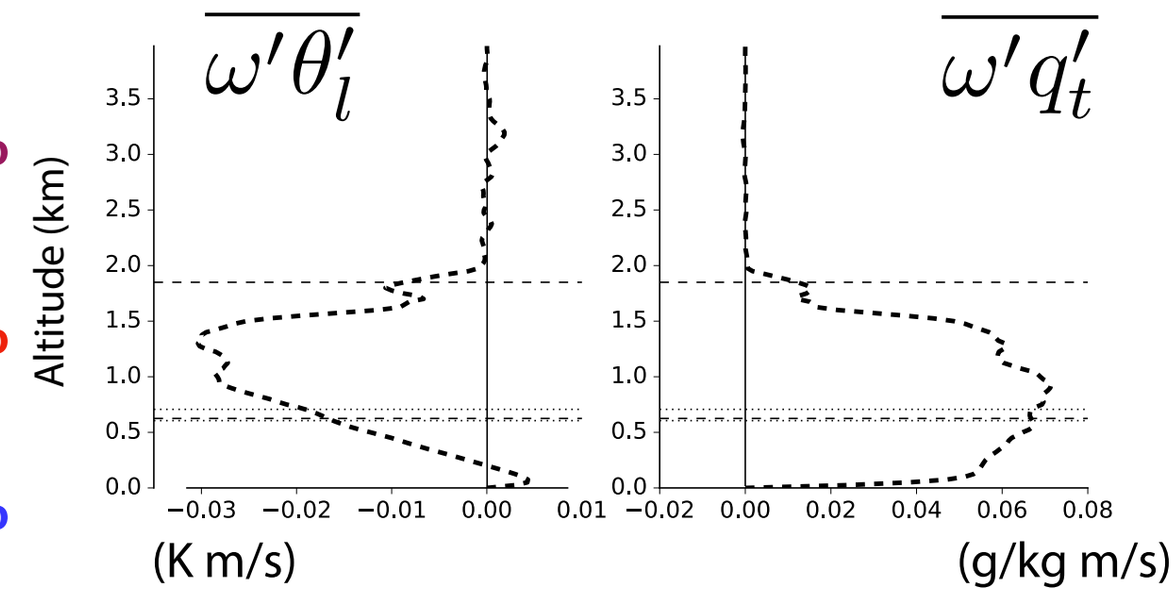
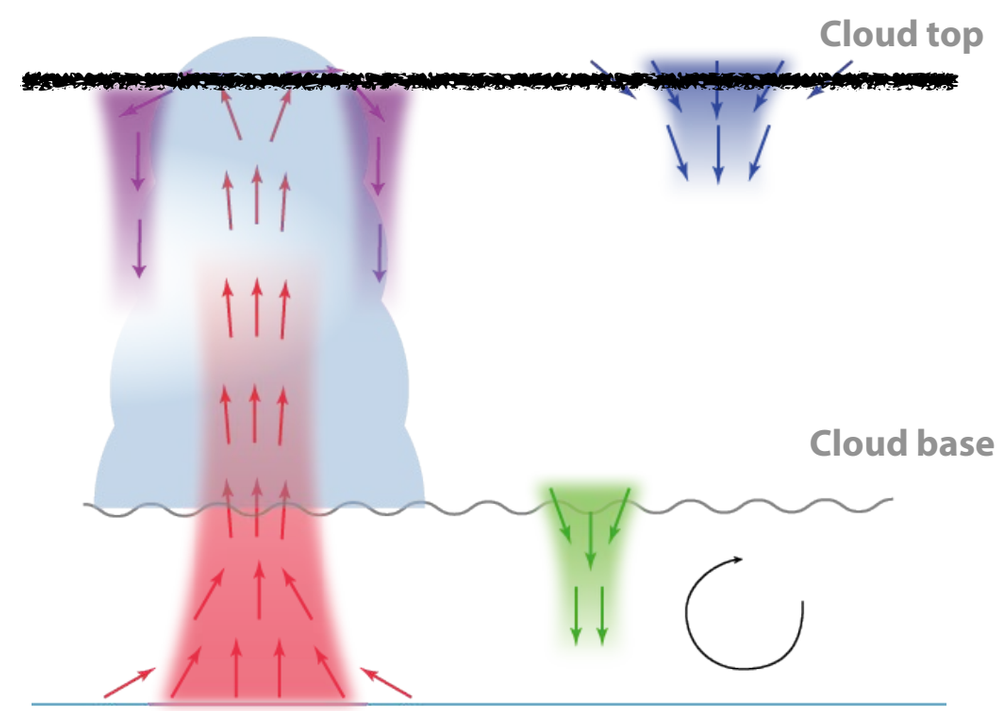
2%

6%

2%

Domain-mean resolved fluxes -----





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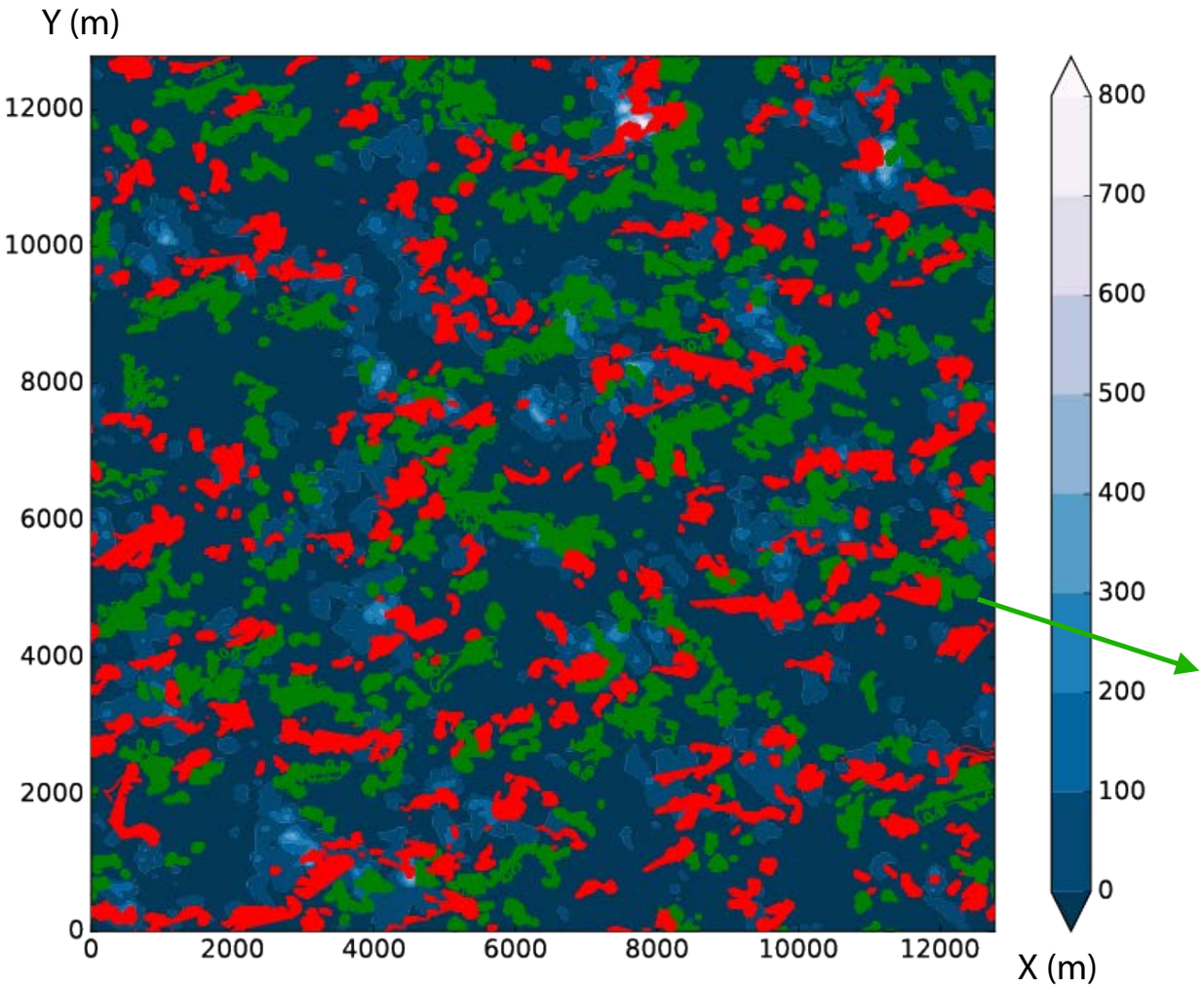
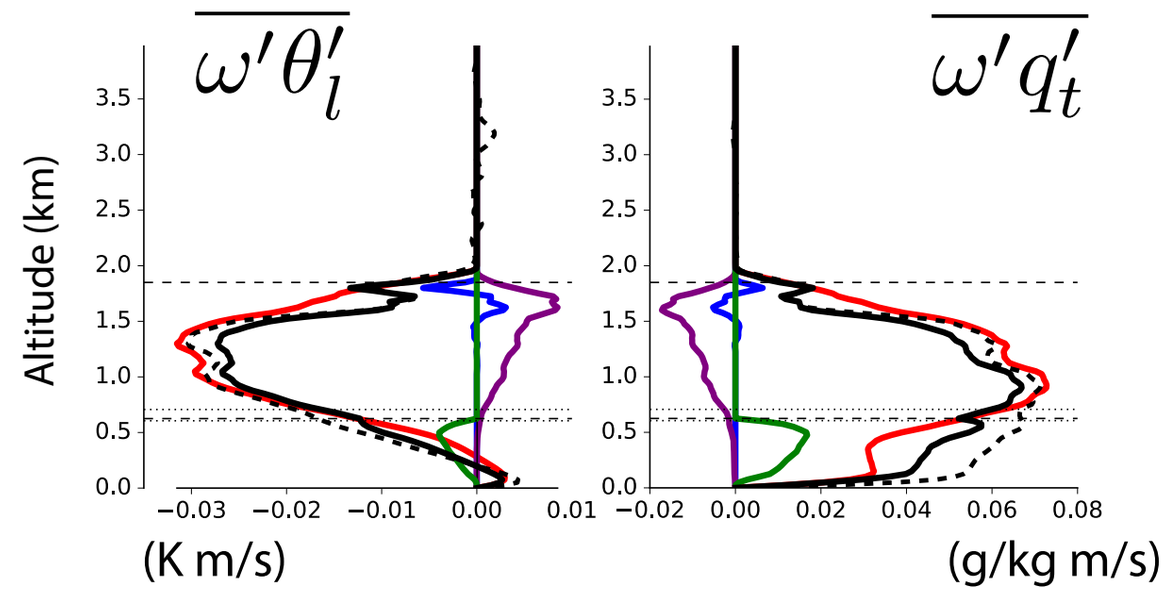
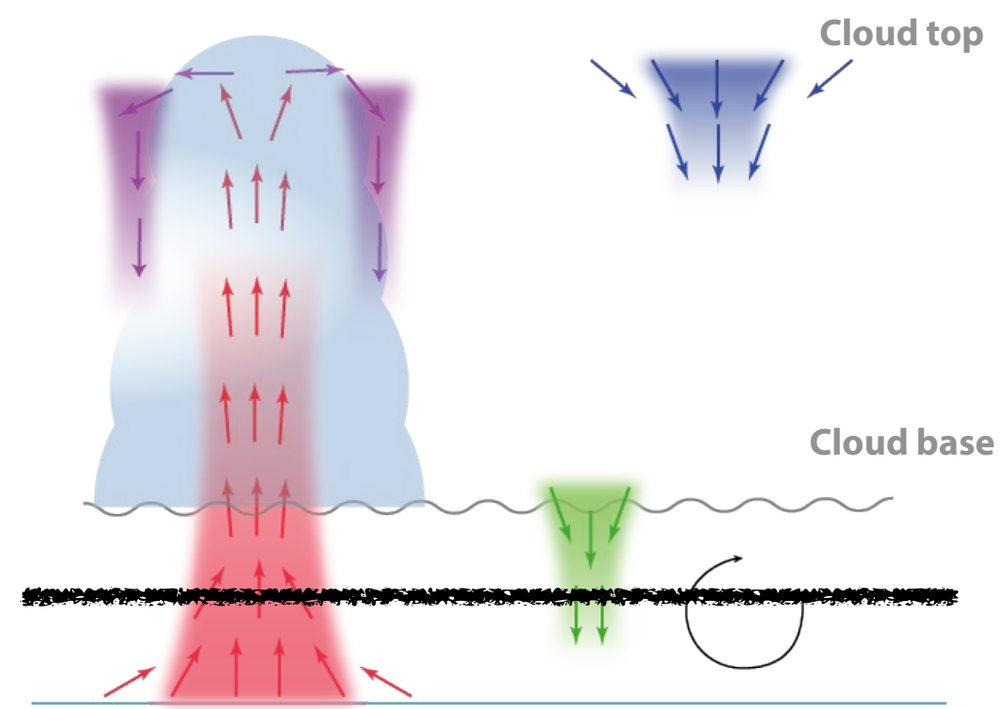


Domain-mean volume:

2%
6%
2%
3%

Domain-mean resolved fluxes -----





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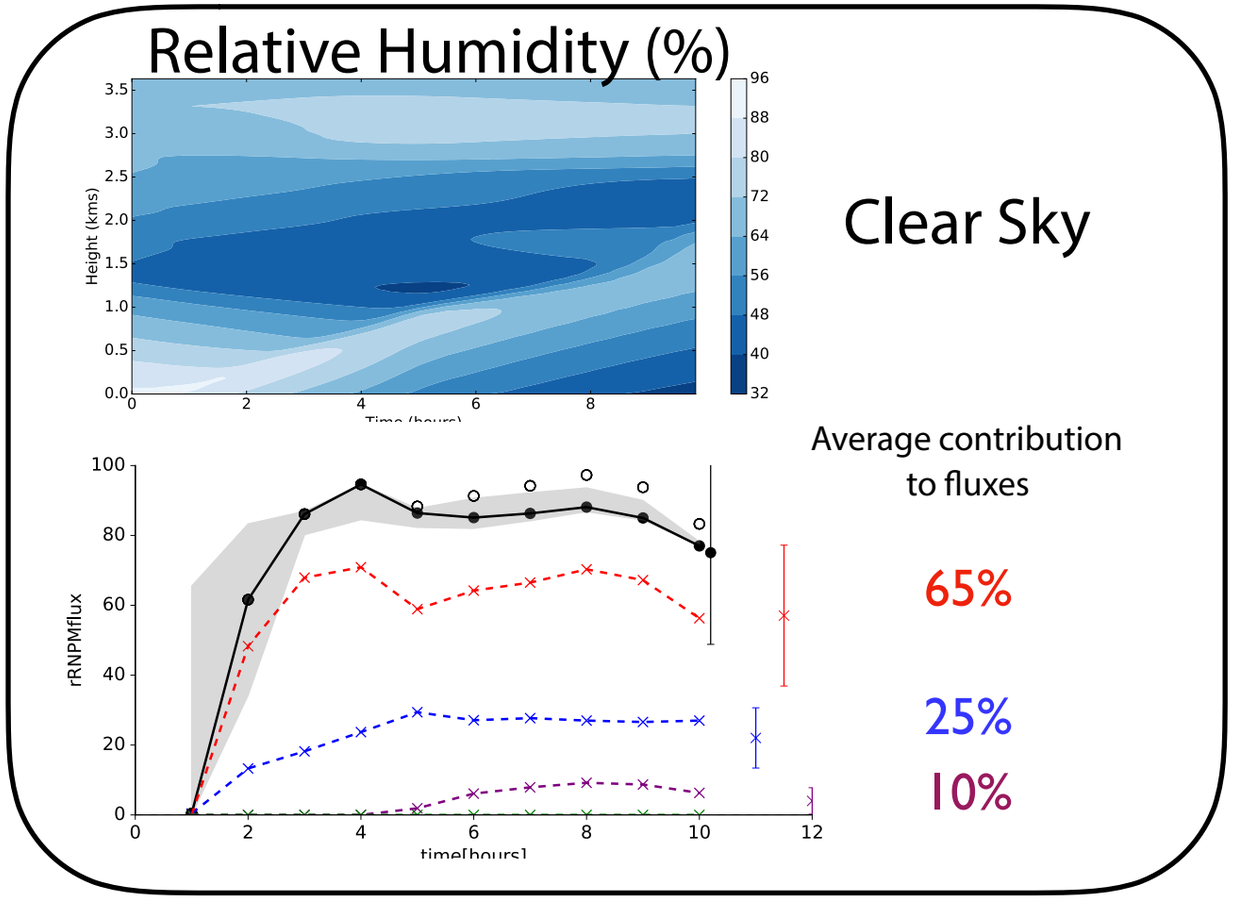
Updraft
Entrained downdraft

Time evolution of boundary layers

Returning shells
Sub-cloud downdraft

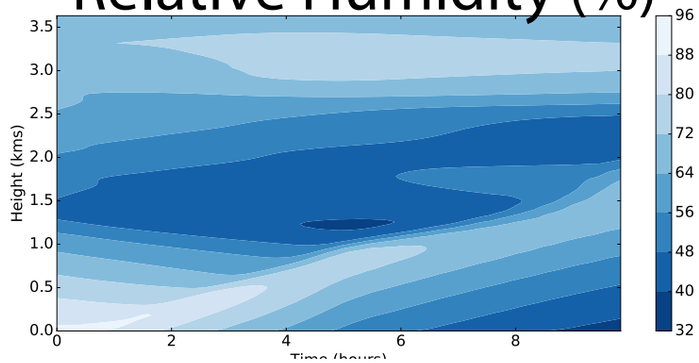


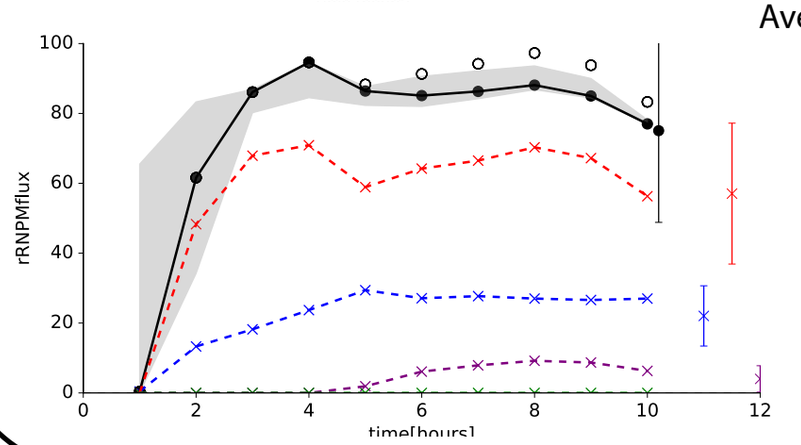
Updraft
Entrained downdraft

Time evolution of boundary layers

Returning shells
Sub-cloud downdraft

Relative Humidity (%)





Clear Sky

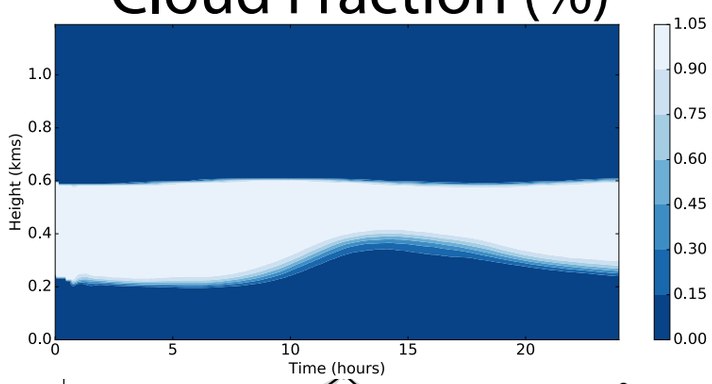
Average contribution to fluxes

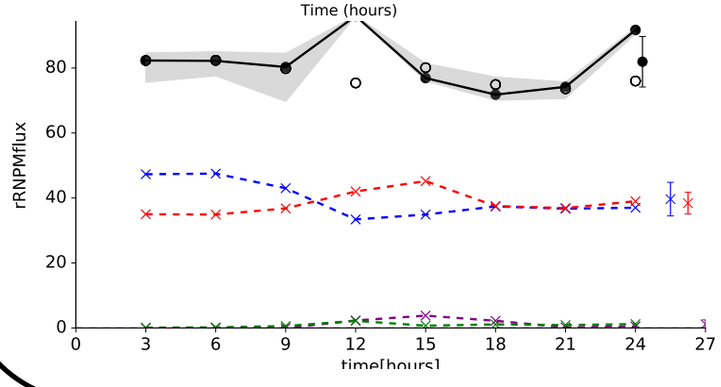
65%

25%

10%

Cloud Fraction (%)





StCu

Average contribution to fluxes

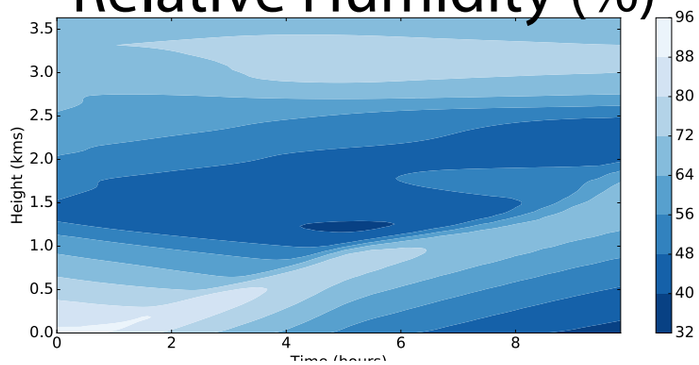
Day	Night
50%	40%
35%	40%
4%	2%
4%	1%

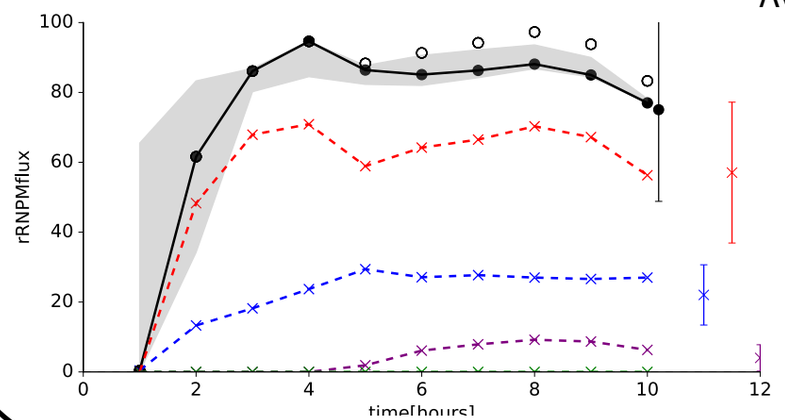
Updraft
Entrained downdraft

Time evolution of boundary layers

Returning shells
Sub-cloud downdraft

Relative Humidity (%)





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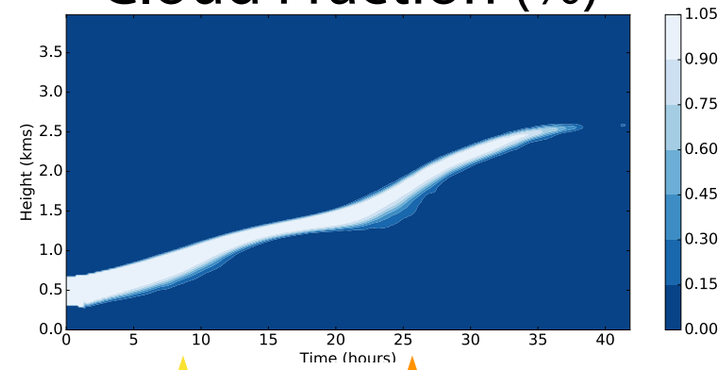
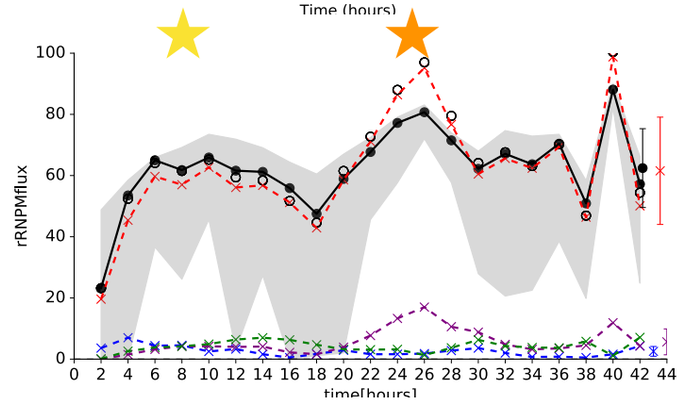


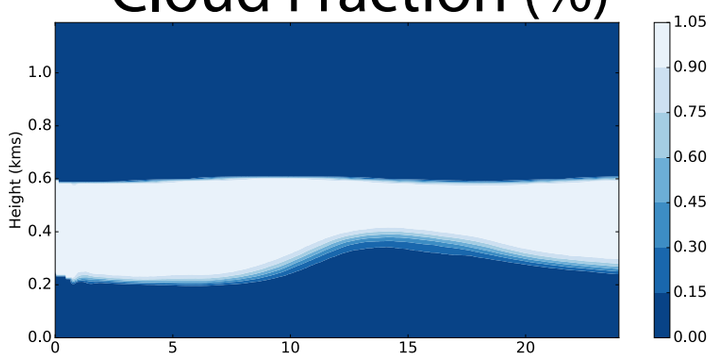
St-to-Cu

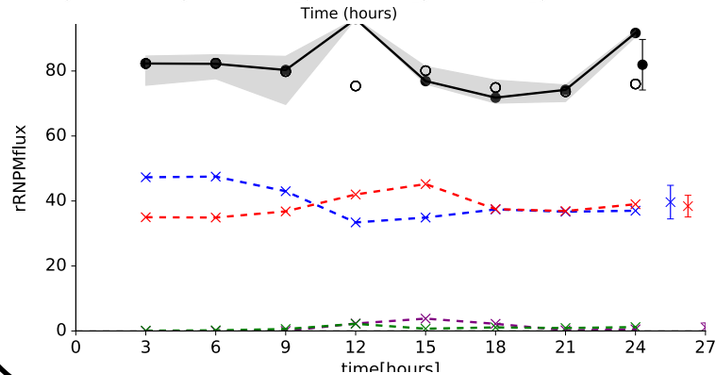
Contribution to fluxes

t+8h	t+26h
60%	95%
5%	2%
4%	1%
5%	17%



Cloud Fraction (%)





StCu

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Updraft
Entrained downdraft

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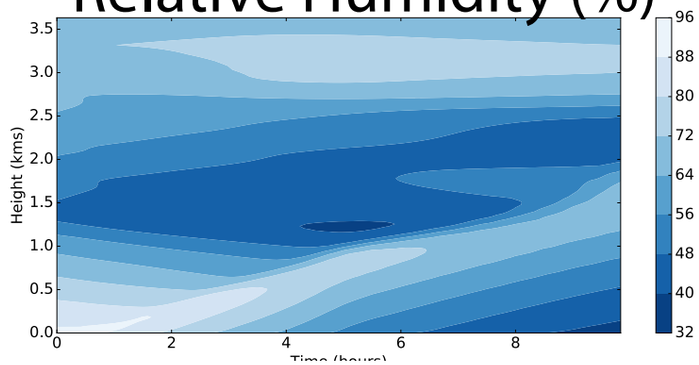
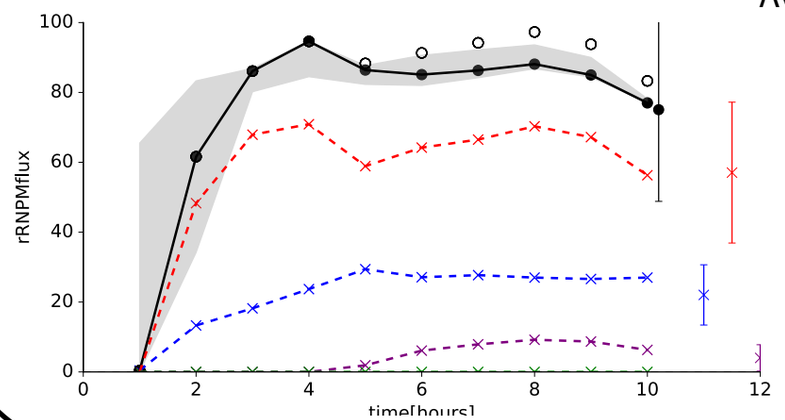
Relative Humidity (%)





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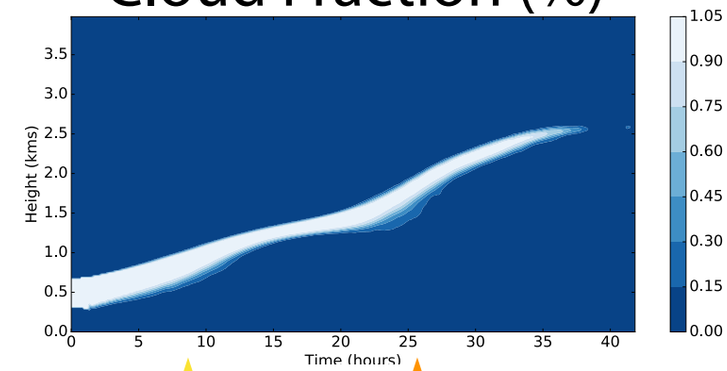
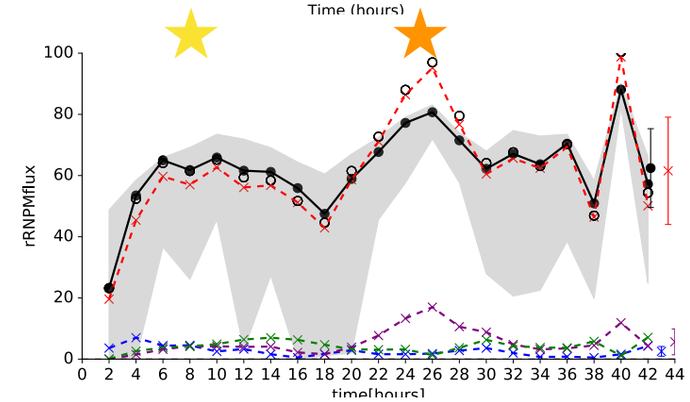


St-to-Cu



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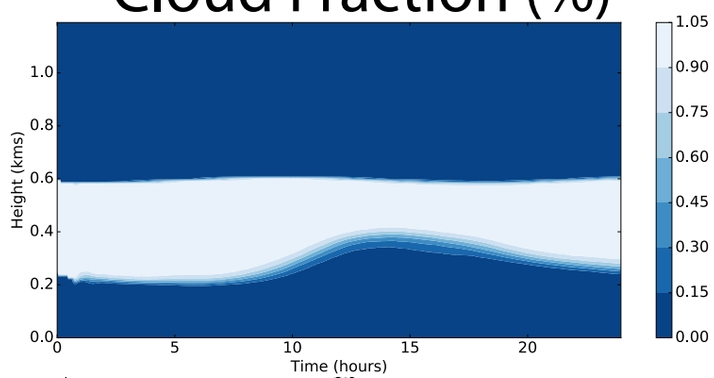
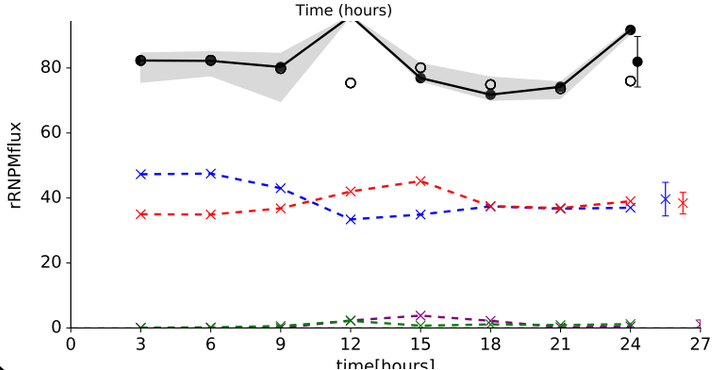
Cloud Fraction (%)





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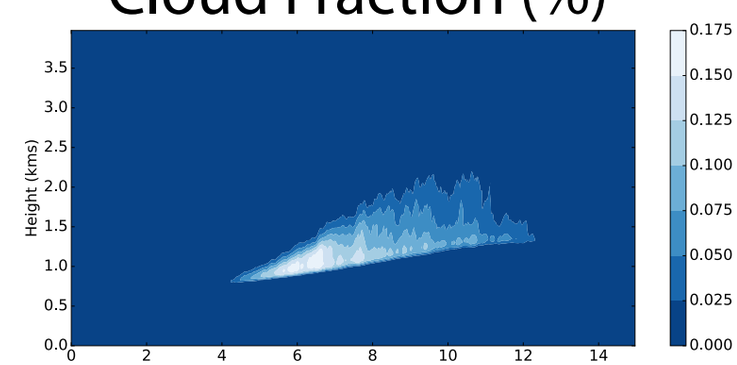
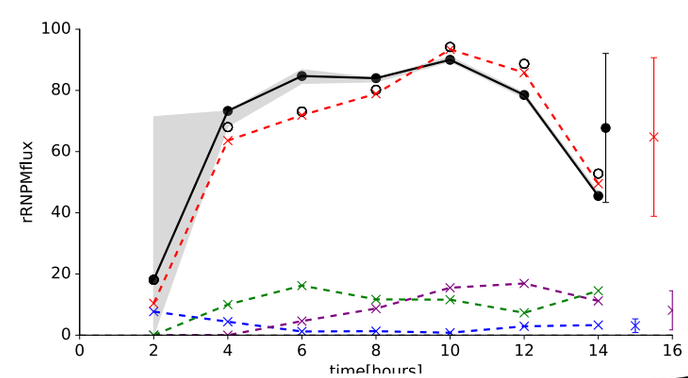




Cu

Average contribution to fluxes

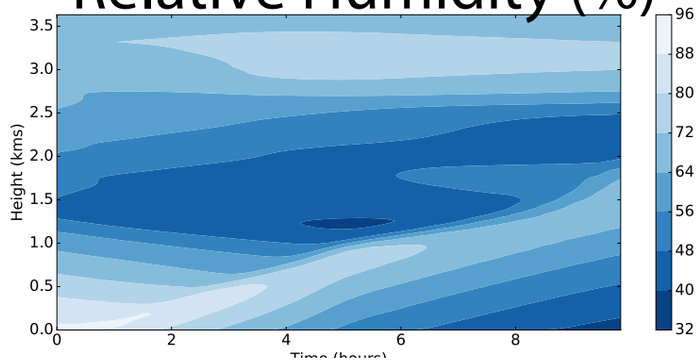
sub-cloud only	
85%	60%
2%	1%
10%	20%
10%	5%

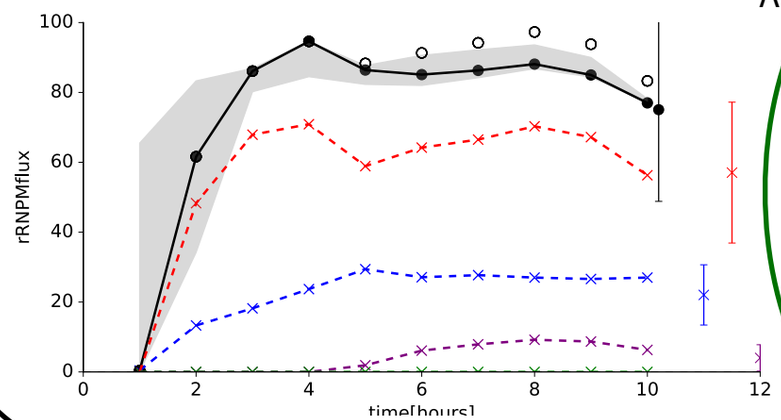
Updraft
Entrained downdraft

Time evolution of boundary layers

Returning shells
Sub-cloud downdraft

Relative Humidity (%)





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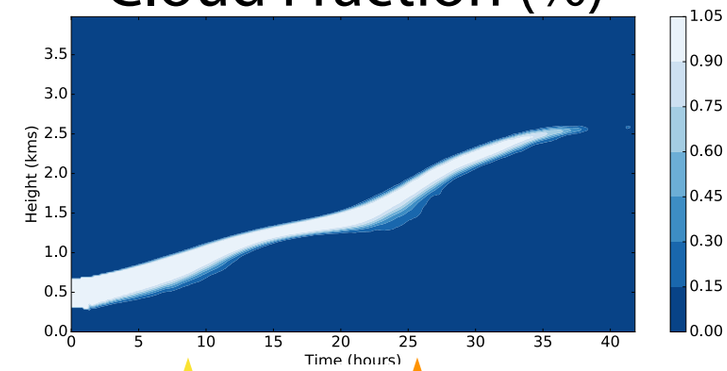

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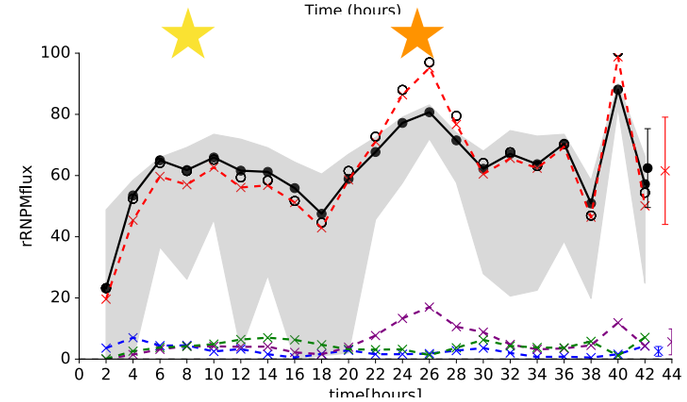
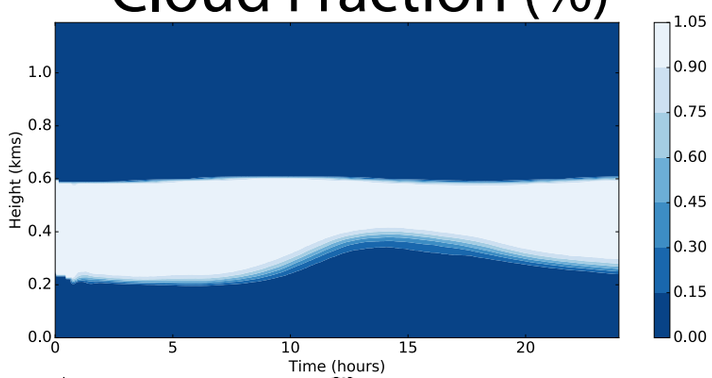
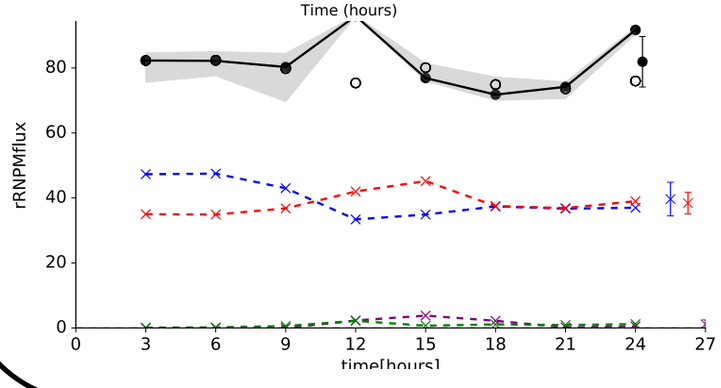


Cloud Fraction (%)





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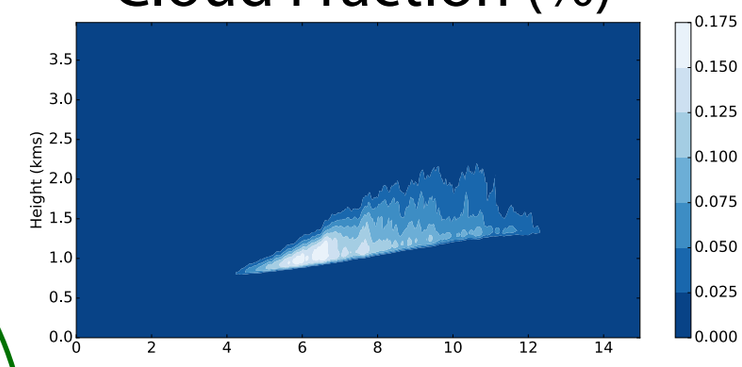

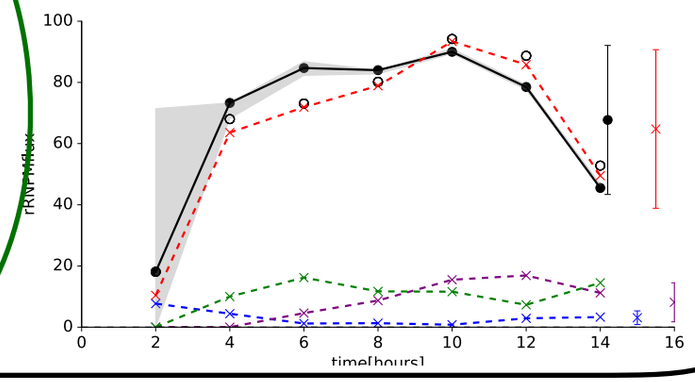

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Coherent structures in observations

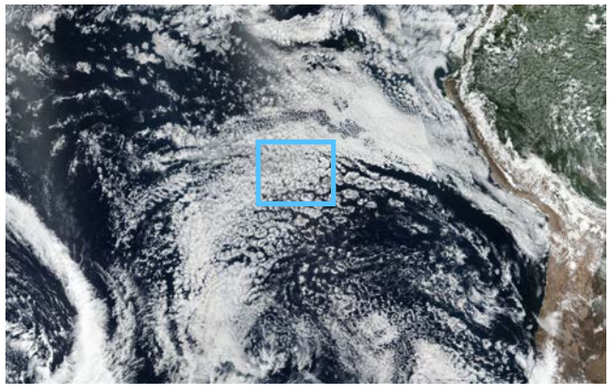
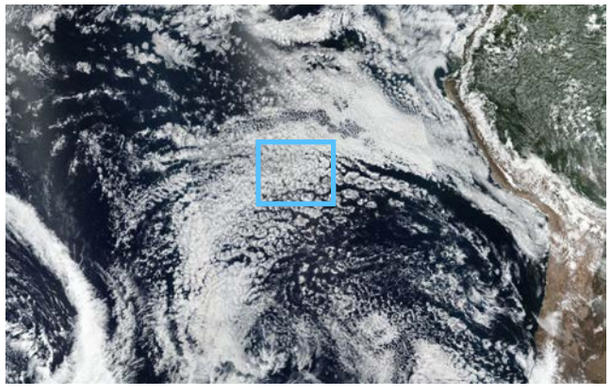


Image Satellite Suomi
07/09/2019

Are LES realistic?
Can we **observe** boundary-layer coherent structures?

Coherent structures in observations



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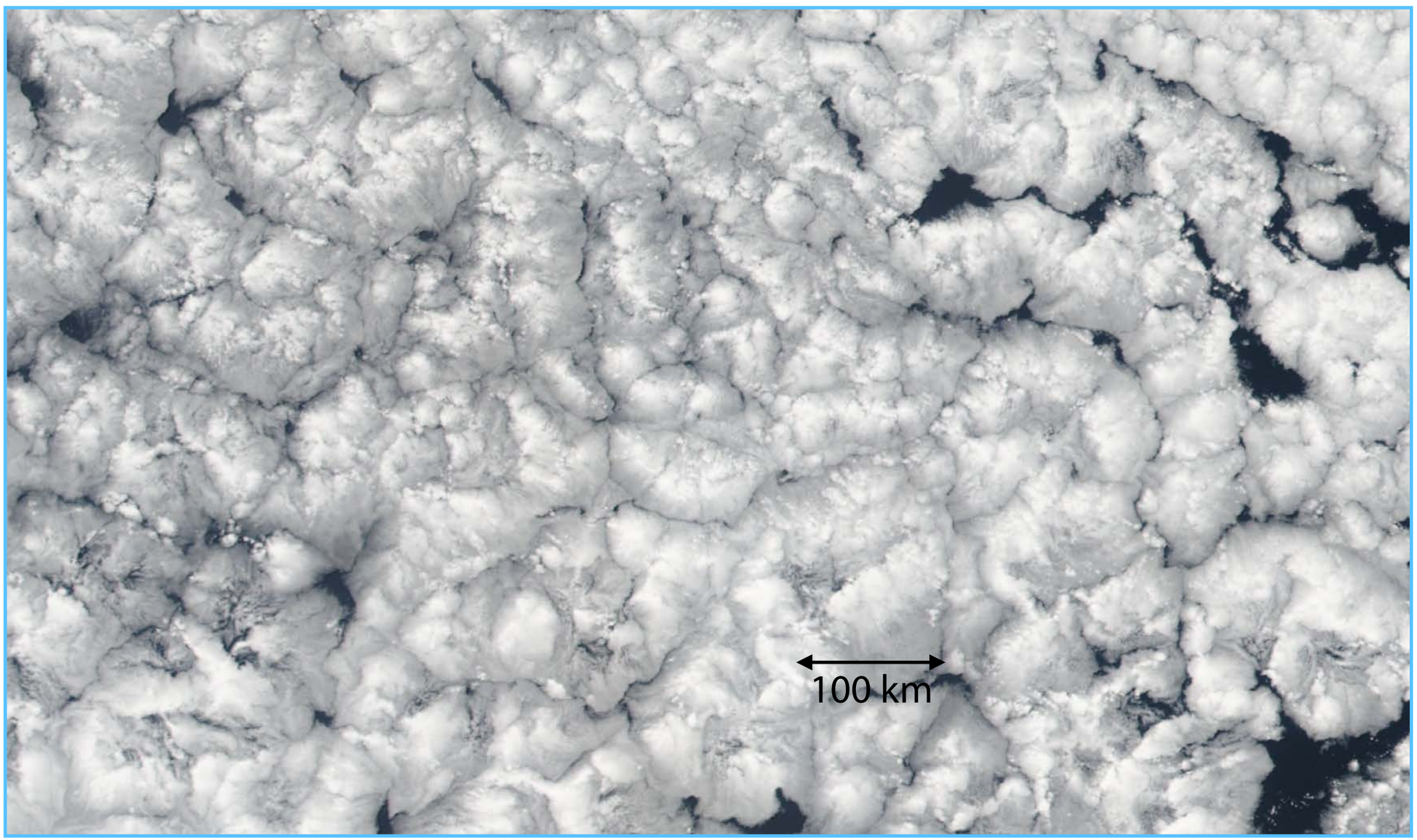

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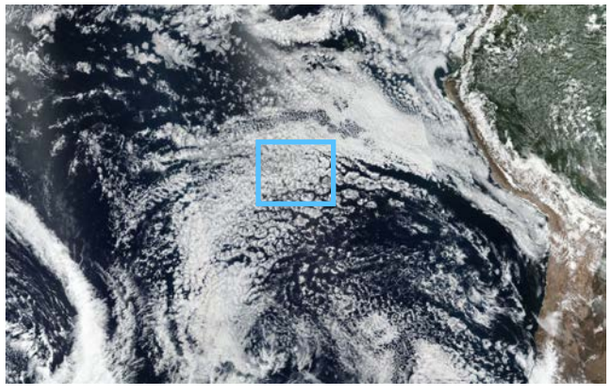

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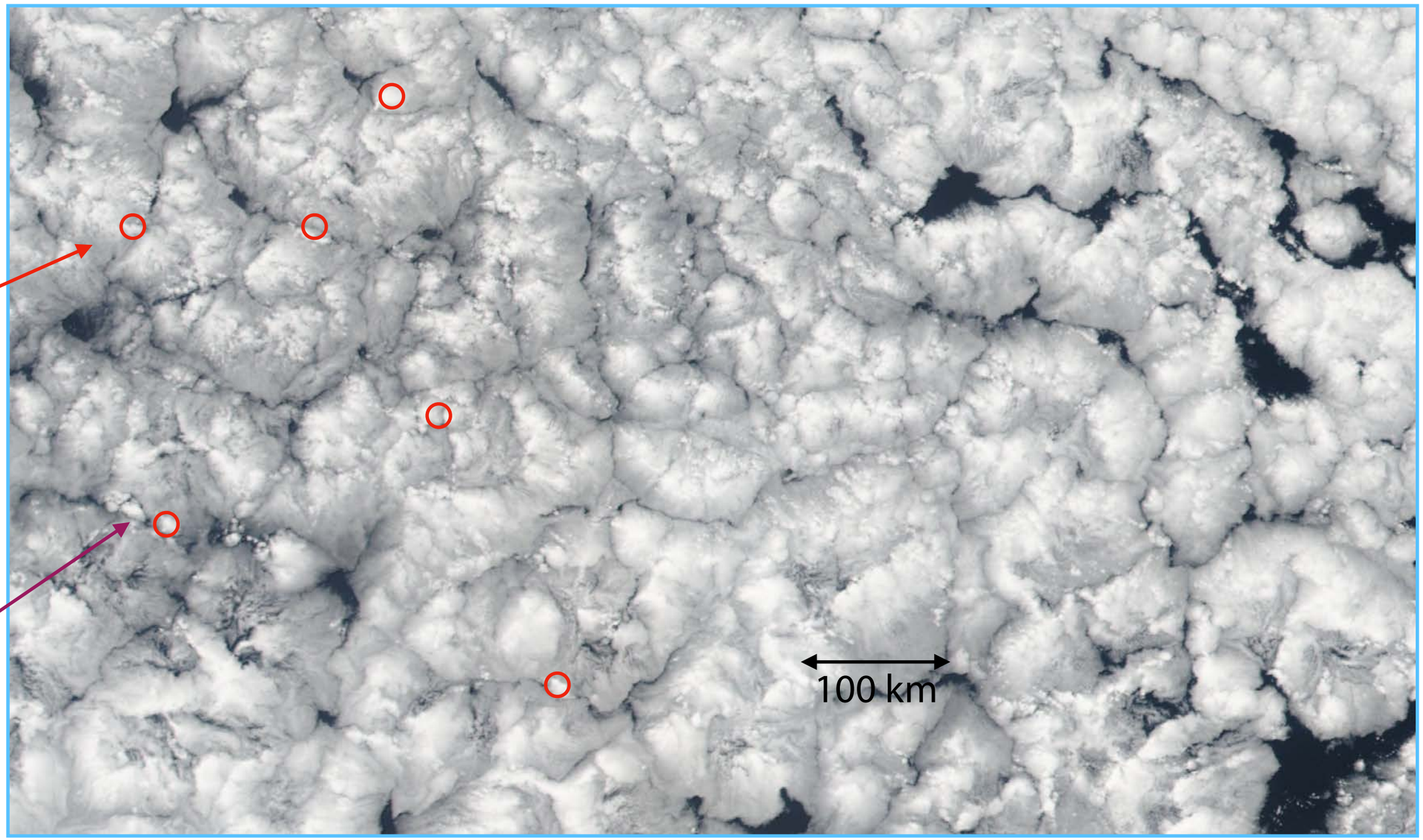

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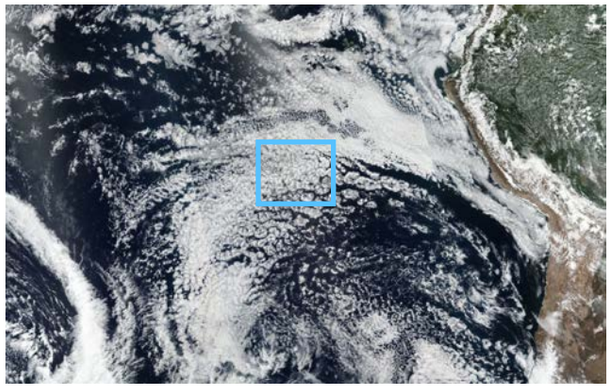

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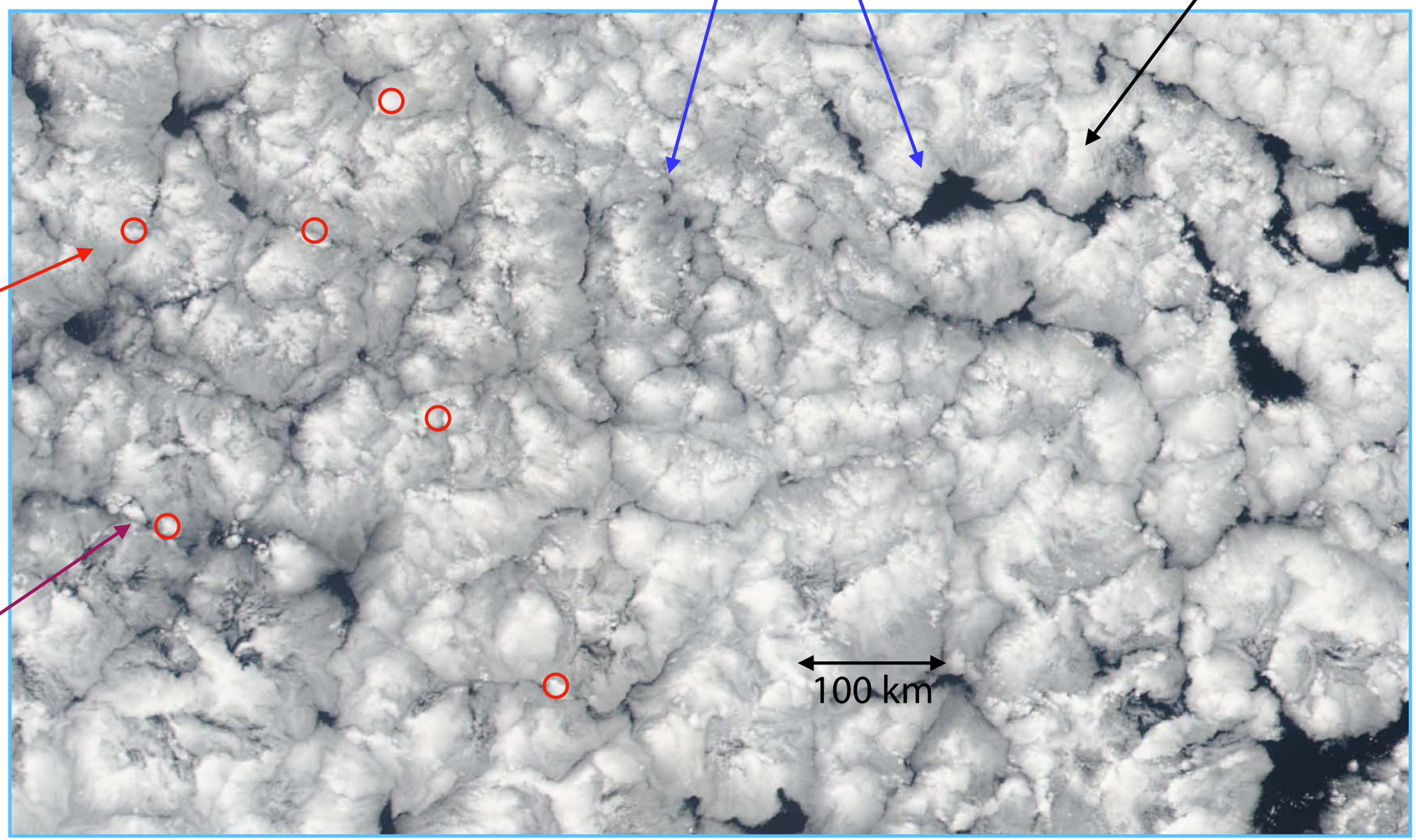


Conclusions

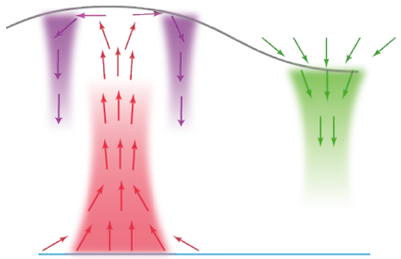
Coherent structures in LES using the MESO-NH model

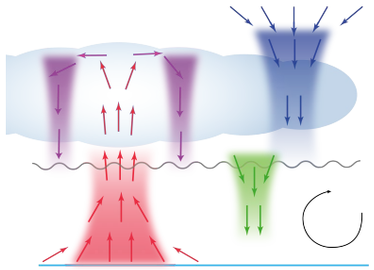
Updrafts contribute the most to heat and moisture transport

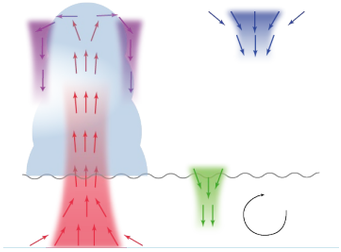
Downdrafts contribute significantly to transport only in StCu simulations (FIRE)

Downward coherent structures 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:

Conclusions

Coherent structures in LES using the MESO-NH model

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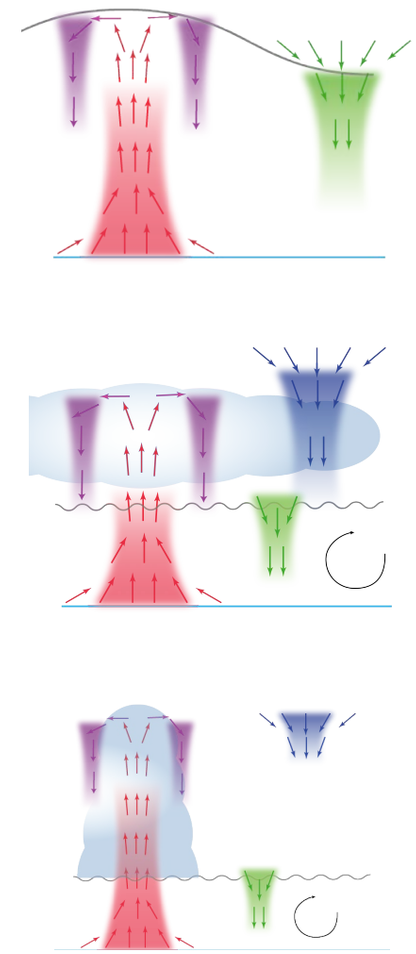


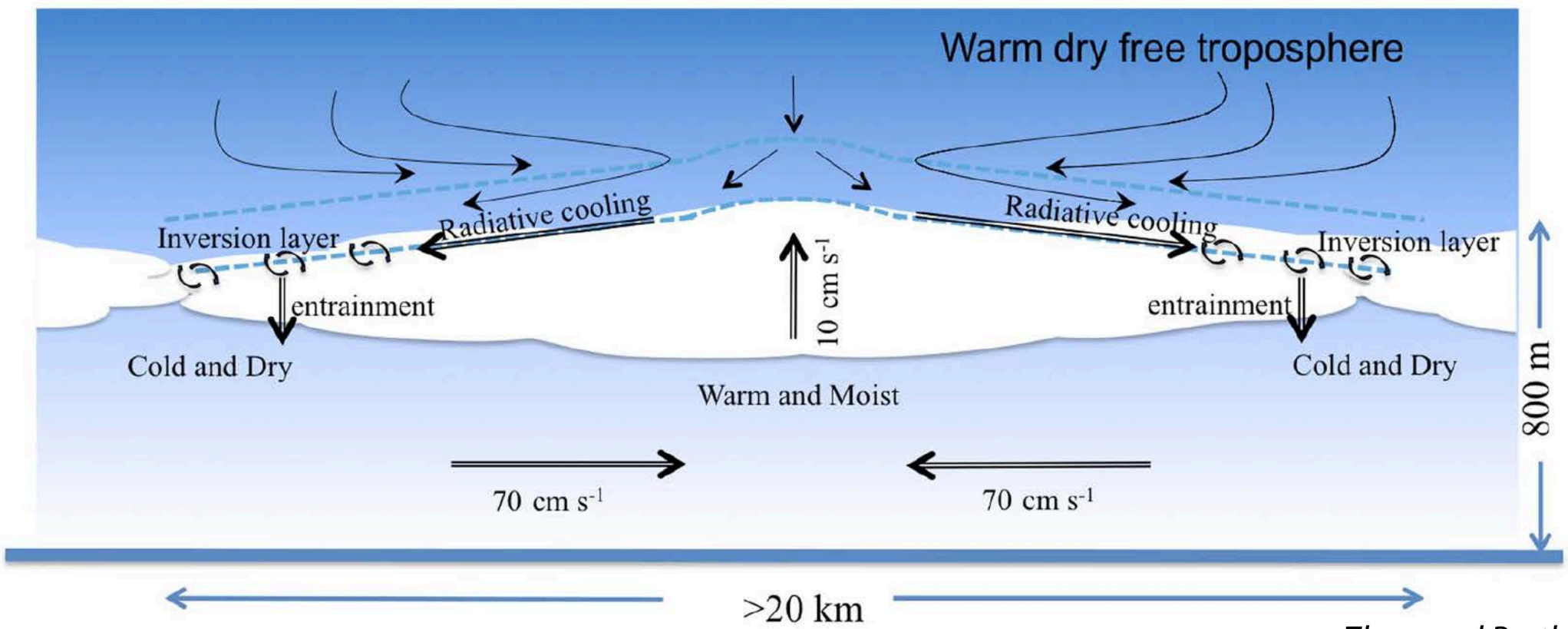
Future work about boundary-layer coherent structures:

- Building better unified parameterizations for low-clouds
  - How should be represented downward motions?
  - Is the **top-hat approximation** relevant for downdrafts?
- Process-oriented analysis of the meso-scale low-cloud organisation
  - What are the drivers of boundary-layer characteristics?
  - Is the **distance between updrafts** important?
- Low-cloud feedback mechanisms
  - Changes in coherent structures **drive** changes in cloudiness.
  - How do coherent structures will change with global warming?

Extra

Physical understanding of downdrafts

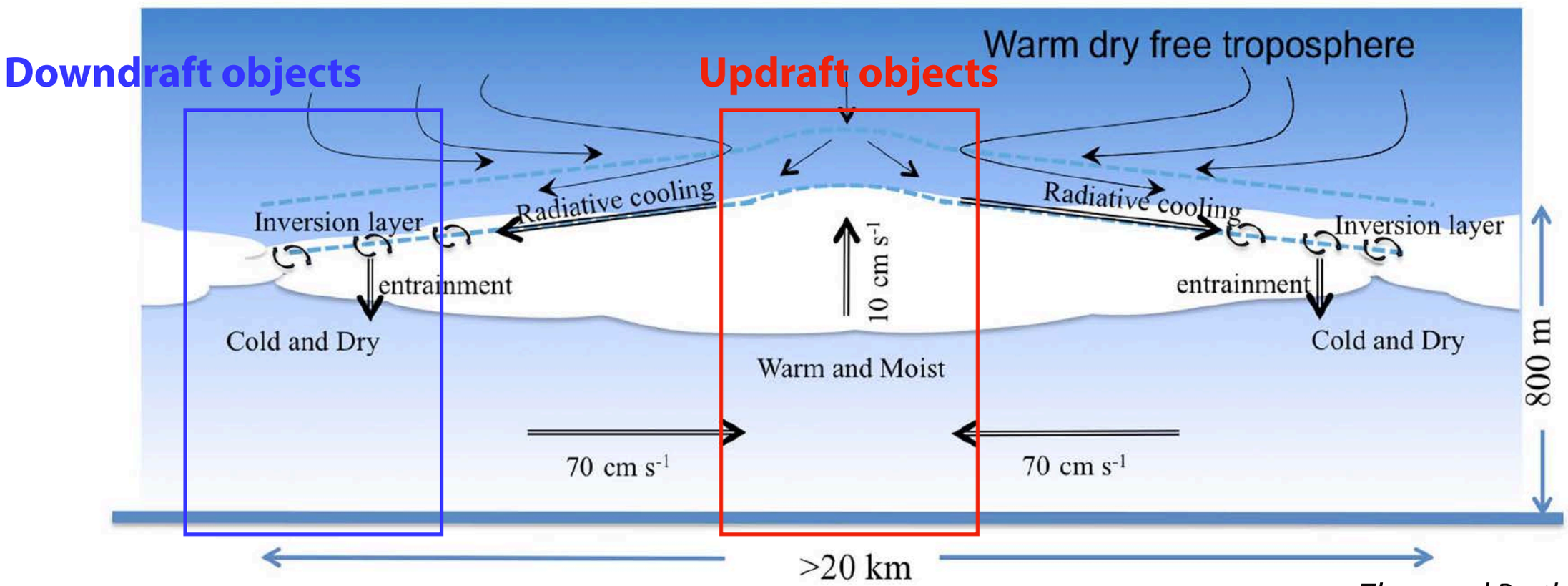
StCu (FIRE)



Zhou and Bretherton (19)

Physical understanding of downdrafts

StCu (FIRE)



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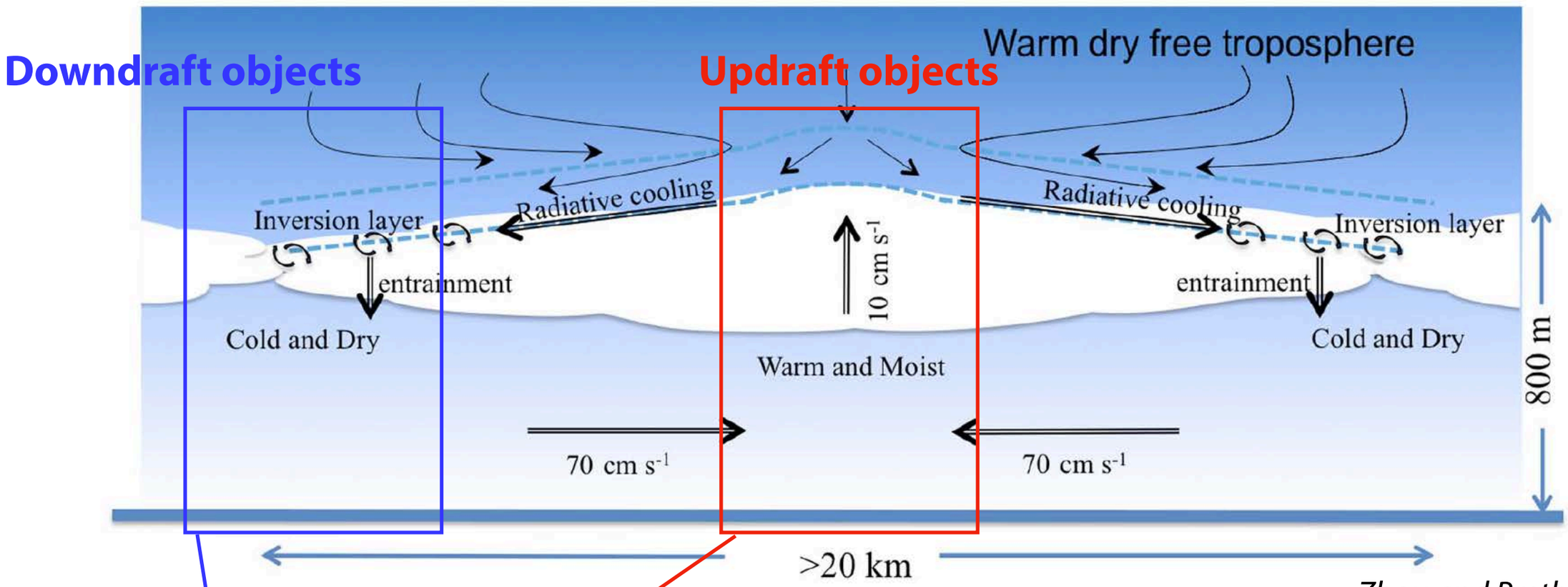
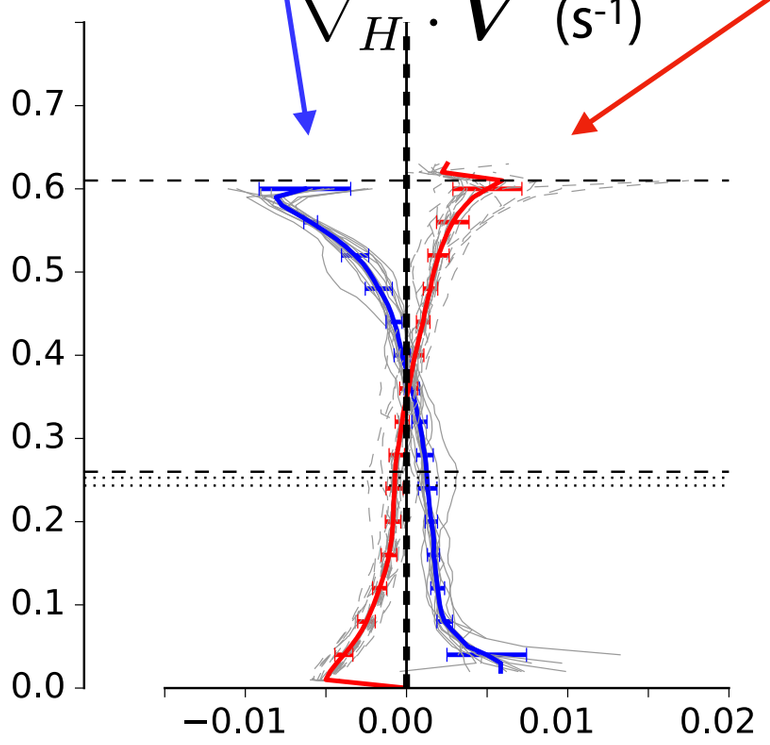


Zhou and Bretherton (19)

Divergence

$\nabla_H \cdot \boldsymbol{V}$ (s^{-1})



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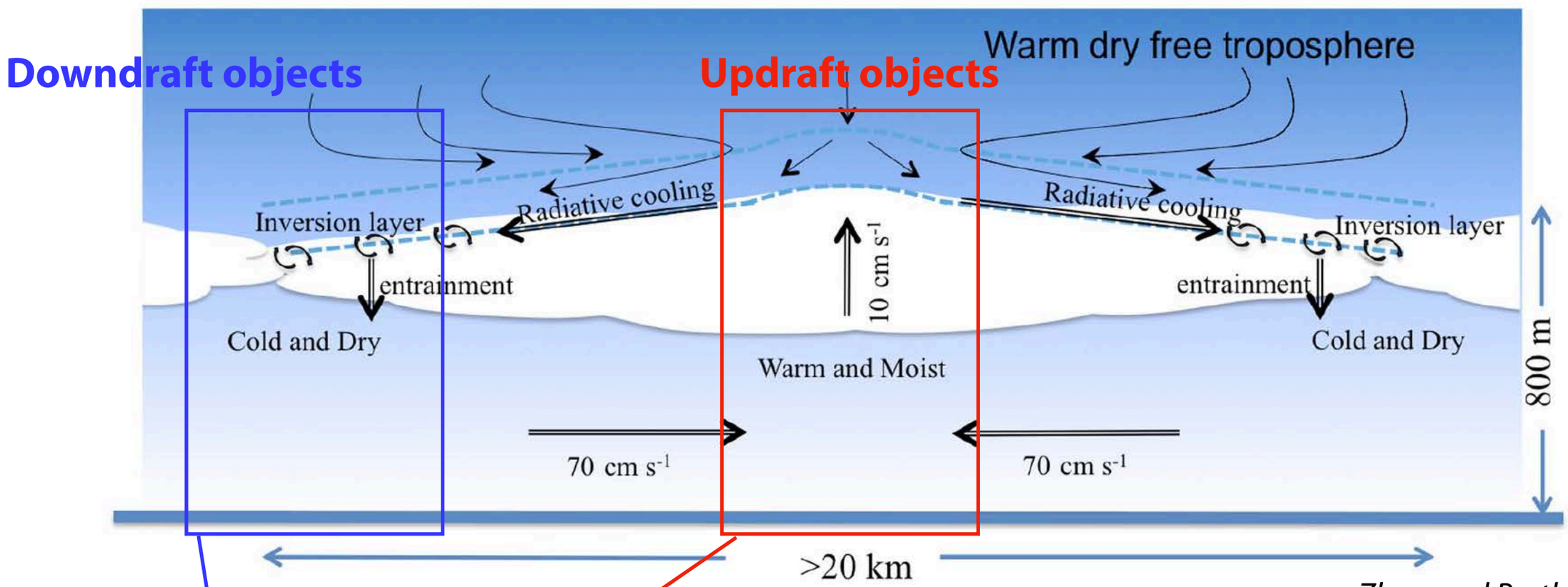

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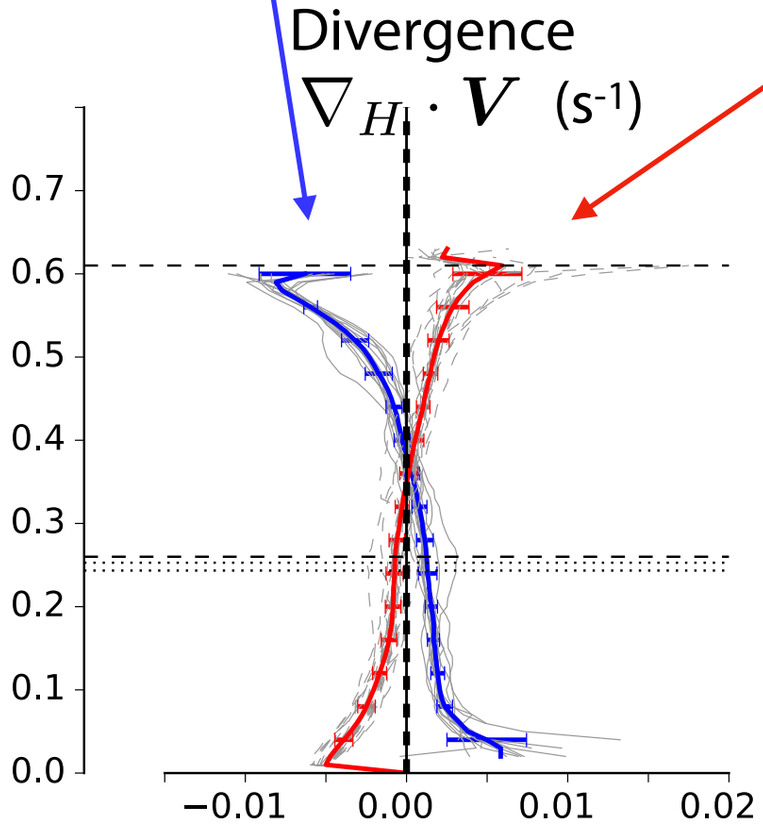
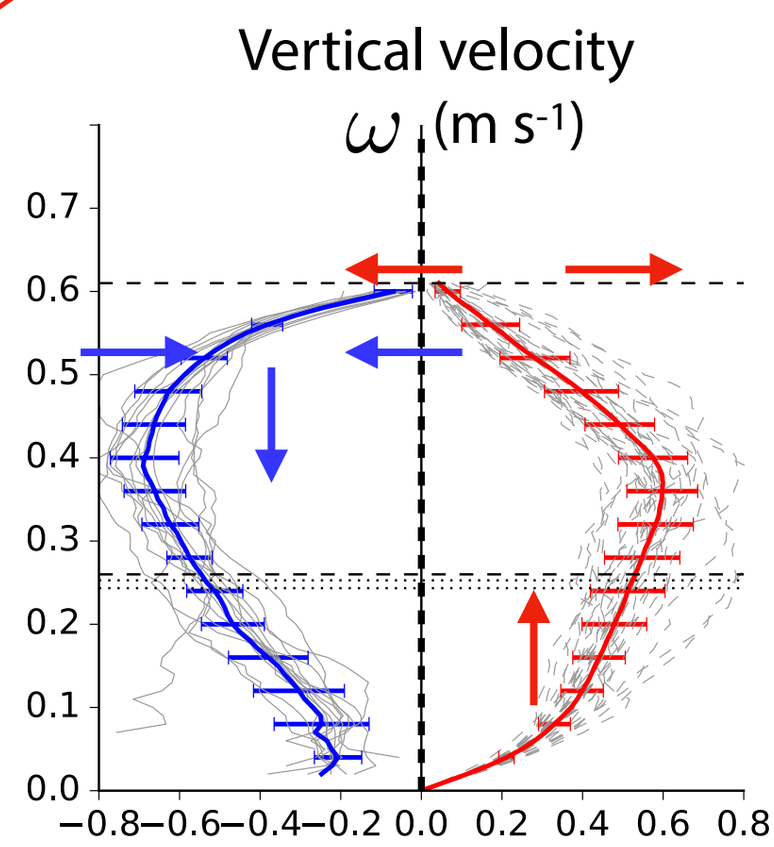
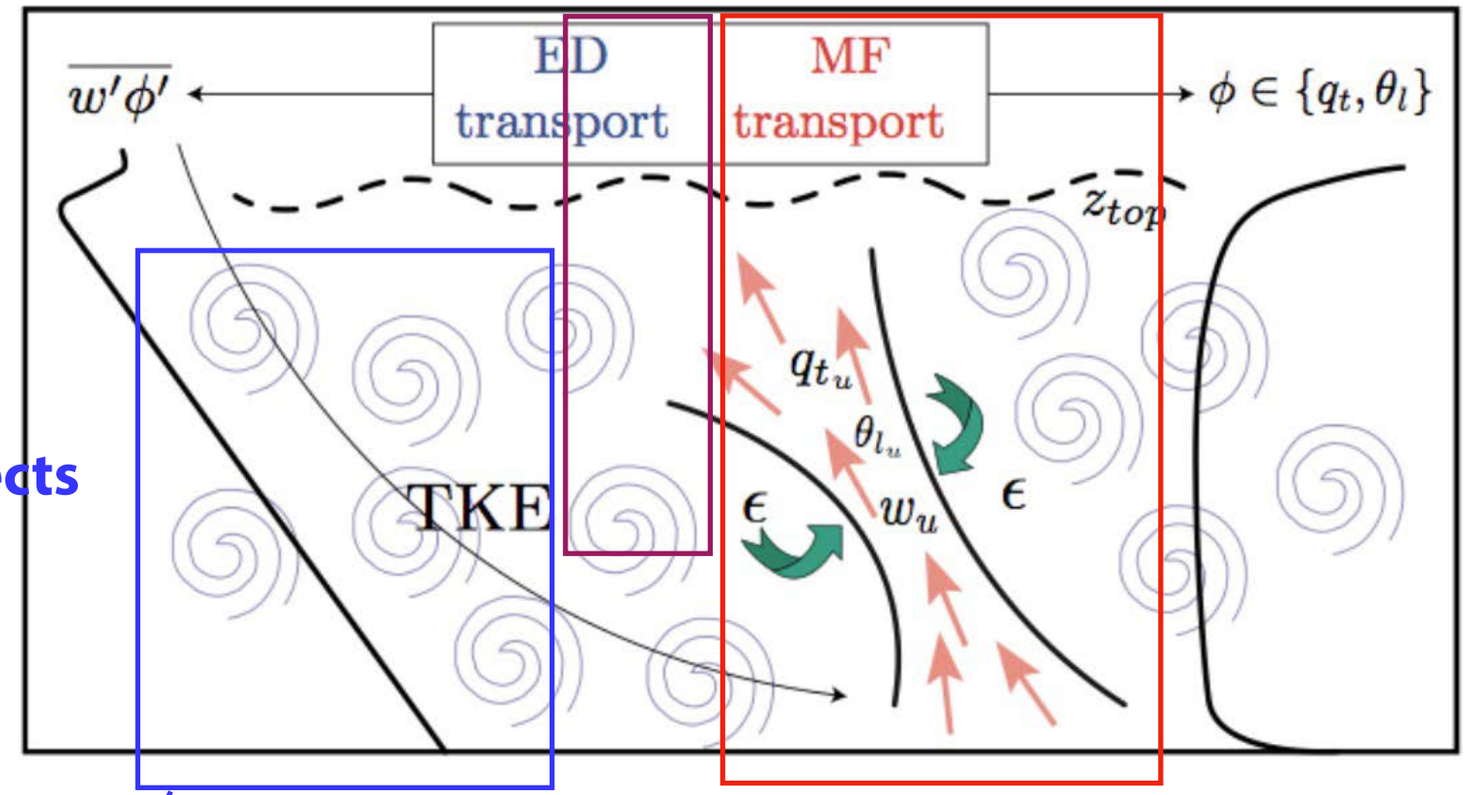




- *Divergence* at the top of updrafts
- *Convergence* where downdrafts start (20-30m below the updraft's divergence)
- Updrafts trigger downdrafts? Then, amplify by buoyancy reversal?

Physical understanding of downdrafts

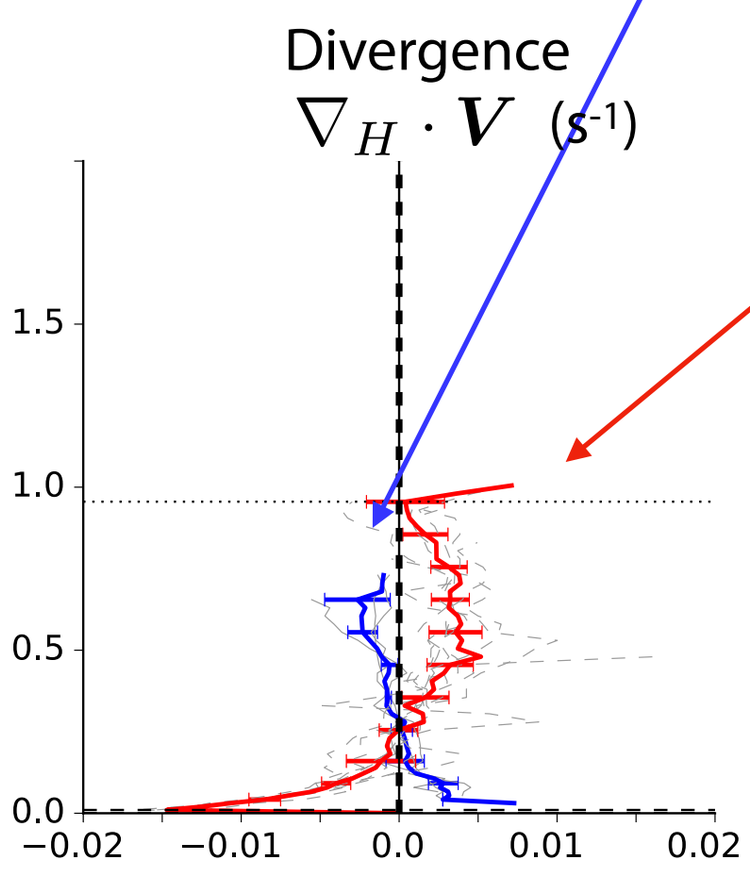
Clear-sky (IHOP)

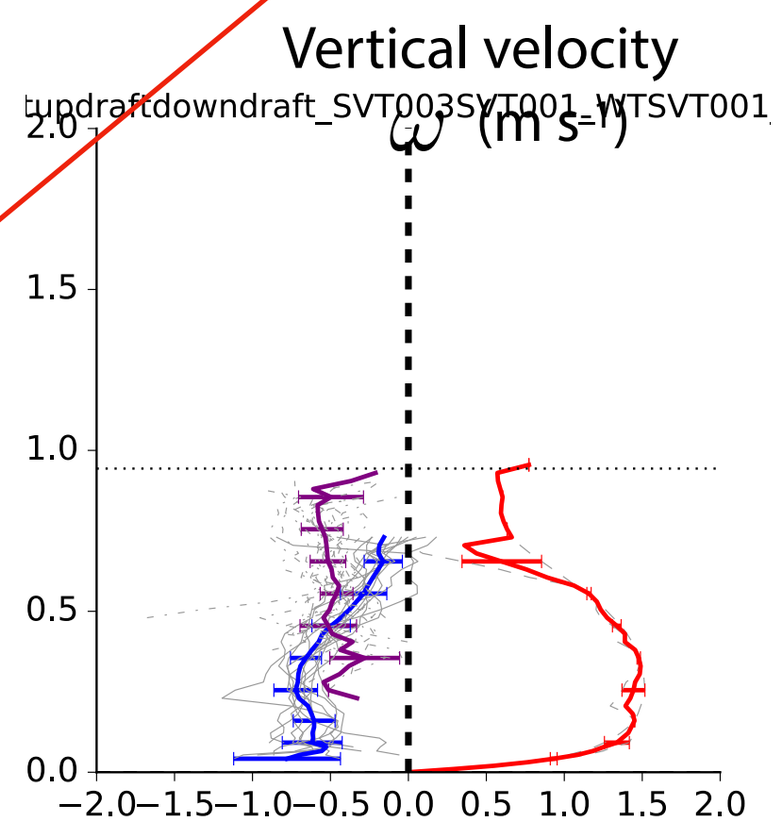


Downdraft objects

Updraft objects

Witek et. al (11)





- *Divergence* at the top of updrafts
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