Object-oriented analysis of coherent subsiding structures in large eddy simulations of boundary layers

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EUREC4A/LMD Meeting, 13/10/22

IPSL

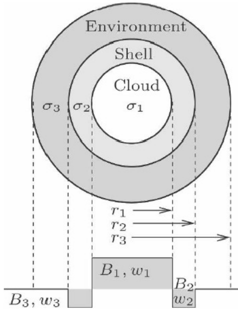
LMD

Subsding coherent structures

- Coherent structures exist in convective boundary layers. For upward motions, they are called updrafts

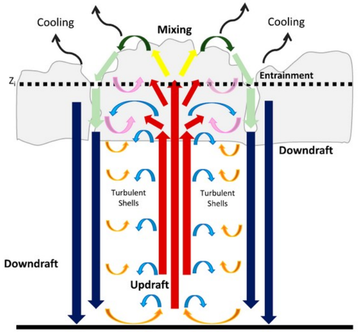
- Subsiding coherent structures also exist in boundary layers. **4 different structures** have already been identified in high-resolution simulations (large-eddy simulations or LES) and observations
  a) Subsiding (or returning) shells in the surroundings of cumulus
  b) Cloud-top downdrafts in stratocumulus
  c) Dry tongues in dry convective boundary layers
  d) Cold pools in deep and shallow convection

a)



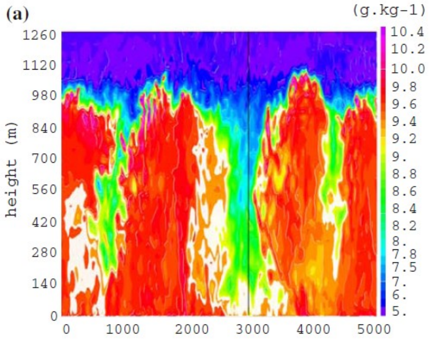
Heus and Jonker (2008)

b)



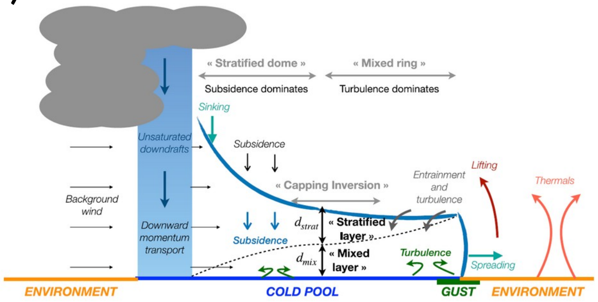
Davini et. al (2017)

c)



Couvreux et. al (2007)

d)

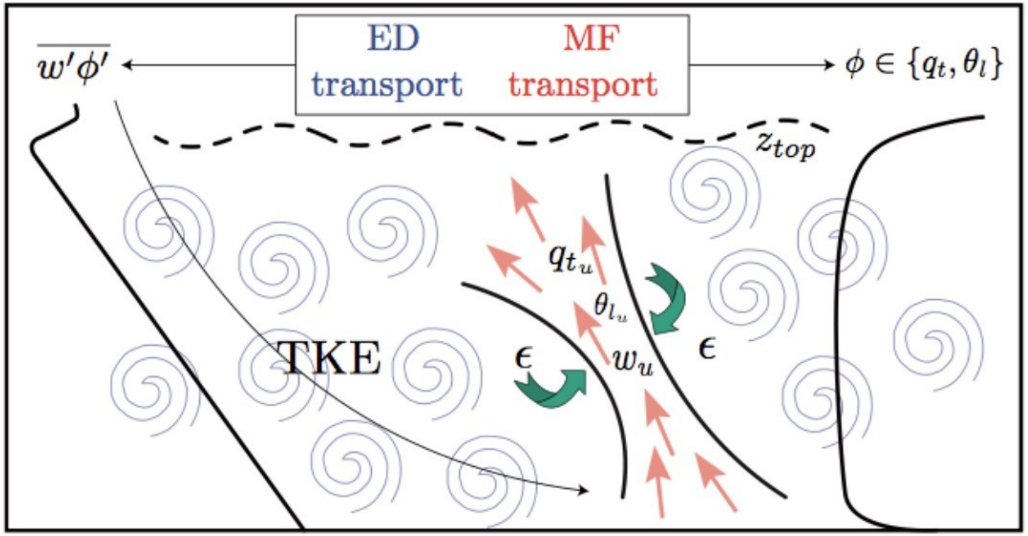


Rochetin et. al (2020)

Subsding coherent structures

- **Parameterizations** use in climate models (GCMs) is often a combinaison between local diffusivity and upward mass fluxes (EDMF schemes).
- Coherent structures are represented with mass flux approximation. All moodels represent updrafts. Almost no operational climate models represent **coherent subsiding structures**
- Questions remain about subsiding structures: diabatic vs adiabatic effects for their trigerring, mesoscale organisations, rain, consistency across boundary layers, etc…

- <u>In this work :</u>
  - **Identifying** coherent structures in large-eddy simulations of boundary layers
  - **Characterize** objects, quantifiy contribution to fluxes
  - Analyse spatial organisation
  - **Discuss** parameterization of downdrafts



Large-eddy simulations

3 simulations using the high-resolution **MESO-NH** model (CNRM/LA)
Clear-Sky convection (IHOP), Cumulus (BOMEX), Stratocumulus (FIRE)

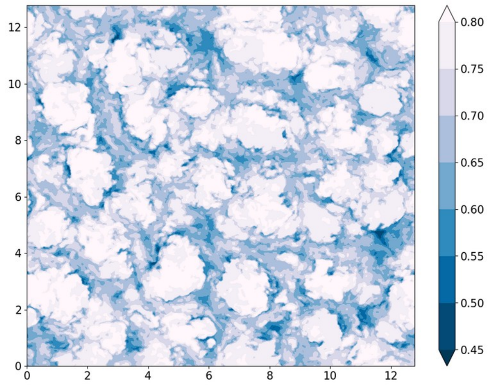
Domain size:
BOMEX/IHOP : 12.8x12.8x4 km^3 ($\Delta x = \Delta y = \Delta z = 25m$) ; $\Delta t = 1s$
FIRE : 25.6x25,6x1,2 km^3 ($\Delta x = \Delta y = 50m$, $\Delta z = 10m$) ; $\Delta t = 1s$

Parameterizations:
Advection: 4^{th} centered ; Temporal: 4^{th} Runge-Kunta
Turbulence: 1,5-order closure
Radiation: None (IHOP), Prescribed LW (BOMEX), ECMWF (FIRE)
Microphysics: None (IHOP), Mixed (BOMEX), 2-moment (FIRE)

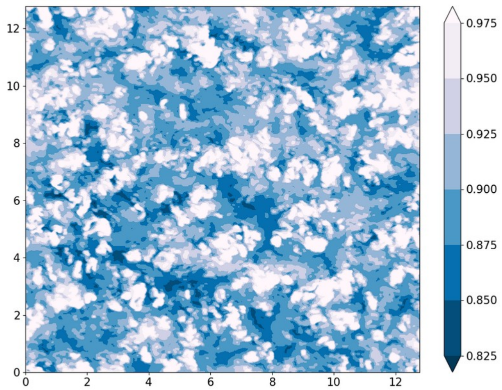
Additional simulations *not analyzed here*: ASTEX, AYOTTE, RICO, ARMCu

Large-eddy simulations

Cross section of **relatuve humidity**
at the top of the mixed layer (zi)

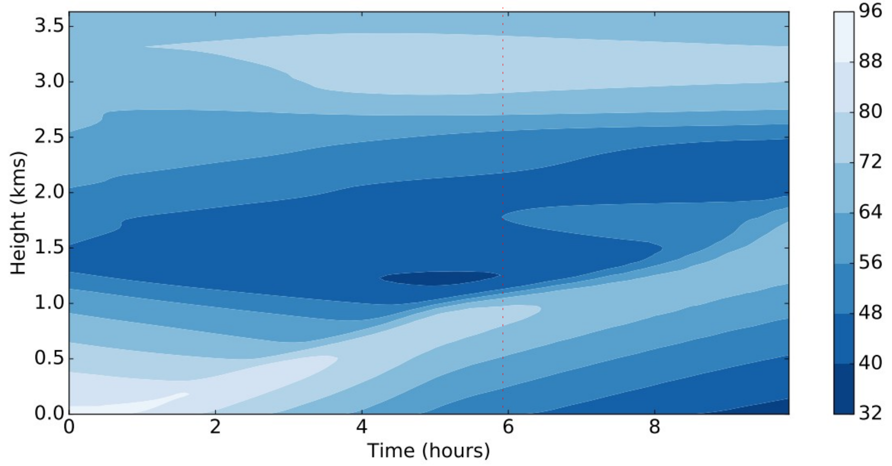


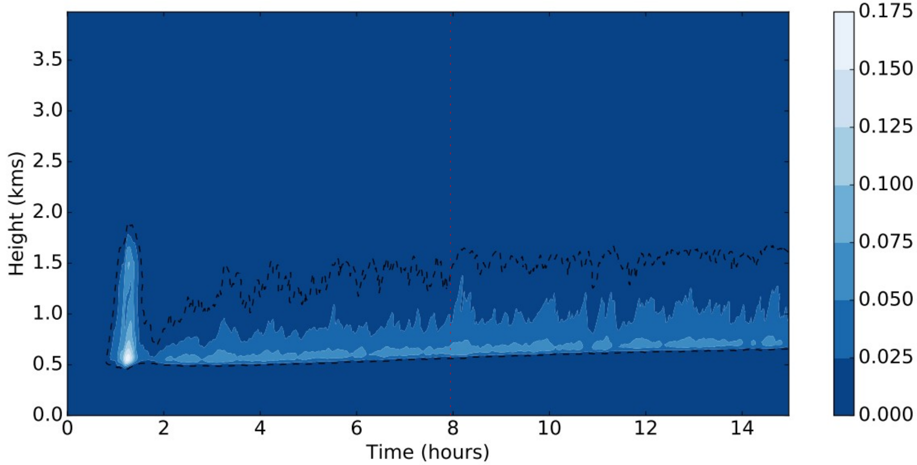
IHOP
(t+6h)



BOMEX
(t+8h)

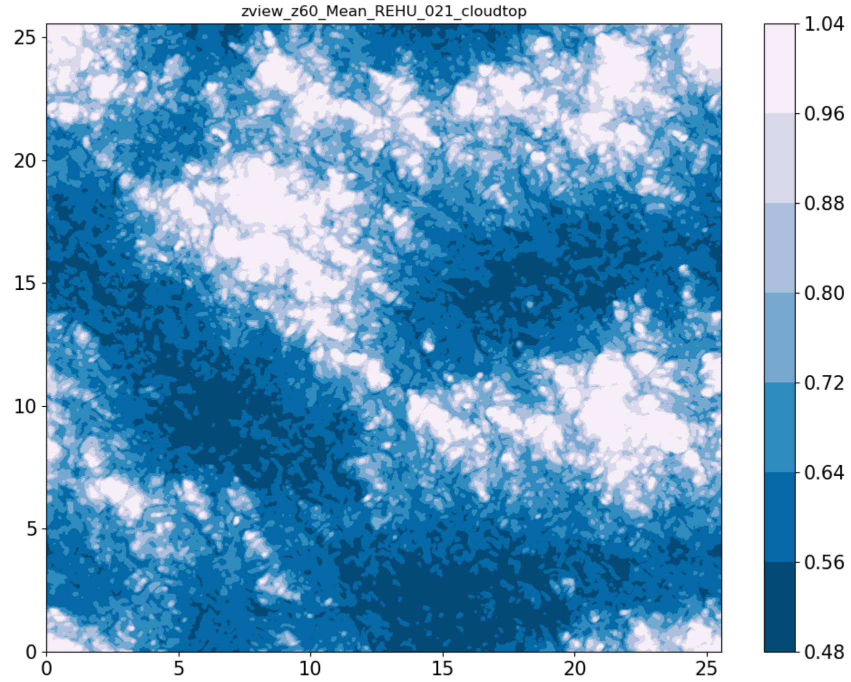
Time evolution of relative humidity



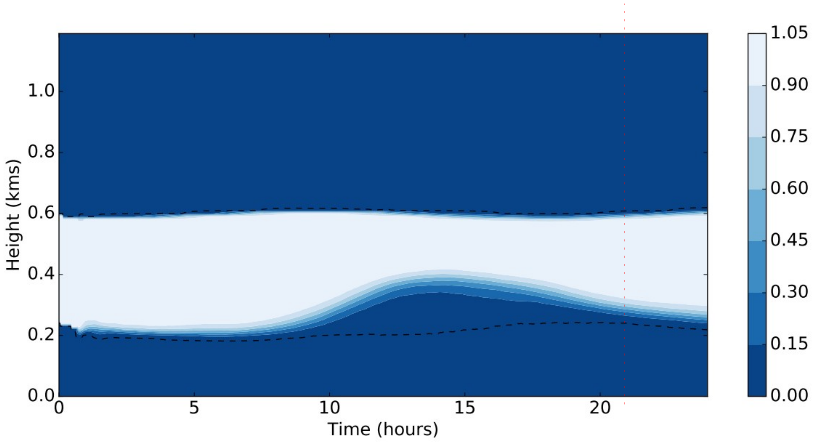


Large-eddy simulations

Cross section of **relatuve humidity**
at the top of the mixed layer (zi)



Time evolution of cloud fraction



FIRE
(t+21h)

Object identification methodology

3 tracers emitted at the surface (s_1), at cloud base (s_2), and at cloud top (s_3) decay with a time scale of 30 min. If clear-sky, s_2 emitted atop the boundary layer, defined as when θ_l increases significantly

Based on *Brient et. al (2019)*, **objects** are defined as follow:

1) Grid cells satisfying condition sampling $\mathbf{CS_s} \cap \mathbf{CS_w}$ (with CS_w the CS for positive/negative vertical velocity)
2) Object are defined by **continuous** CS cells (26-connectivity)
3) Objects are selected if big enough $\mathbf{V>V_{min}}$

In this study, we fix m=1 and V_{min} = 0,02 km^3

Code available here: https://gitlab.com/tropics/objects

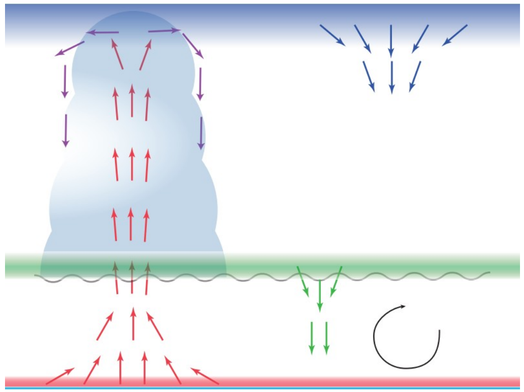
Condition sampling $\mathbf{CS_s}$ is defined as:

$$\left\{(x, y, z) \in CS_s \quad | \quad s'(x, y, z) > \sigma(z)\right\}$$

with:

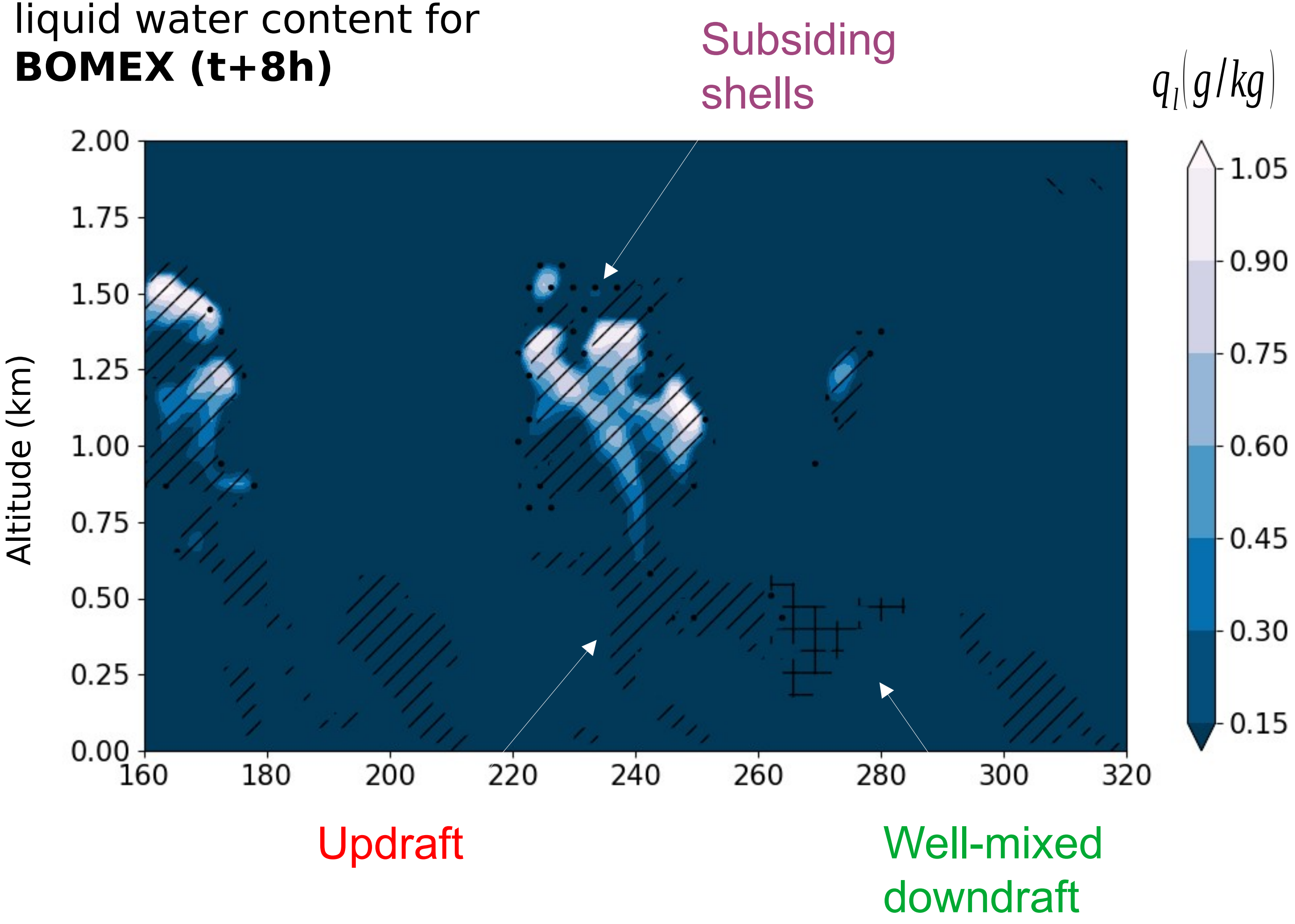
$$\sigma(z) = m \times \max(\sigma_s(z), \sigma_{min}(z))$$

$$\sigma_{min}(z) = L \cdot \frac{0.05}{z - z_1} \int_{z_1}^{z} \sigma_s(z) dz$$

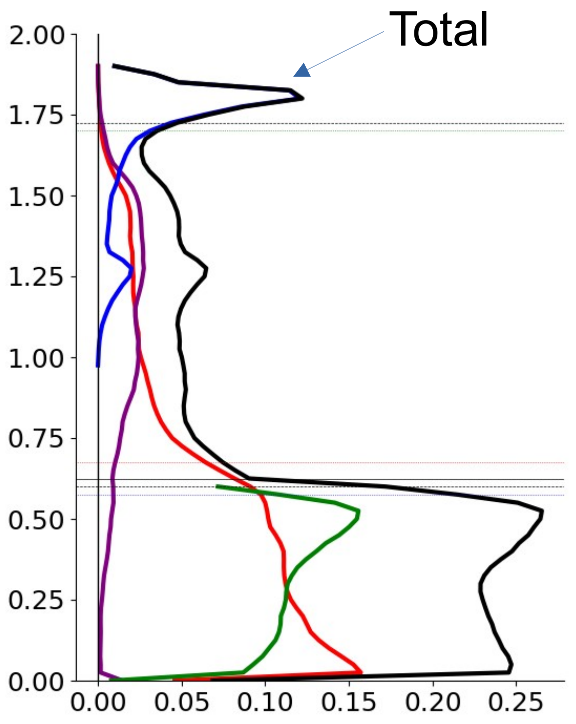


Object identification methodology

Vertical cross section of liquid water content for **BOMEX (t+8h)**

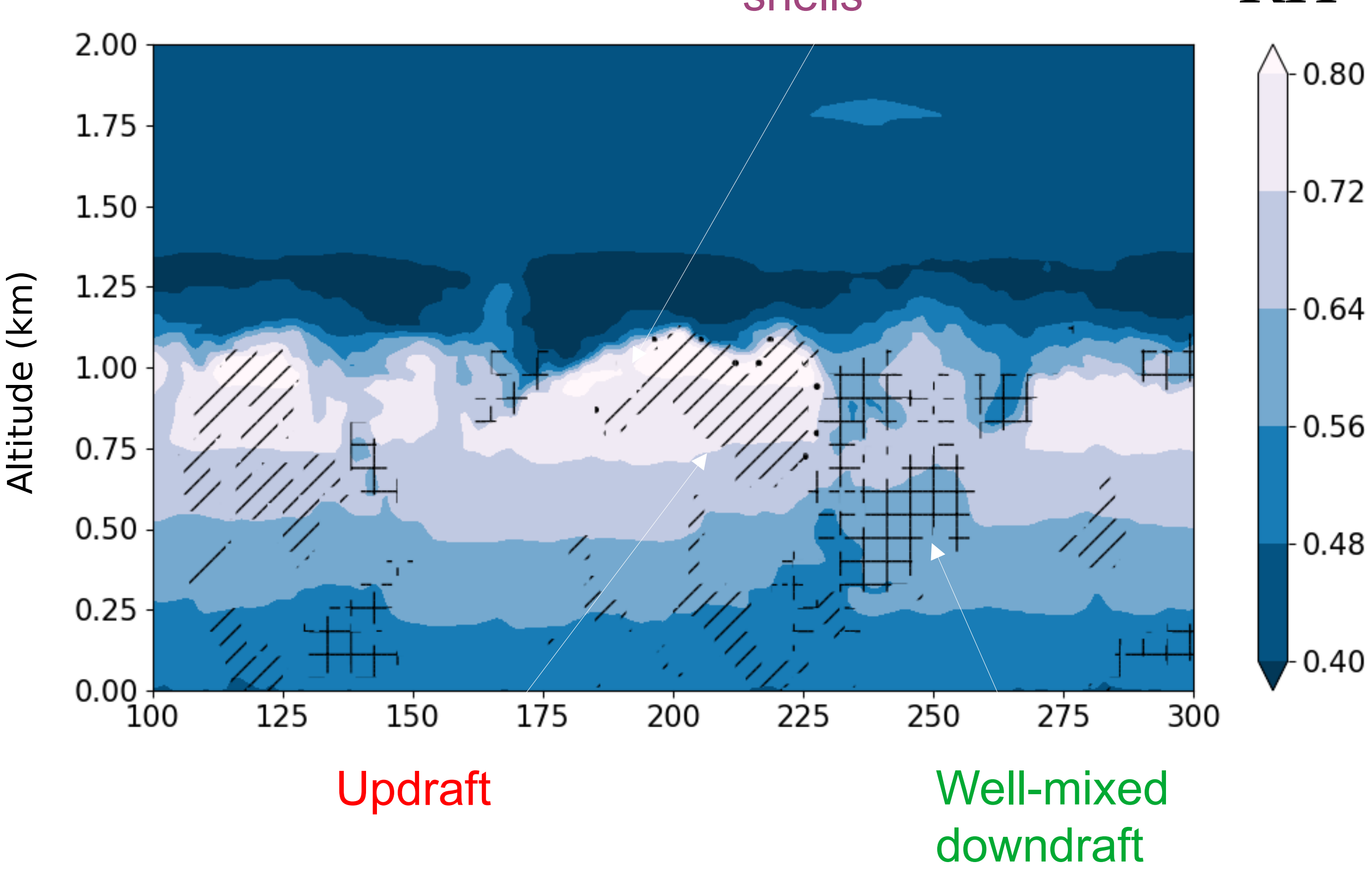


Domain-mean object frequency

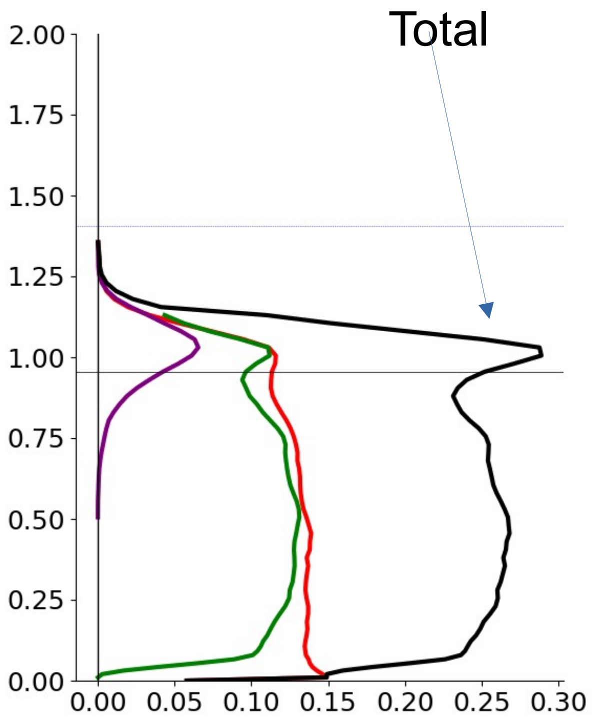


Object identification methodology

Vertical cross section of relative humidity for **IHOP (t+6h)**

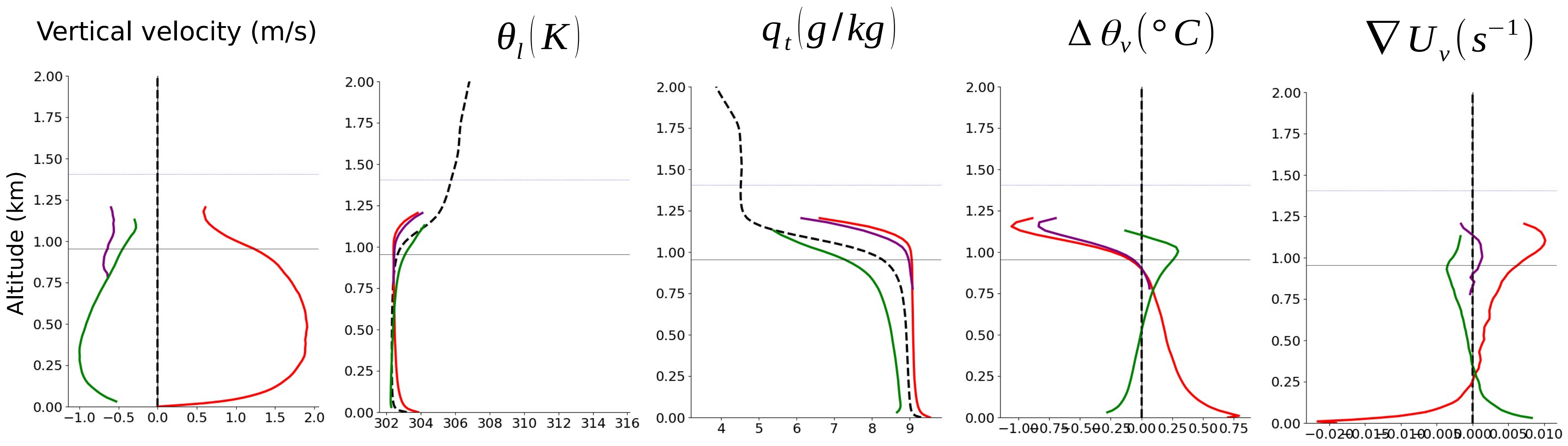


Domain-mean object frequency



Mean object characteristics in IHOP

Updraft
Subsiding shells
Well-mixed downdraft



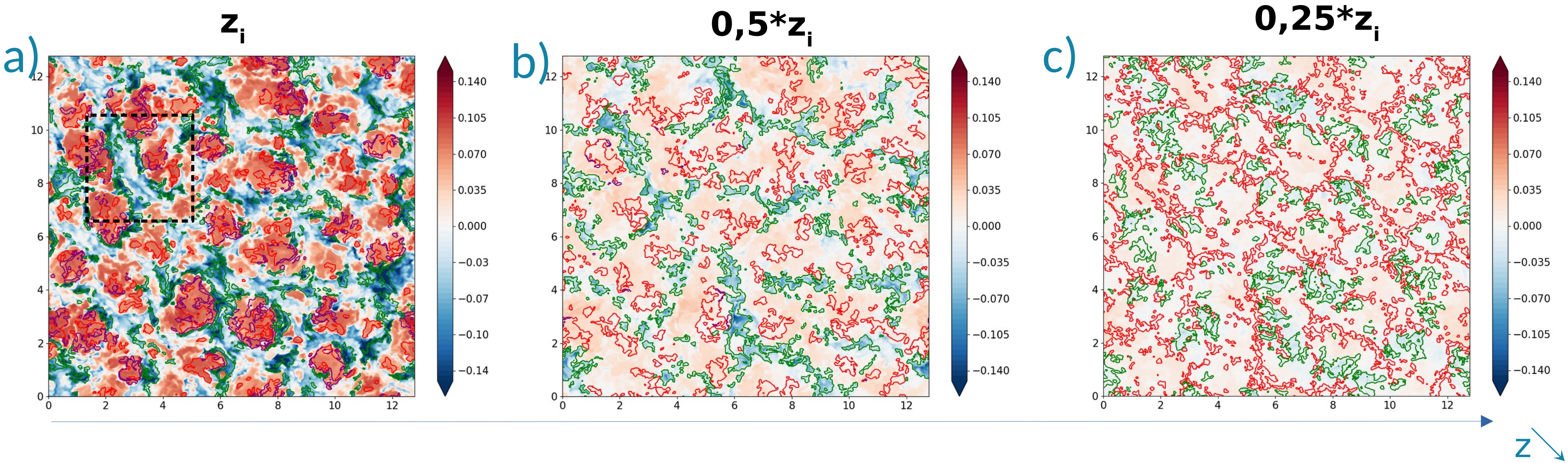
- Vertical velocity:
- Bell-shaped profiles maximizing in the middle of the well-mixed layer (slightly below for IHOP dry tongues)
- Returning shells around -0,7m/s on average

- Temperature and humidity
- Well-mixed downdrafts warmer and drier than updrafts (and the environnment).
- Returning shells have **similar** humidity profiles than updrafts

✓ Buoyancy
✓ Updrafts are positvely buoyant at the surface, become negatively buoyant at the top of ML
✓ Downdrafts start positively buoyant and changes sign in the middle of the mixed layer

✓ Divergence
✓ At surface, updrafts converge while downdrafts diverge
✓ Atop the well-mixed layer, downdrafts converge and updrafts diverge
✓ Zero convergence of updrafts/downdrafts where vertical velocity maximizes

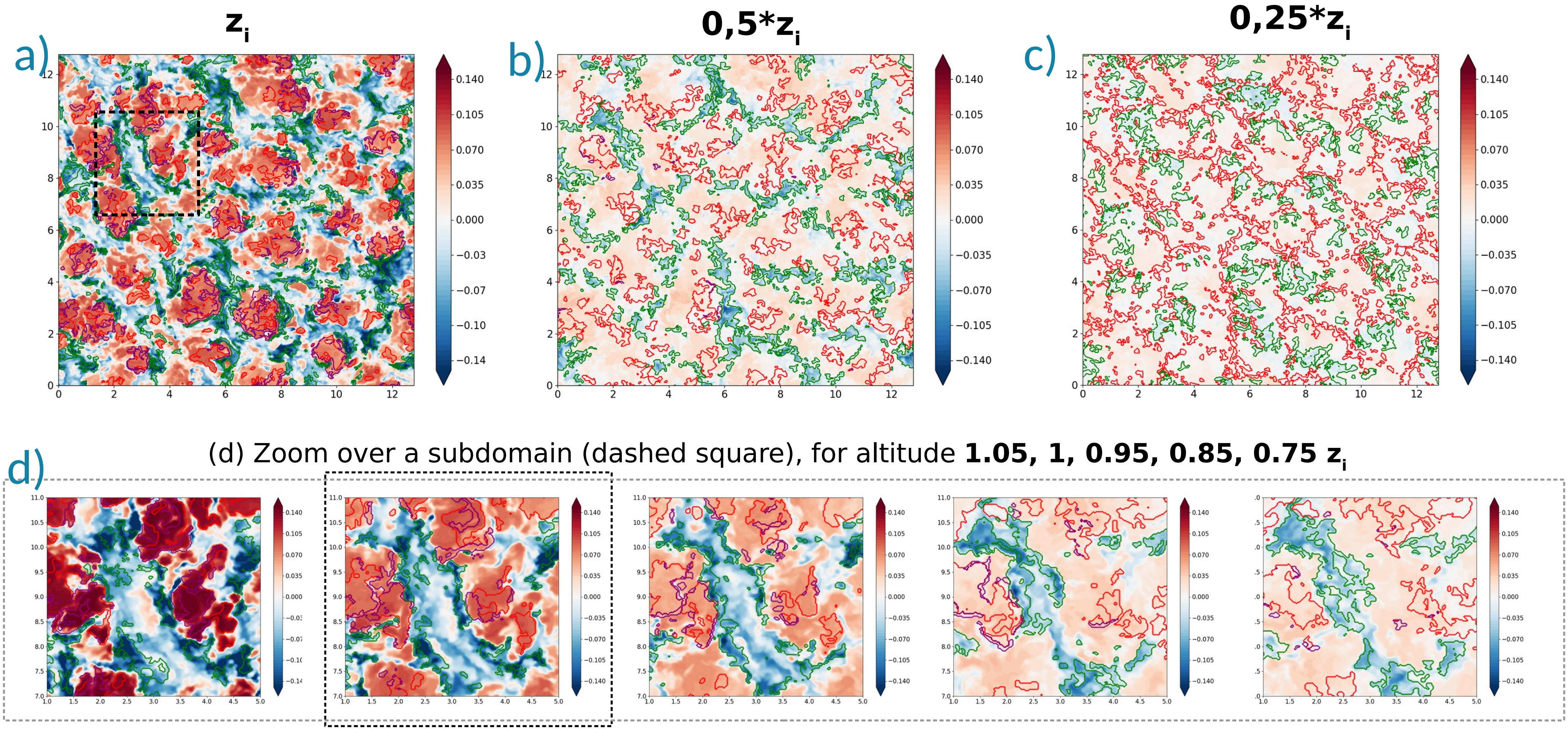
Spatial organisation in IHOP (clear sky)



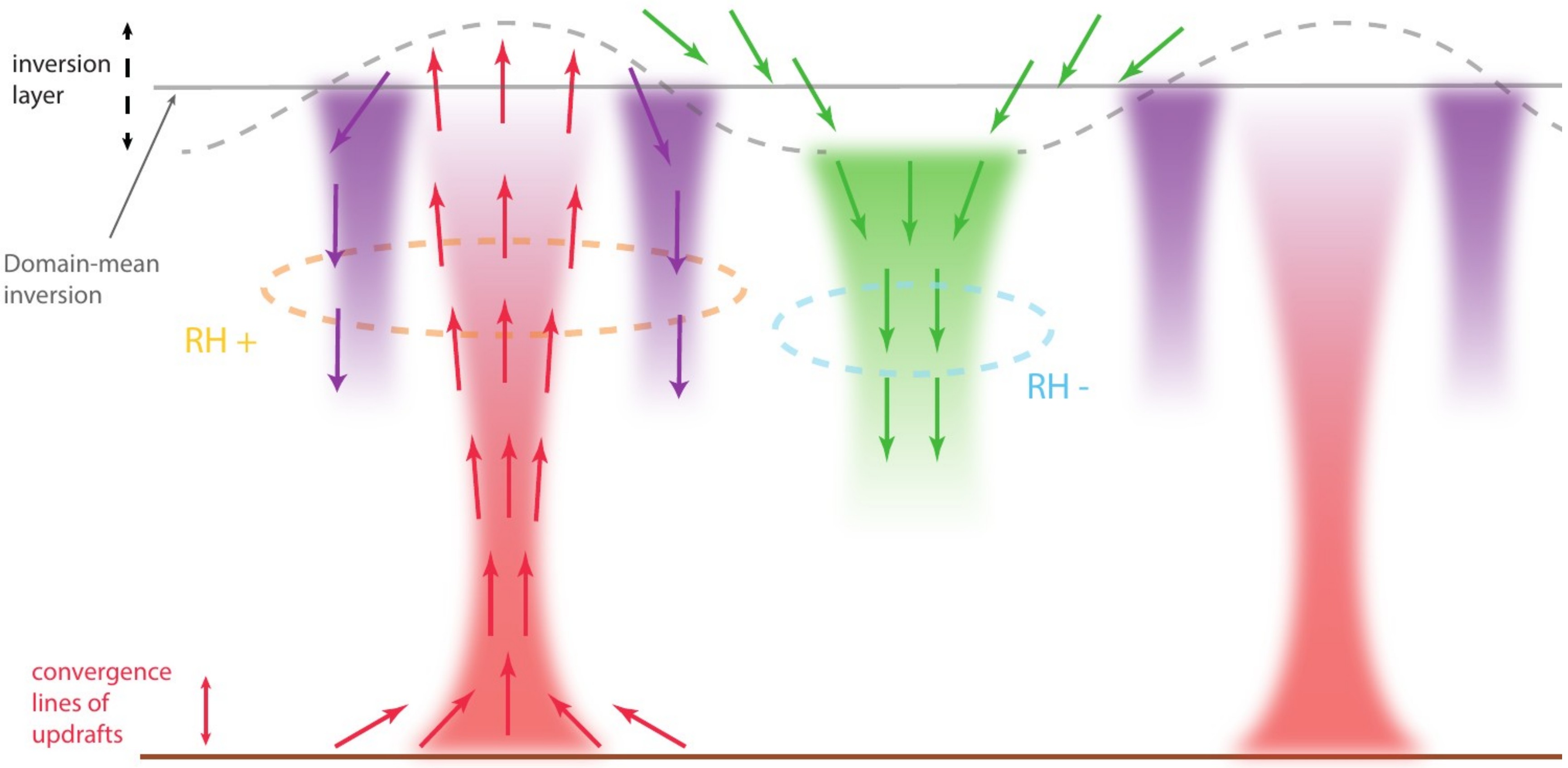
Anomalies of **relative humidity** relative to the domain average at the inversion $\mathbf{z_i}$ (a), $\mathbf{0.5z_i}$ (b), and $\mathbf{0.25z_i}$ (c). Object-defined updraft plumes, subsiding shells and dry tongues are represented as contours

- At the inversion z_i, updrafts have cells sizes of around **2 km diameter** with returning shells at their boundaries and downdrafts between them
- At $z=0.5z_i$, updrafts are smaller in size, and downdrafts are elongated and **interconnected** dry structures located between updrafts. Updraft cores are not associated with maximum relative humidity.
- At $z=0.24z_i$, updrafts are structures organized as **thin lines**. Downdrafts have circular shapes surrounded by updrafts' lines. They are relatively dry.

Spatial organisation in IHOP (clear sky)

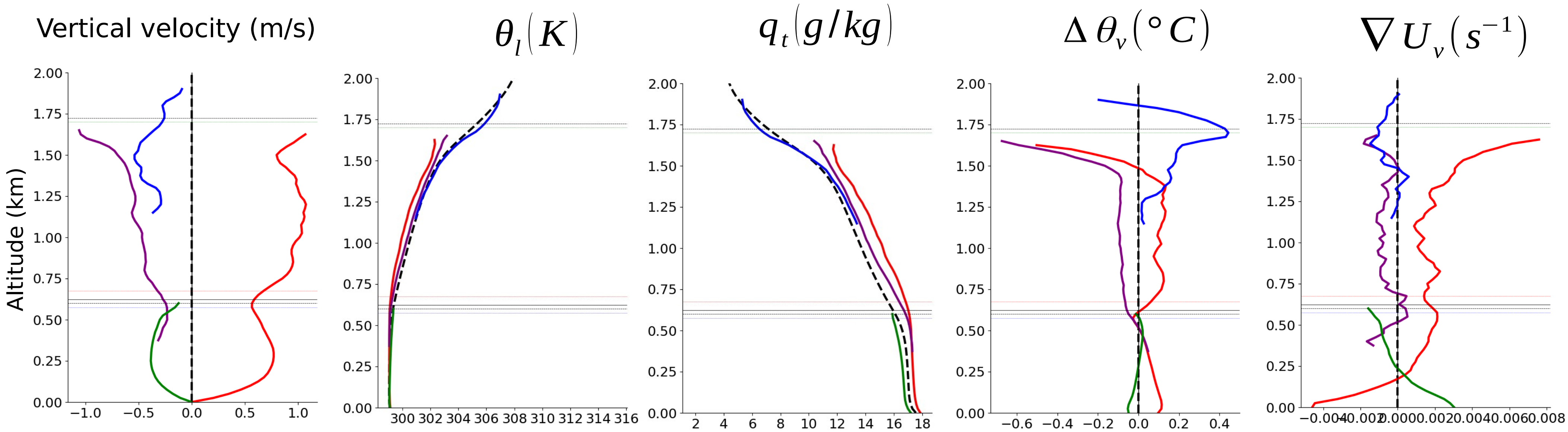


Schematic of coherent structures in the dry convective boundary layer



Mean object characteristics in BOMEX

Updraft
Subsiding shells
Well-mixed downdraft
Cloud-top downdraft



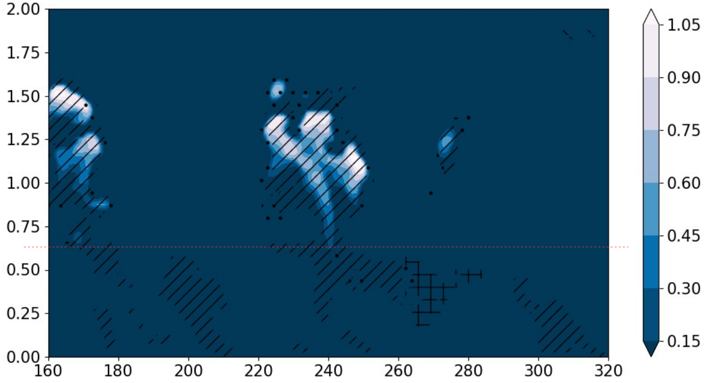
- Vertical velocity:
- Bell-shaped profiles maximizing in the middle of the well-mixed layer
- Increase of updraft velocity in the cloud layer
- Returning shells reach the sub-cloud layer

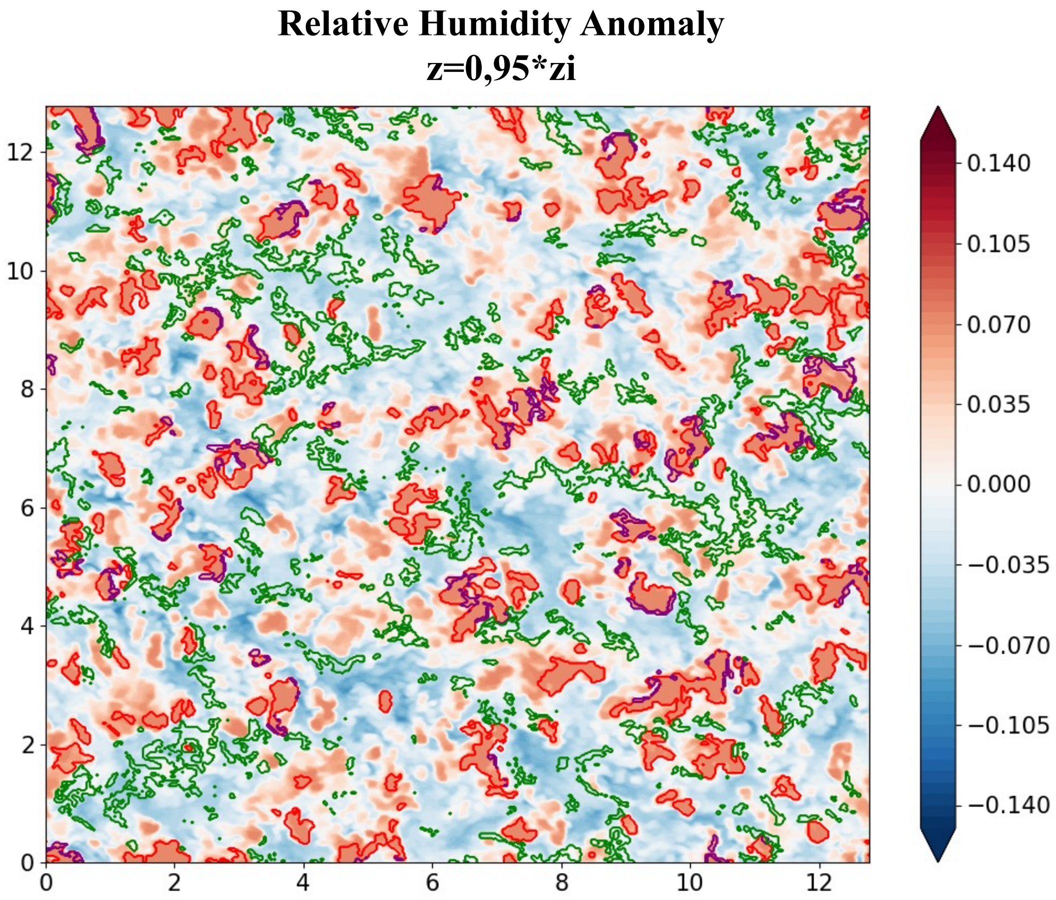
- Temperature and humidity
- Well-mixed downdrafts warmer and drier than updrafts (and the environnment).
- Returning shells have **similar** characteristics than updrafts

- ✓ Buoyancy
- ✓ Updrafts are positvely buoyant at the surface and in the cloud layer, become negatively buoyant at the top of ML
- ✓ Downdrafts start positively buoyant and changes sign in the transition layer

- ✓ Divergence
- ✓ At surface, updrafts converge while downdrafts diverge
- ✓ At the top of the well-mixed layer, downdrafts converge and updrafts diverge
- ✓ Zero convergence of updrafts/downdrafts where vertical velocity maximizes

Spatial organisation in BOMEX



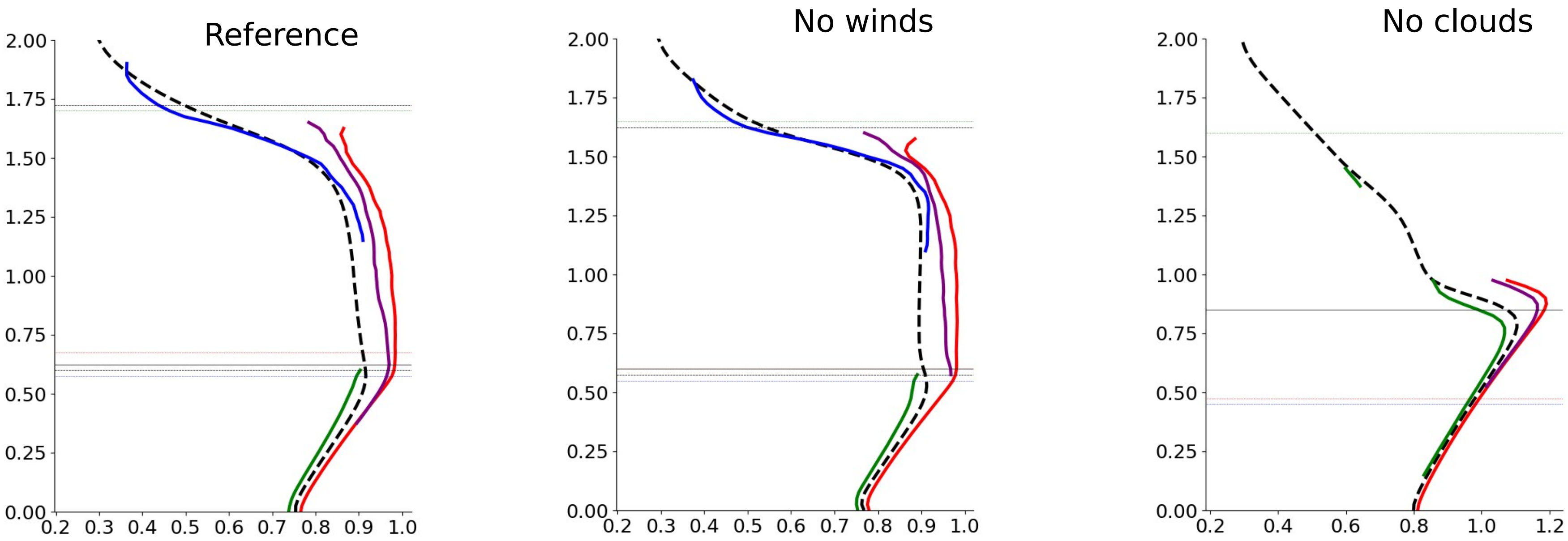


- The spatial organisation of the cumulus sub-clou layer ismore complicated
- Well-mixed downdrafts are located in clear-sky regions, relatively close to updrafts

- **Let's simplify the system ==> No winds or no clouds**

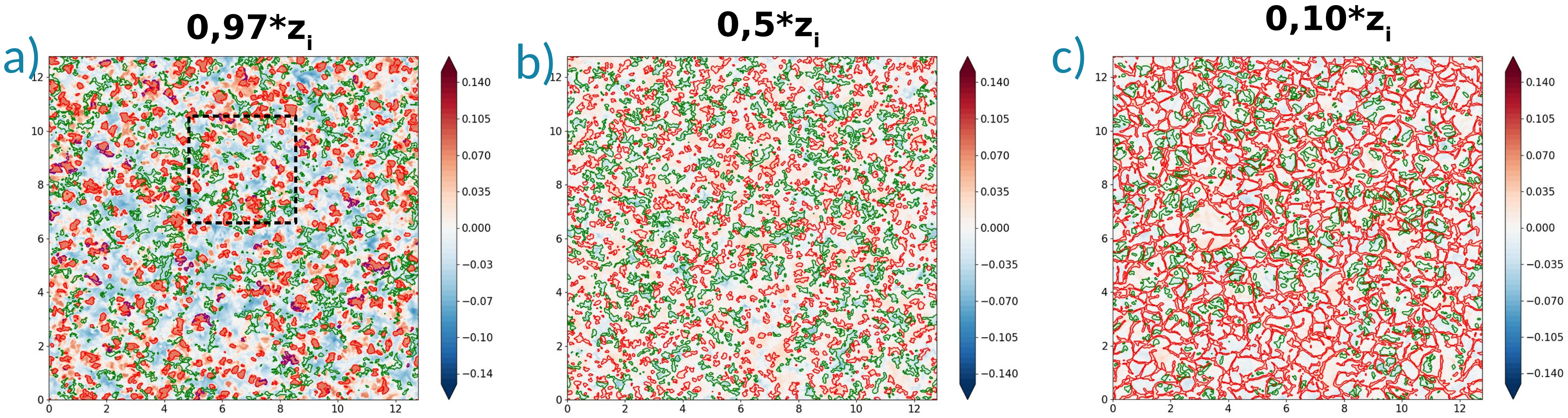
Sensitivity tests

Relative humdity



- Relative humidity profile remains really similar without winds. Small difference of LCL and LNB
- Without clouds, the separation between updrafts/retuning shells and well-mixed donwdrafts exist

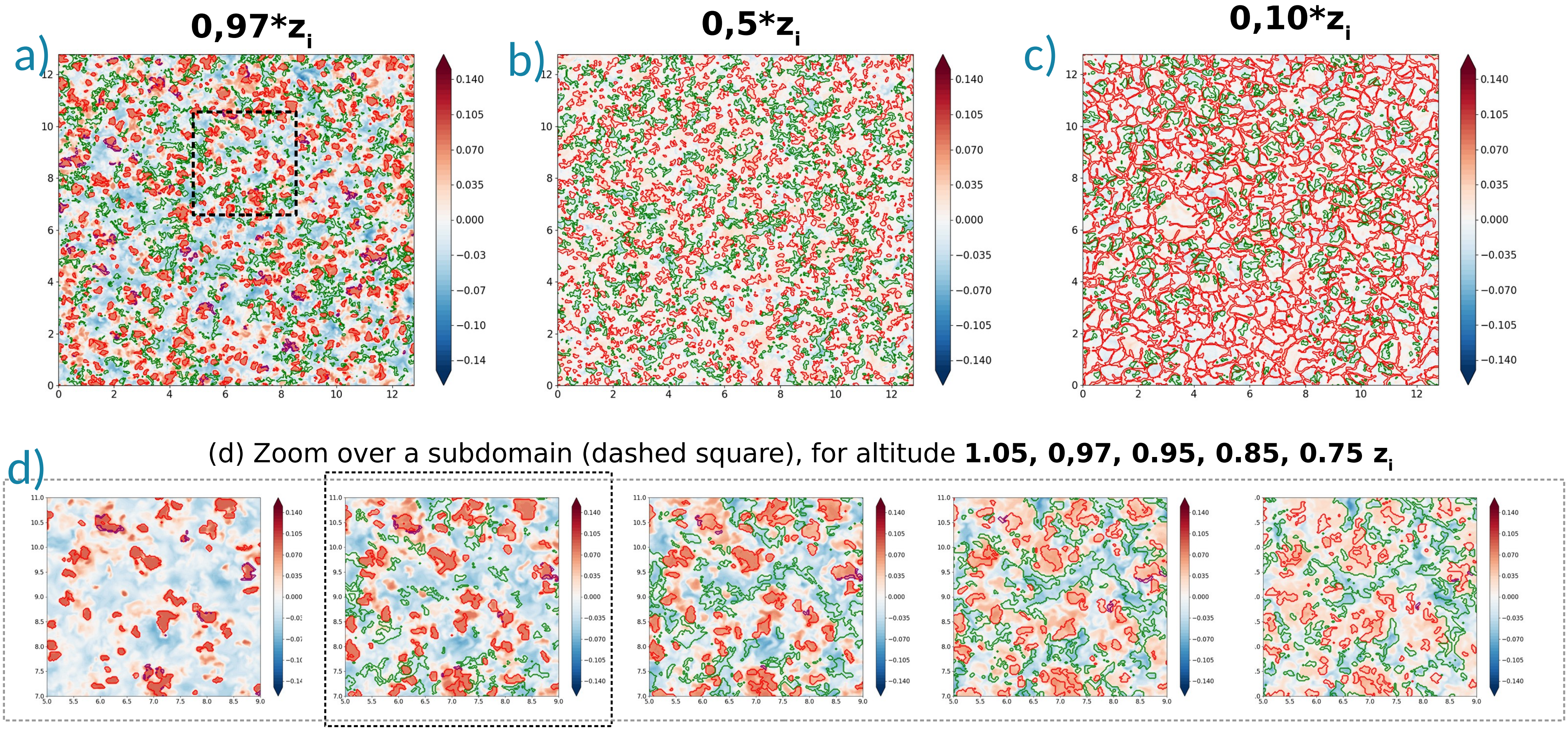
Spatial organisation in BOMEX without winds



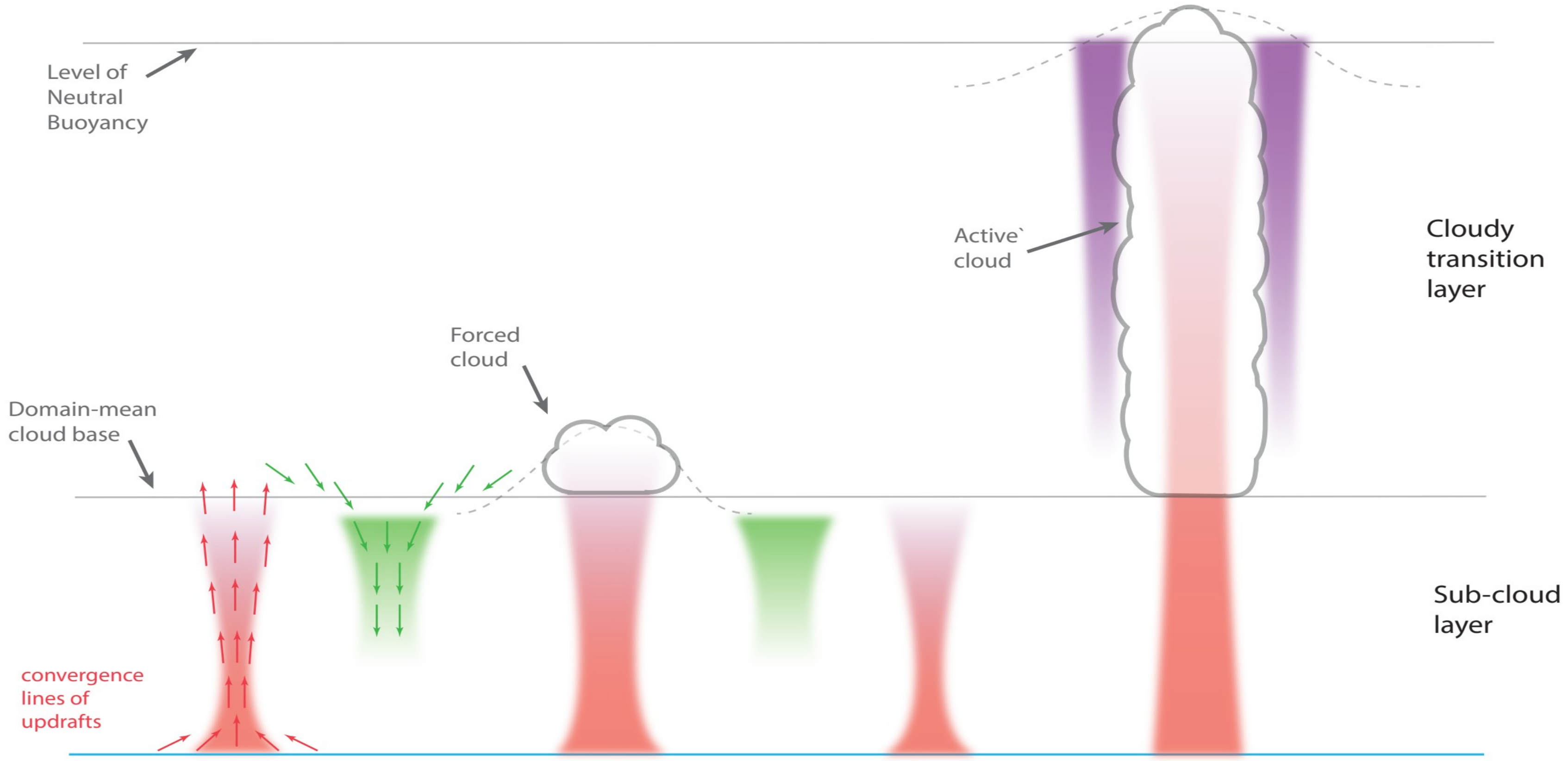
Anomalies of **relative humidity** relative to the domain average at the inversion **0,97z_i** (a), **0.5z_i** (b), and **0.10z_i** (c). Object-defined updraft plumes, subsiding shells and dry tongues are represented as contours

- At the inversion z_i, updrafts are small (**0,5-1 km diameter)** sometimes with returning shells at their boundaries. Downdrafts are close to updrafts
- At $z=0.5z_i$, updrafts and downdrafts are numerous. No spatial pattern can be clearly seen.
- At $z=0.1z_i$, updrafts structures show a network of organized **thin lines (spoke pattern)**. Downdrafts are relatively circular in the milddle of a circle created by updrafts. They are relatively dry.

Spatial organisation in BOMEX without winds



Schematic of coherent structures in the shallow convective boundary layer

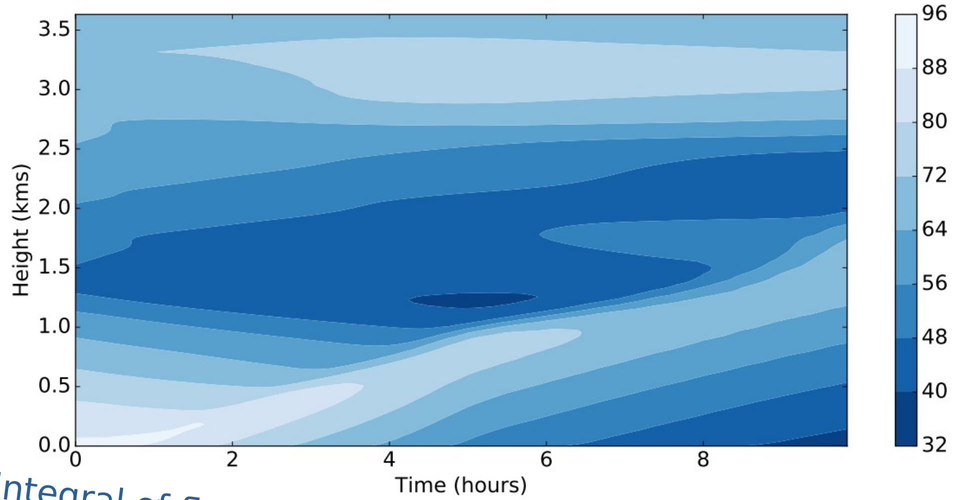


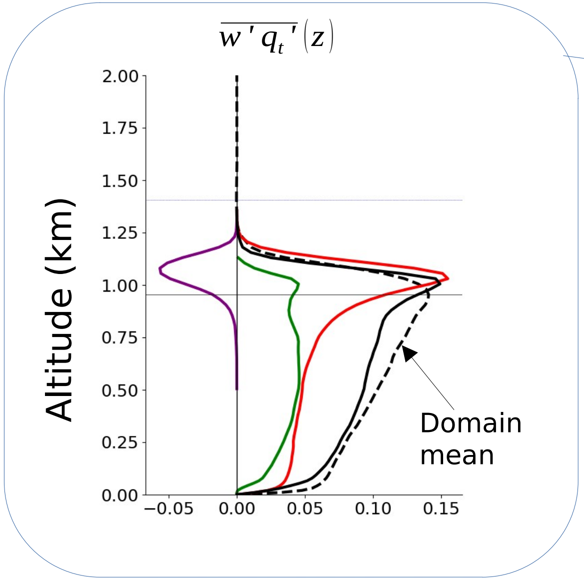
Contribution to turbulent transport of moisture

IHOP

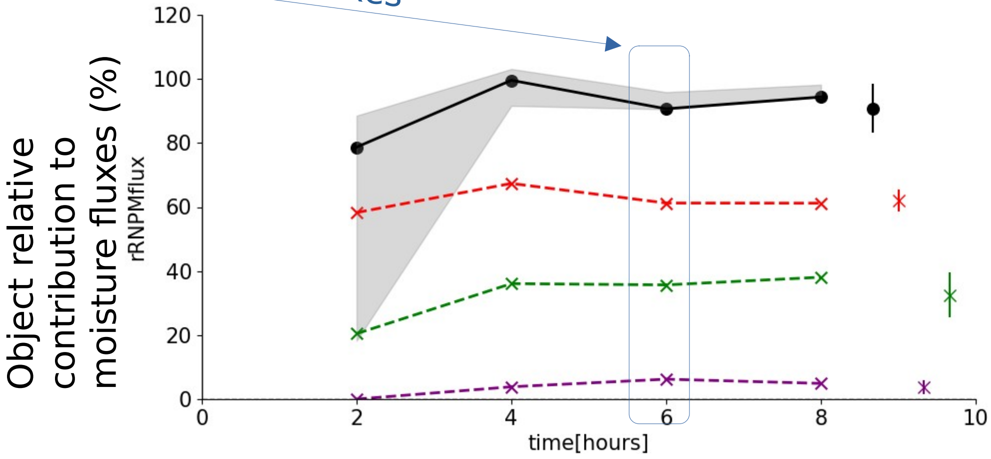
<u>Why coherent subsiding structures matter?</u>

- Objects carry most of moisture (>90%)
- In the dry convective boundary layer, updrafts carry 60% of moisture, well-mixed downdrafts 30%, and returning shells 2-5%
- **Boundary-layer deepening** does not change this result





Vertical integral of fluxes

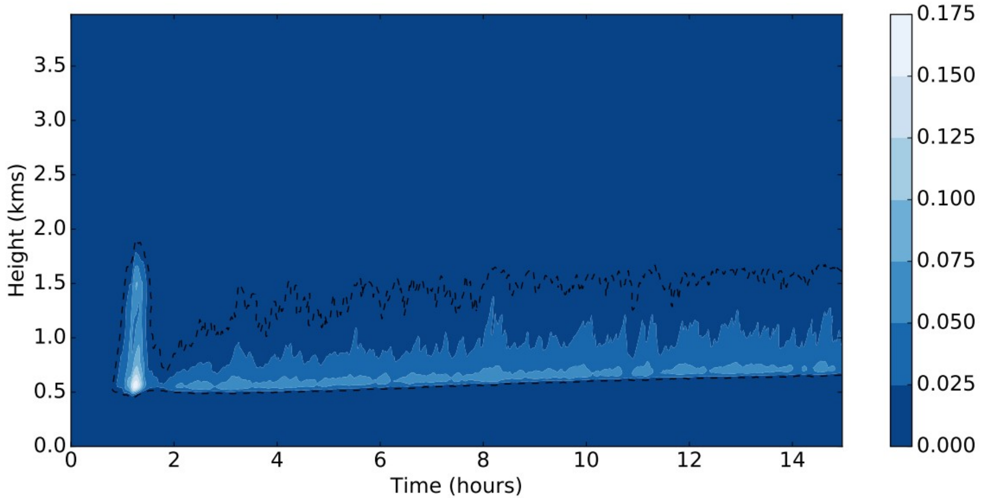


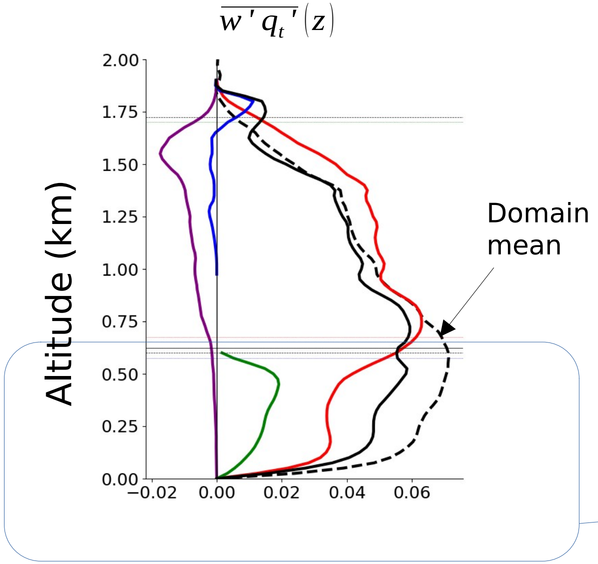
BOMEX

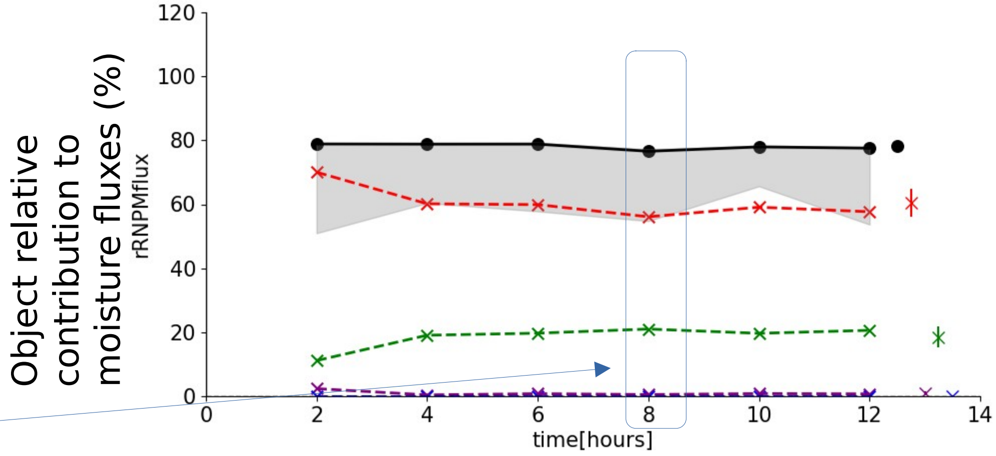
Contribution to turbulent transport of moisture

Why coherent subsiding structures matter?

- In the sub-cloud well-mixed layer, updrafts carry 60% of moisture, well-mixed downdrafts 20%, and returning shells 0%
- Objects carry most of moisture (80%)
- The sub-cloud layer is **similar** to the dry convective boundary layer







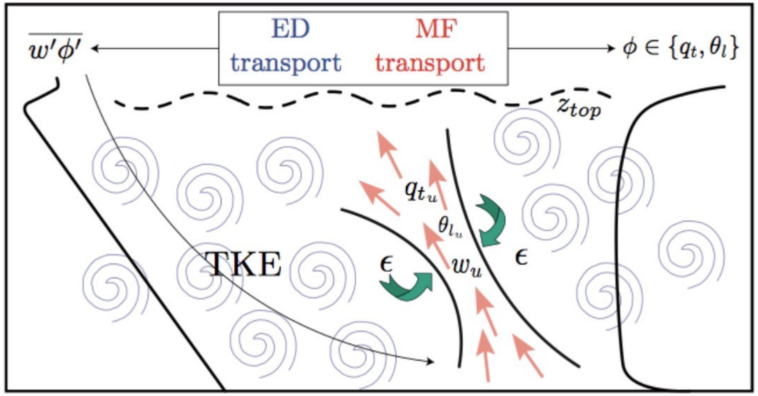
Discussion

3 points to discuss

1) Do we need to parameterize downdrafts with a mass flux assumption?

Usual representation of turbulent fluxes by local and non-local transport

$$\overline{\omega'\phi'} = (\overline{\omega'\phi'})_{ED} + (\overline{\omega'\phi'})_{MF} = -K_\phi \frac{\partial \overline{\phi}}{\partial z} + M_u(\phi_u - \overline{\phi})$$



Decomposition of turbulent fluxes by a type of structures (e.g. downdrafts):

$$F_i = \alpha_i(\overline{\omega_i} - \overline{\omega}) \cdot (\overline{\phi_i} - \overline{\phi})$$ 1) mean

$$+ \frac{1}{N}\sum_j \sum_{(x,y)\in j} (\omega - \overline{\omega_j}) \cdot (\phi - \overline{\phi_j})$$ 1) Intra-object variance

$$+ \frac{1}{N}\sum_j N_{i,j}(\overline{\omega_j} - \overline{\omega_i}) \cdot (\overline{\phi_j} - \overline{\phi_i})$$ 1) Inter-object variance

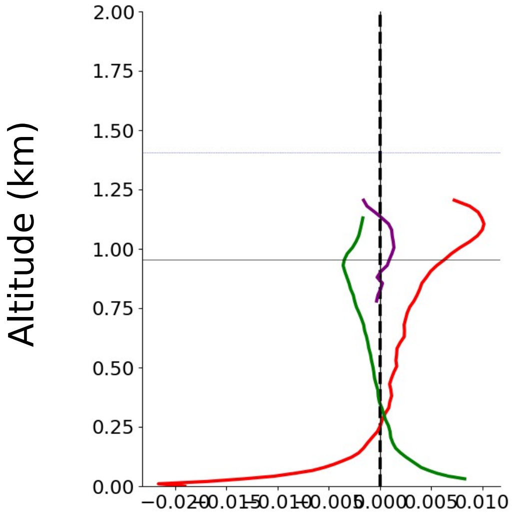
1) Future work: improving the **LMDZ thermal parameterization** to take into account a **downward mass flux transport**

Discussion

3 points to discuss

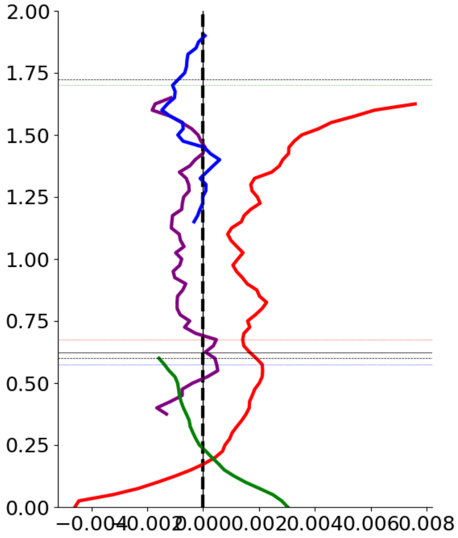
2) Downdraft trigerring

IHOP



$\nabla U_v (s^{-1})$

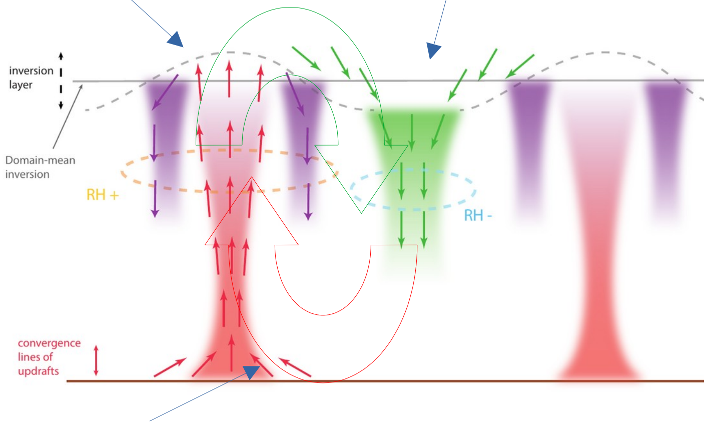
BOMEX



$\nabla U_v (s^{-1})$

Overshoot : positive pressure anomaly, horizontal divergence, negatively buoyant

Convergence between two updrafts, positive buoyancy, strong mixing



Overturning circulation in the well-mixed layer

Downdrafts trigger in the transition layer (entrainment zone) by the proximity of upward thermal plumes and divergence/convergence mechanism

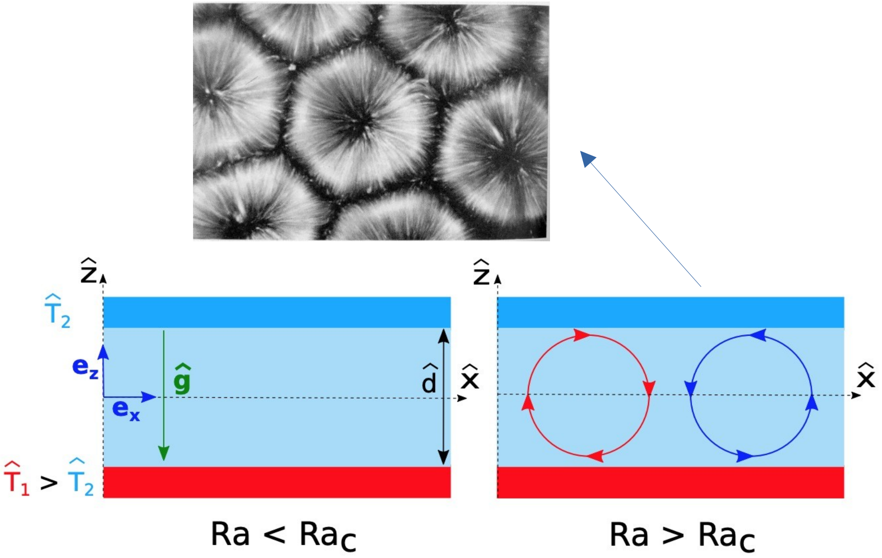
Diabatic effects amplifiy downdraft strength (StCu)

Discussion

3 points to discuss

3) Mesoscale organisation and the Rayleigh-Bénard convection (RBC) theory

Rayleigh-Benard theroy:
Horizontal fluid layer of height D confined between two thermally well conduction, parallels plates (withtemperature difference). If **temperature difference** > a critical value, the conductive motionless state is unstable and **convection** sets in. **Pattern of convective cells** occur.



Atmospheric boundary layers show **adibatic trigerring** of downdrafts and **cellular organisation** (both in IHOP and BOMEX)

Strong similarities with the Rayleigh Bénard convection

Differences with RBC
- Top-plate not rigid (entrainment occur)
- Phase changes (clouds) above and below the well-mixed layer (Cu and StCu)
- Aspect ratio of 1-2 : Work for IHOP

Discussion

<u>3 consequences of these results</u>

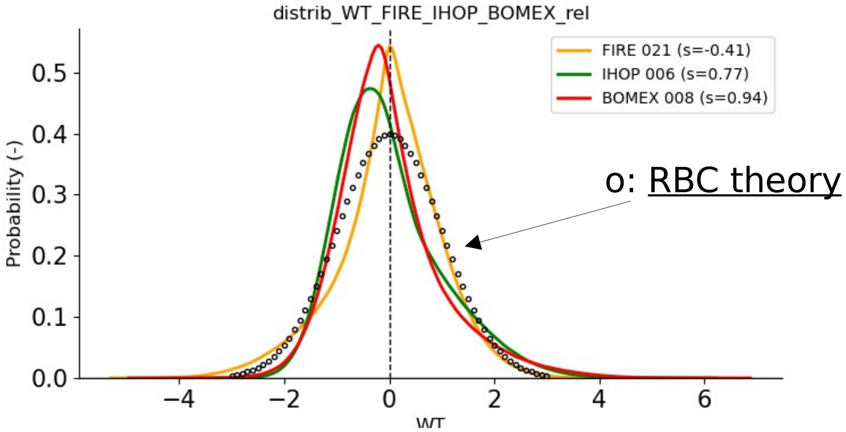
3) Mesoscale organisation and the Rayleigh-Bénard convection (RBC) theory

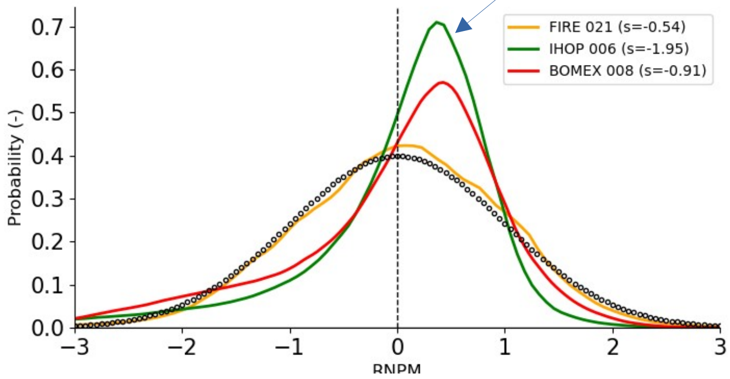
<u>Differences with RBC</u>

- Top-plate not rigid (**entrainment** occur)

Skewed distributions linked to PBL-top vertical gradient (entrainment rate)

Probability density distributions of normalized distributions of vertical velocity (left) and total humidity (right)





Deviations from RBC likely linked to strength of PBL-top entrainment

Conlusions and perspectives

Conclusions

- Identifying **coherent structures** is efficient to understand the boundary-layer dynamics in large-eddy simulations
- The continental dry convective boudary layer and the marine shallow convective sub-cloud layer share similar thermodynamical characteristics and turbulent transport
- Downdrafts in well-mixed layer can be considered as the **coherent compensating subsidence** of thermals, as one would expected with the Rayleigh Bénard theory
- Understanding downdrafts is linked to better understading the mesoscale organisaiton of boundary layers

Perspectives

- Estimate whether a **downward mass flux** improve boundary layer in the LMDZ model
- Investigate the ability to explain **observed mesoscale organisations** with this overturning circulation (importance of **decoupling** in stratocumulus-topped boundary layers)
- Investigating **low-cloud feedback** with coherent structures

- ***A lot of exciting upcoming work on boundary-layer dynamics, coherent structures, and mesoscale organisation***