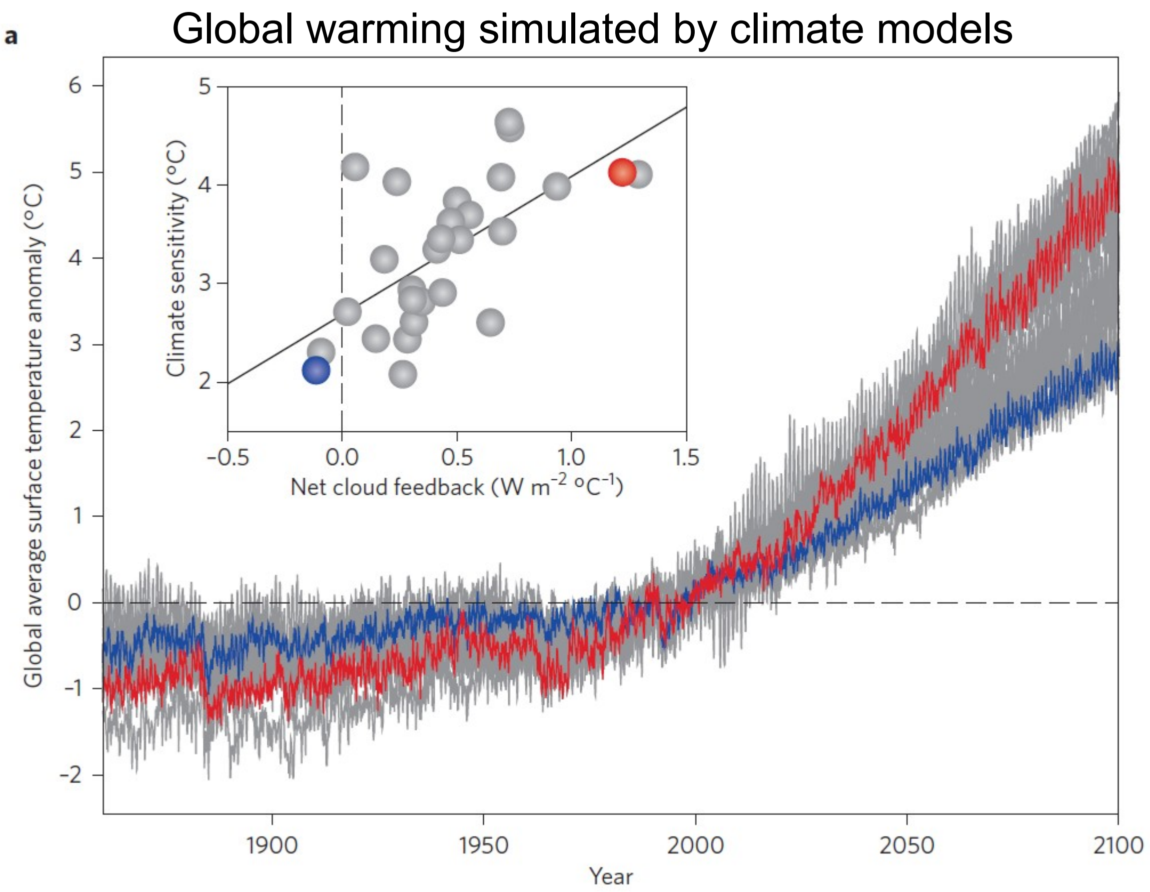
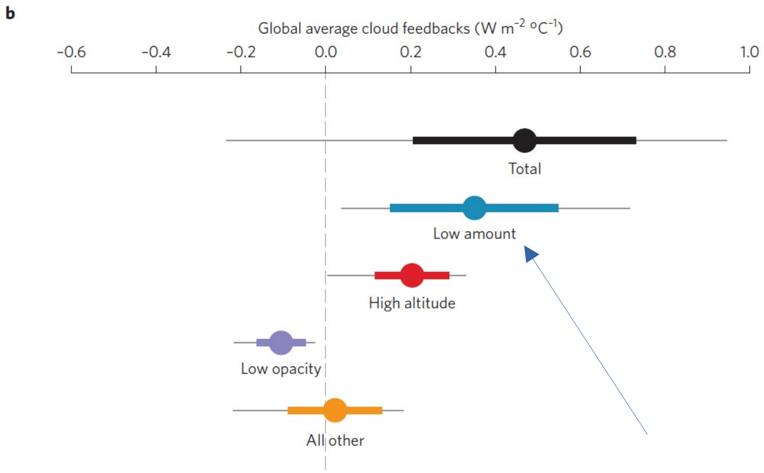
Morphology of Stratocumulus clouds, boundary-layer dynamics and cloud feedback

Florent Brient
Sorbonne Université - LMD/IPSL

Journées GDR Défis théoriques des sciences du climat
28 mai 2024

Clouds of uncertainty



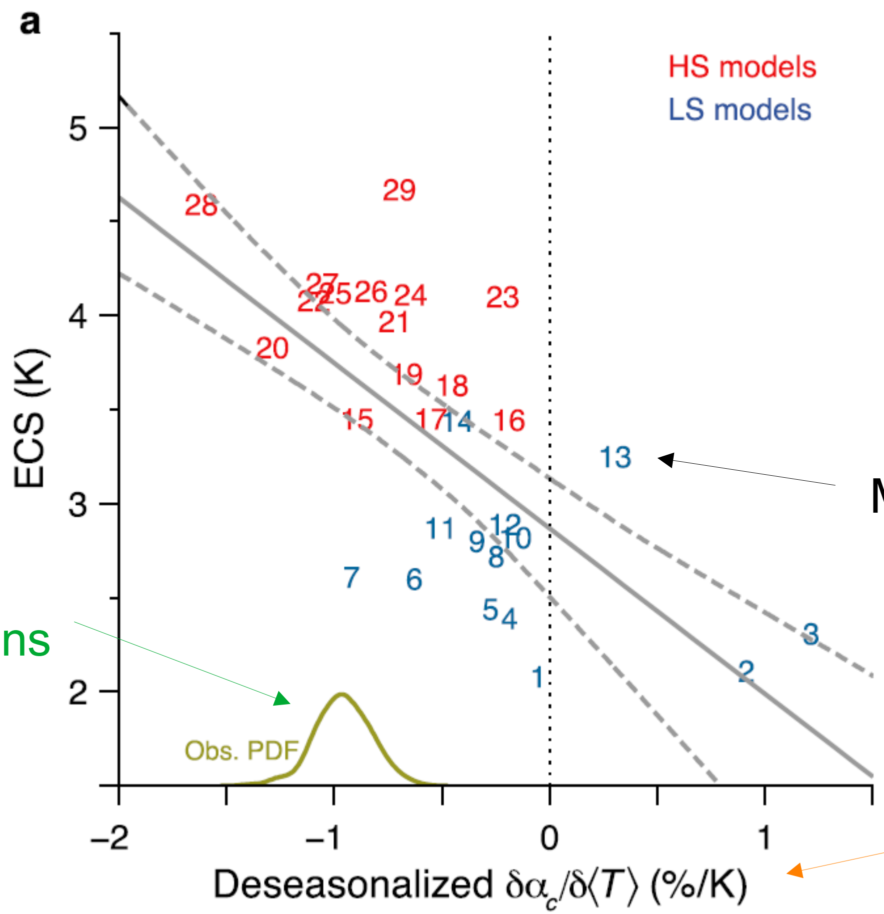


The **low cloud response** remains the most important uncertainty in climate-change projections <u>for a given increase in carbon dioxide concentrations</u>

Zelinka et al (2017)

Constraining cloud changes

Climate sensitivity



Satellite observations

Models

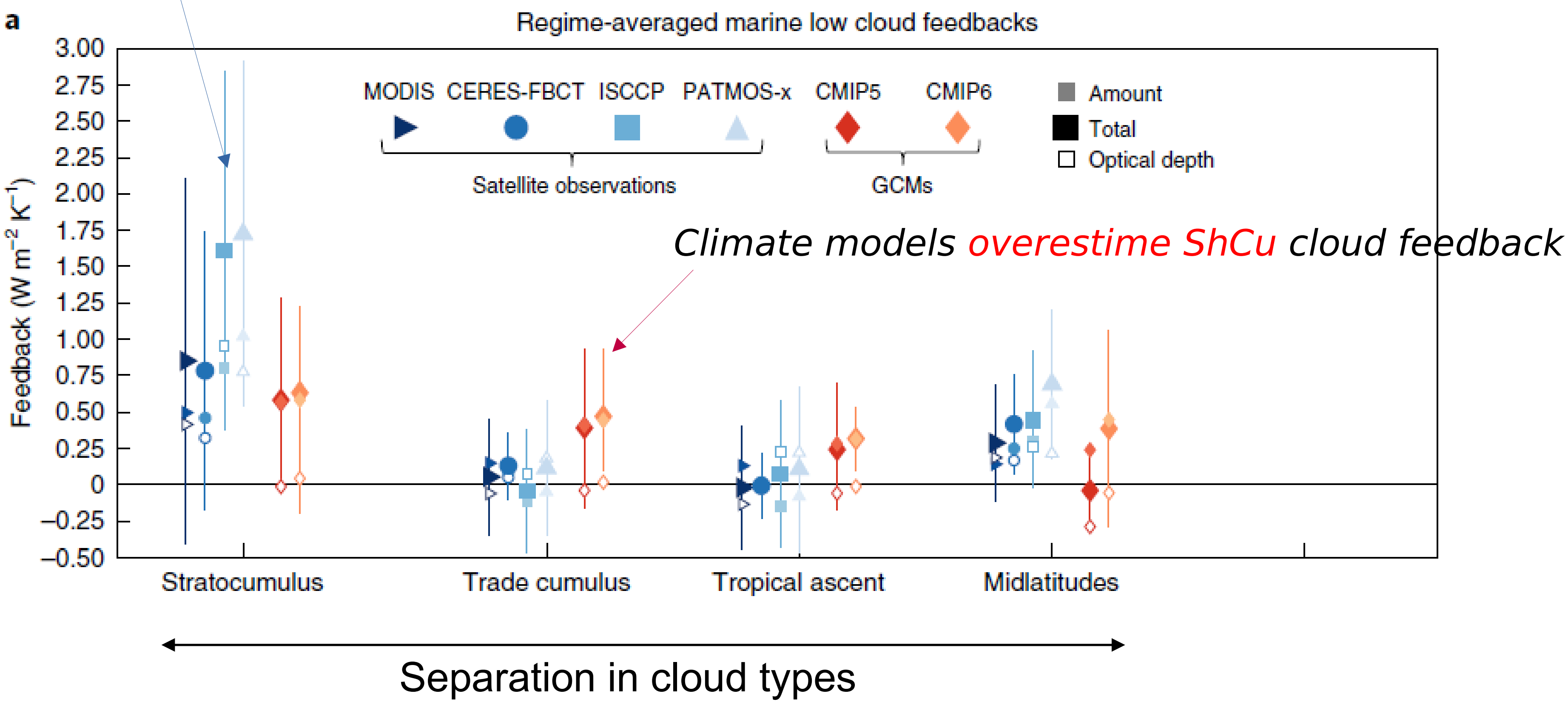
<u>Emergent constraint:</u>
Climate models that show a present-day **decrease** in cloud albedo with warming and **a high climate sensitivity seem more realistic**

Observable low-cloud variability

Brient and Schneider (2016)
Brient (2020)

Constraining cloud changes

Climate models *underestimate StCu* *cloud feedback*



Myers et al (2021)

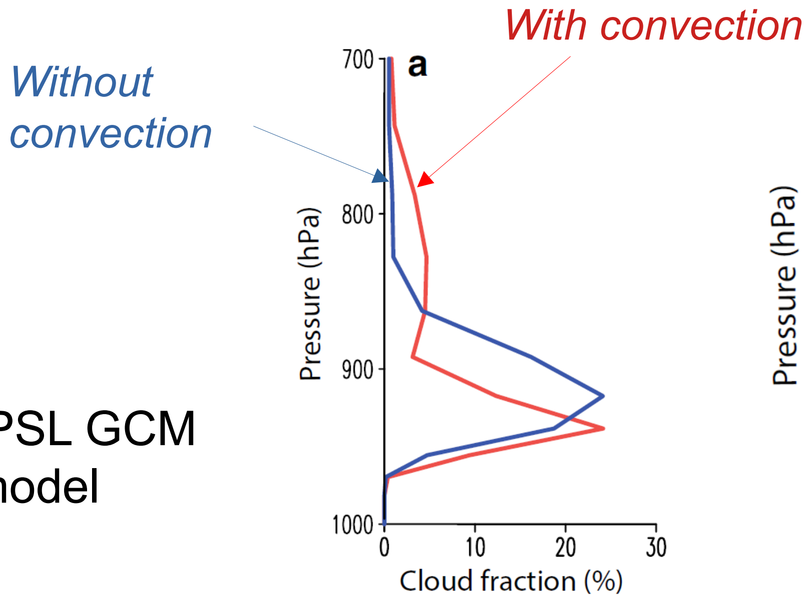
Constraining cloud changes

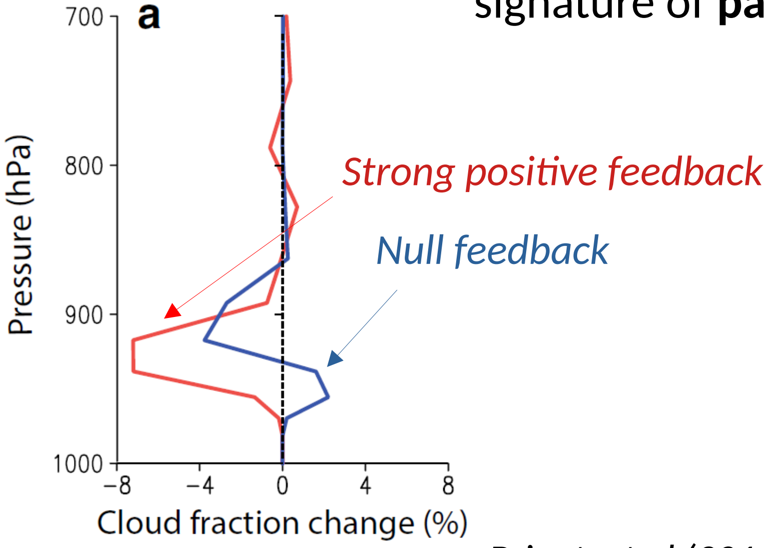
Shallowness of tropical low clouds as a predictor of climate models' response to warming

Florent Brient[1] · Tapio Schneider[1,2] · Zhihong Tan[1,2] · Sandrine Bony[3] · Xin Qu[4] · Alex Hall[4]

The shallow cumulus **cloud response** is due to the interaction between **parameterized turbulence and convection.**

The **shallowness** of cloudiness is a signature of **parameterizations**

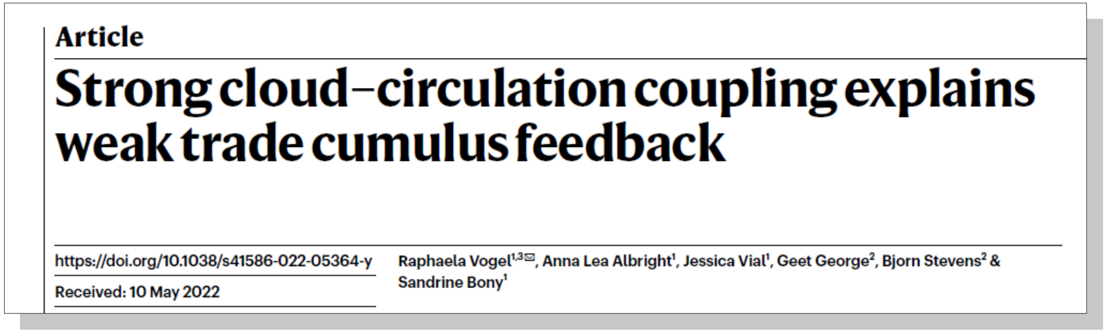




IPSL GCM model

Brient et al (2016)

Constraining cloud changes



Article

Strong cloud–circulation coupling explains weak trade cumulus feedback

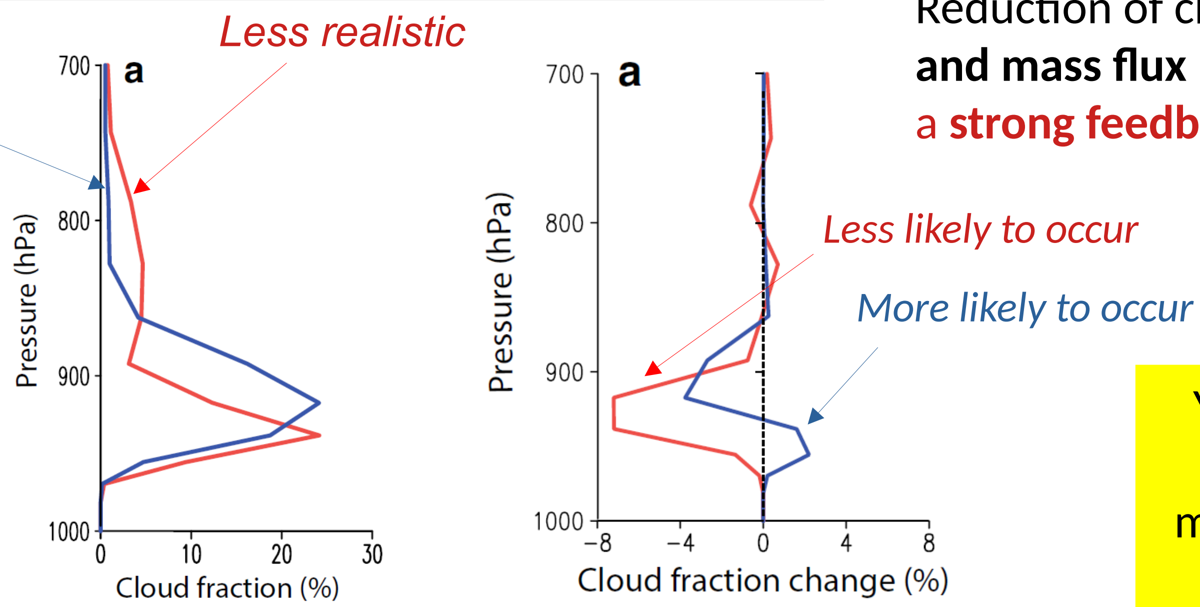
https://doi.org/10.1038/s41586-022-05364-y

Received: 10 May 2022

Raphaela Vogel[1,3] ✉, Anna Lea Albright[1], Jessica Vial[1], Geet George[2], Bjorn Stevens[2] & Sandrine Bony[1]

The **EUREC4A field campaign** provides information (data) to constrain mass flux and cloud vertical distribution

More realistic



IPSL GCM model

Vogel et al (2022)

Reduction of cloudiness by **convection and mass flux** is **less realistic** and thus a **strong feedback is unlikely to occur**

Yet we still **don't** have a clear, robust physical mechanism for **low-cloud feedback**

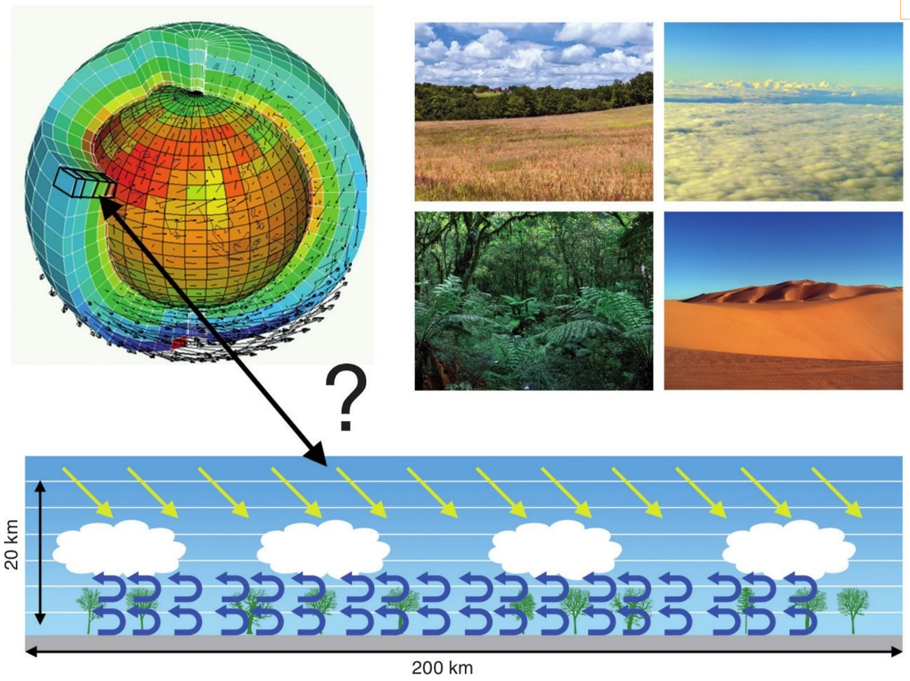
Understanding: Modeling and parameterization

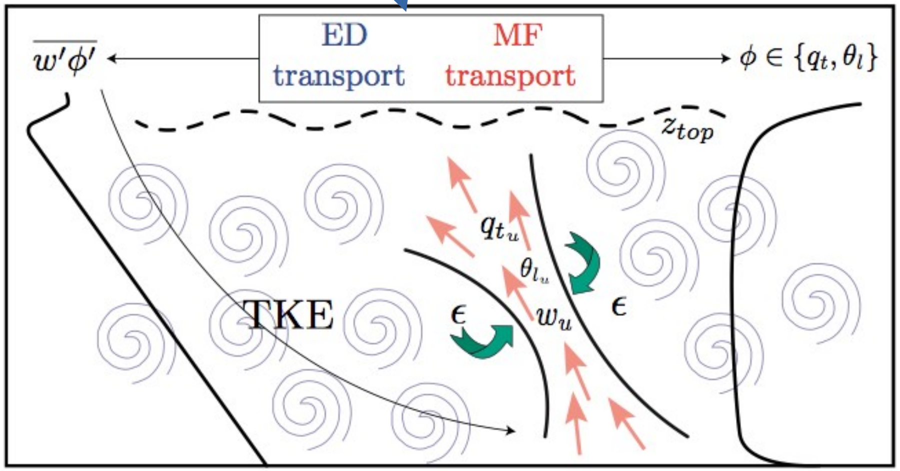
Climate models aim to represent climate variability for different time scales at length scales of around 50-100 km

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

Resolved

Parameterized





Witte et al (2010)

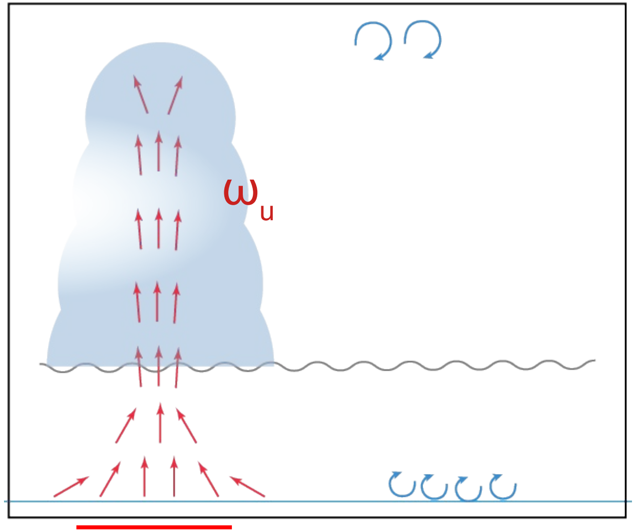
Understanding: Modeling and parameterization

Climate models aim to represent climate variability for different time scales at length scales of around 50-100 km

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

Resolved

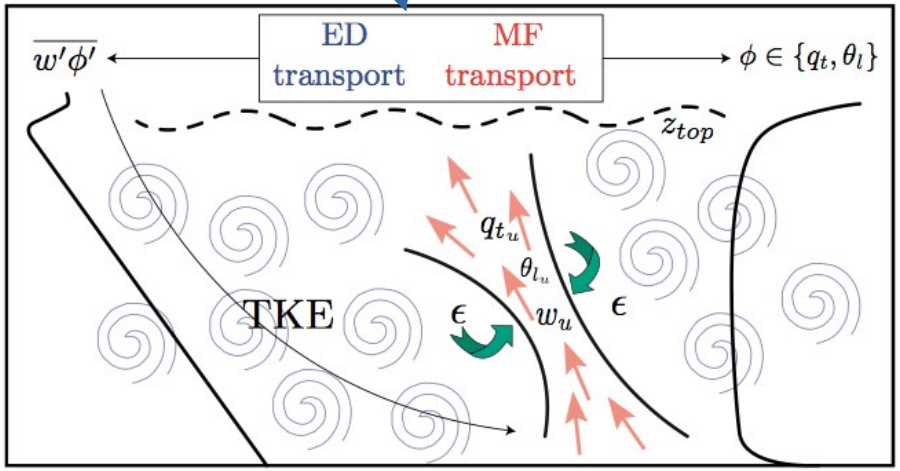
Parameterized



α_u

Compensating subsidence:

$\omega = \alpha_u \omega_u + (1-\alpha_u)\omega_d$



Witte et al (2010)

High-resolution modeling

Reproducing atmospheric boundary layers to better understanding **coherent structures, boundary-layer dynamics** and the **mesoscale organisation**

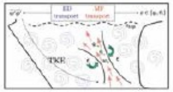
High-Resolution models are the tool for that purpose

The Meso-Nh model is the French mesoscale non-hydrostatic model

Meso-NH
mesoscale non-hydrostatic model

http://mesonh.aero.obs-mip.fr/mesonh57

Several boundary layers are simulated, three are mostly studied

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

<u>Domain size:</u>

- 12.8x12.8 km^2 (25.6x25.6 km^2 for StCu)
- Double periodic

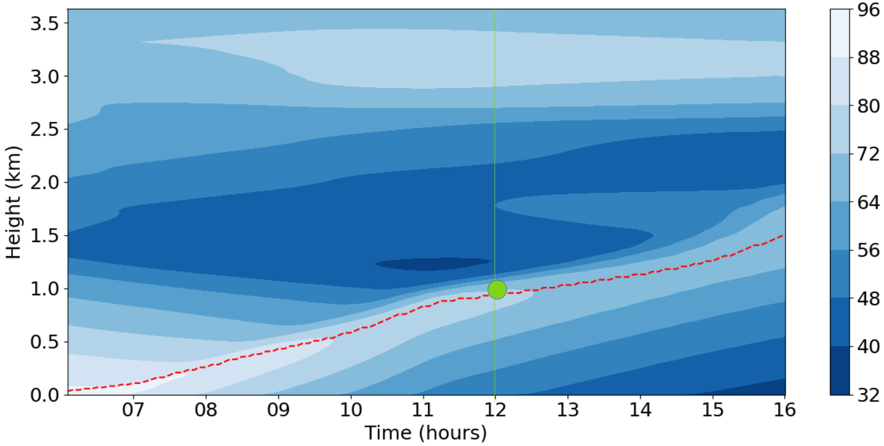
<u>Resolution:</u>

- $\Delta x=\Delta y=25m$ (50m StCu)
- $\Delta z=25m$ (10m StCu)
- $\Delta t=1$ sec

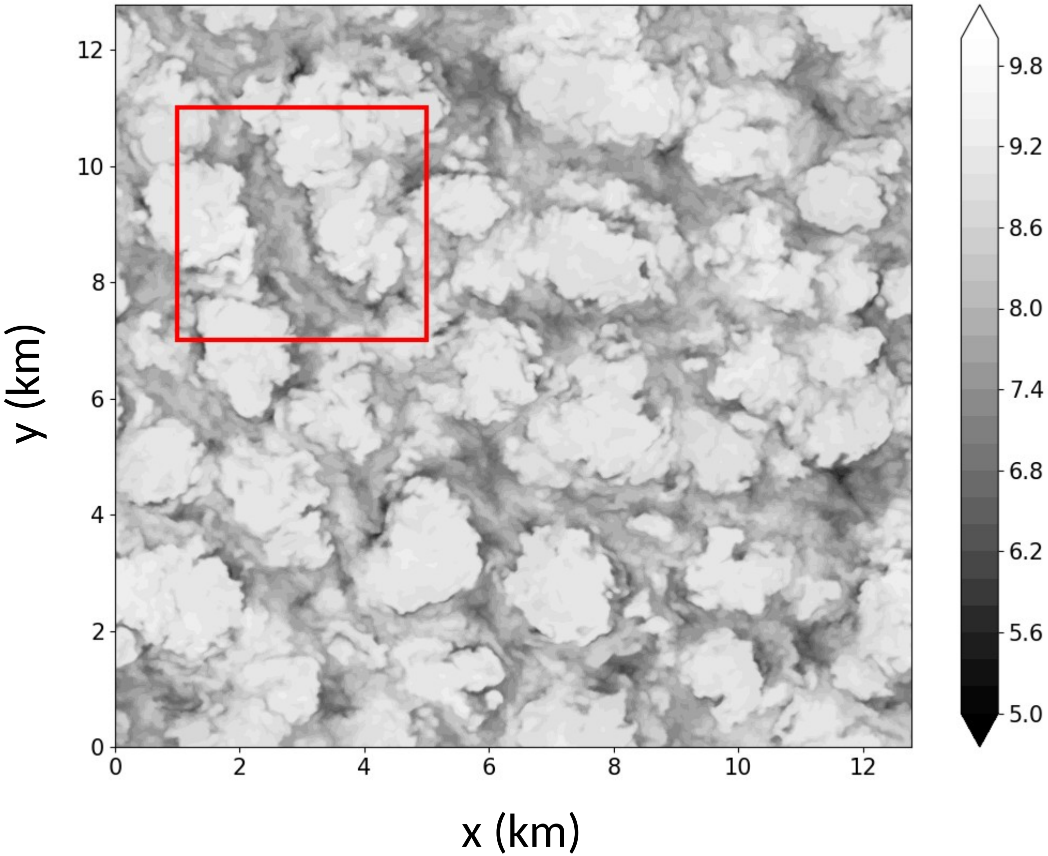
High-resolution modeling

The clear-sky convective boundary layer
→ no clouds !

Time evolution of averaged Relative Humidity (%)



Cross section of Total humidity (g/kg) at the inversion altitude (zi)



Coherent structures

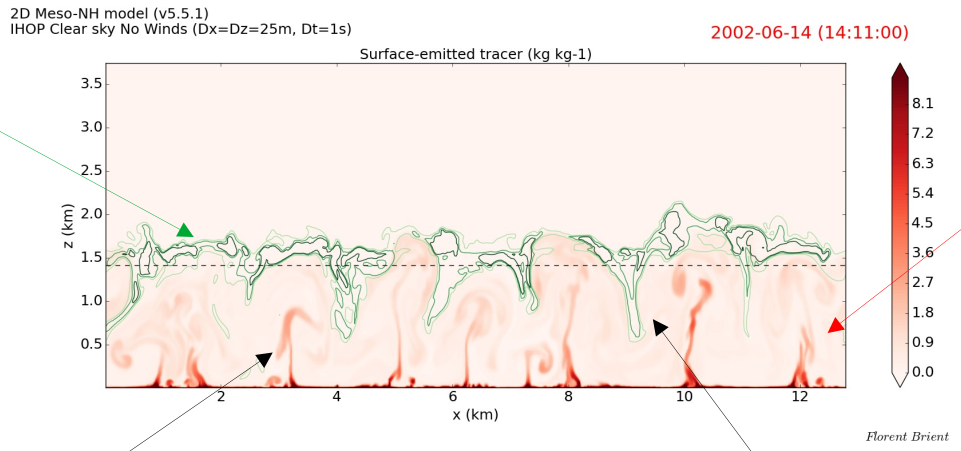
coherent turbulent structures = parts of the flow that have logical interconnections and form a unified whole

Definition:

- **3D Coherent structures** are defined with **passive tracers** emitted at the surface, PBL-top and cloud base
- Ensemble of grid boxes satisfying 2 conditional sampling : CS = {s'(x,y,z)>m*σs(z)} based on *Couvreux et. al (10)* (with s'(x,y,z) anomalies of tracer concentrations) and CS_w for positive/negative vertical velocity
- Object = **3D Contiguous** cells of positive CS (sharing face, edge, corner)
- Selected object = Object with volume **larger than V_{min}**

https://gitlab.com/tropics/objects

Cloud tracer emitted at the PBL top



Cloud tracer emitted at the surface

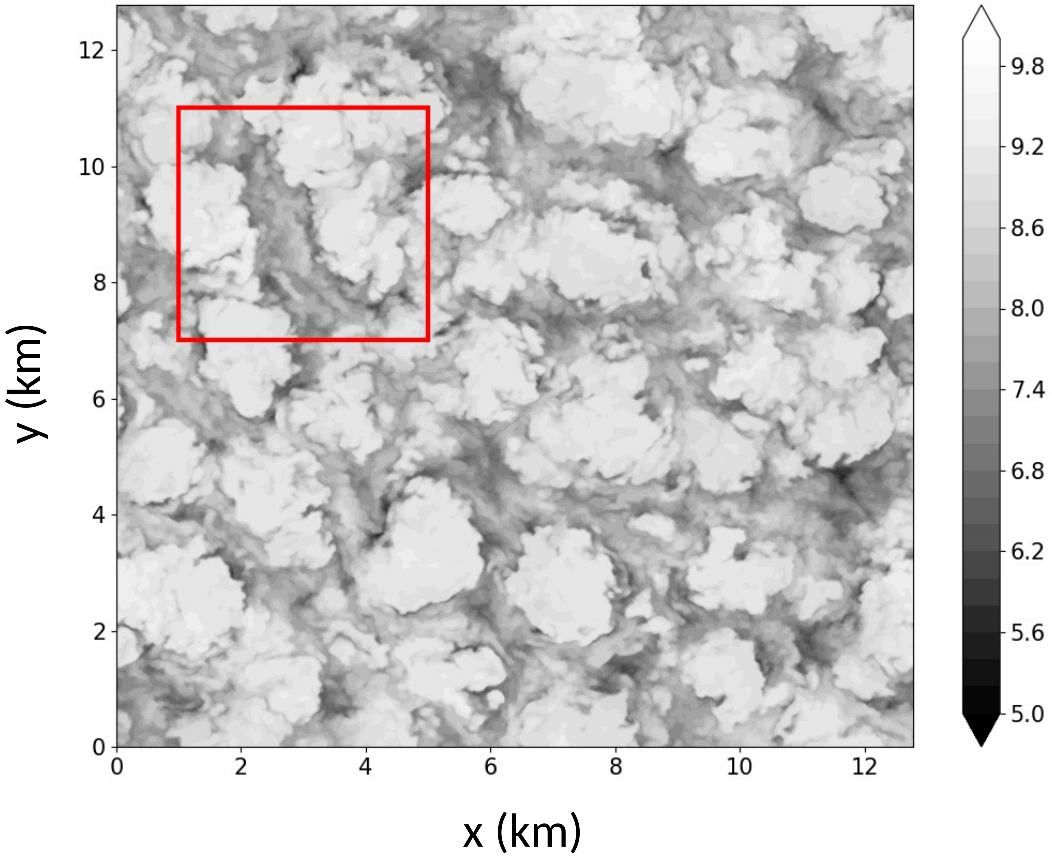
2D simulation of a diurnal cycle of a Dry Convective Boundary Layer (clear-sky) [LINK]

1 updraft

1 downdraft

High-resolution modeling

The clear-sky convective boundary layer
→ no clouds !



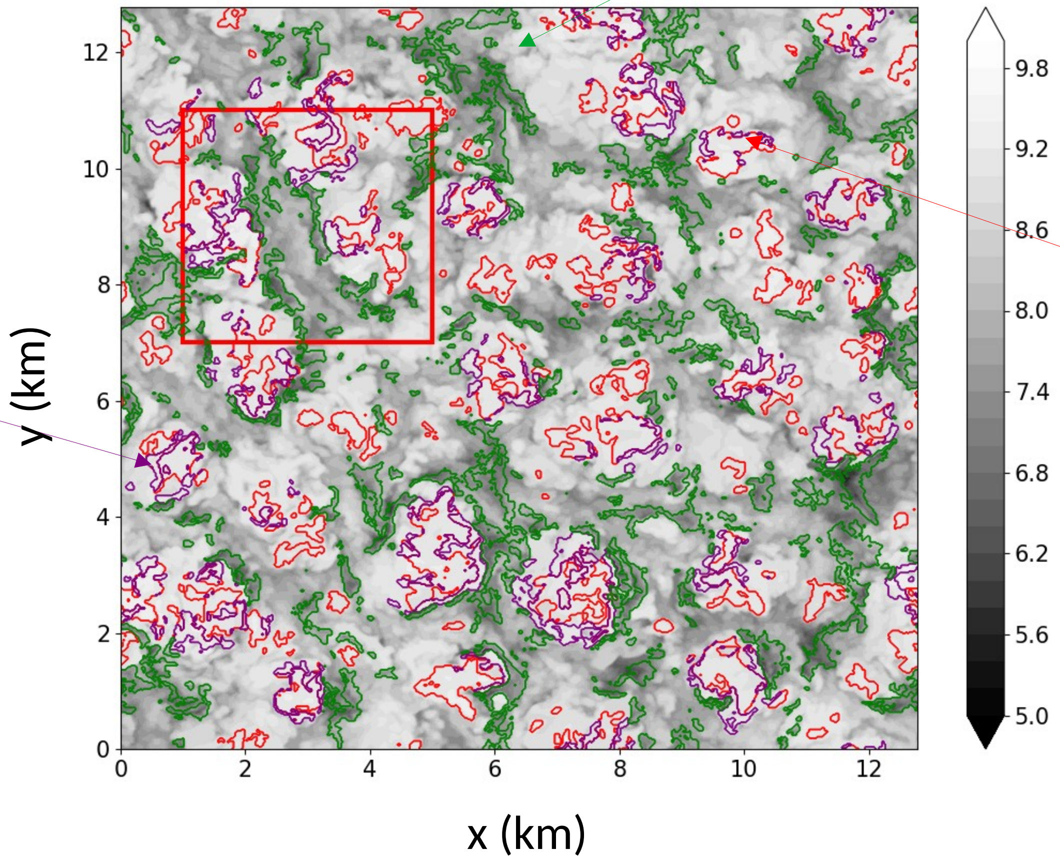
Total humidity (g/kg) at the inversion altitude (zi)

High-resolution modeling

The clear-sky convective boundary layer
→ no clouds !

Downdraft (between cells)

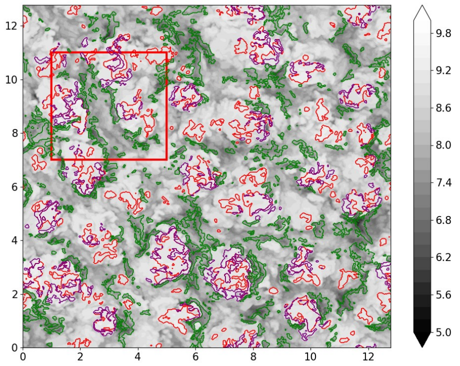
Total humidity (g/kg) at the inversion altitude (zi)



Subsiding shells (around updrafts)

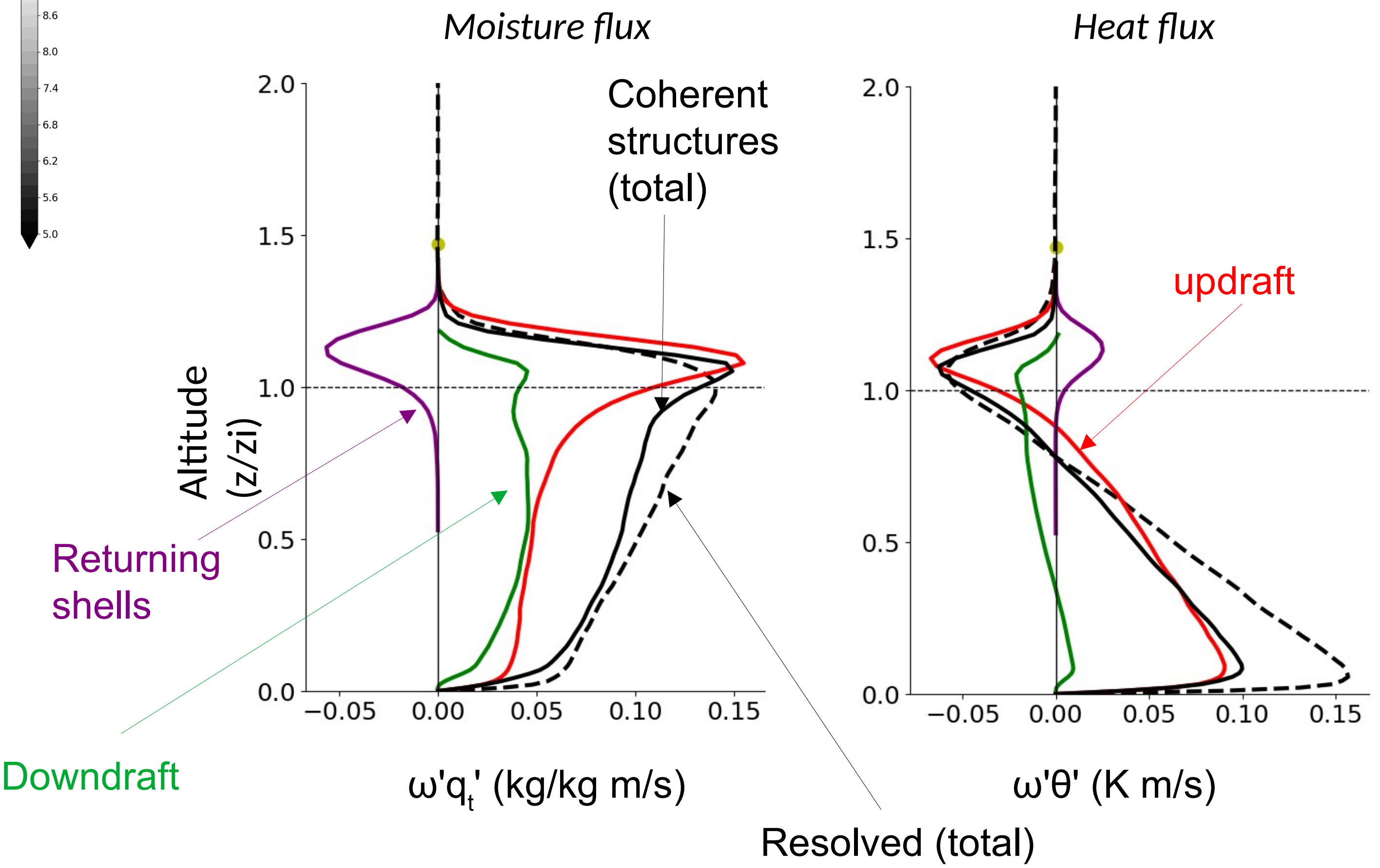
Updraft (in the center cells)

Coherent structures: Fluxes

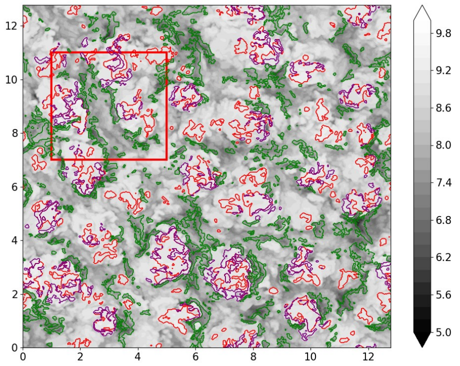


Coherent structures cover **25% of the domain**, but contribute to 70% of resolved **heat** fluxes and 90% of **resolved** moisture fluxes

Downdrafts contribute to around **20%** of resolved fluxes

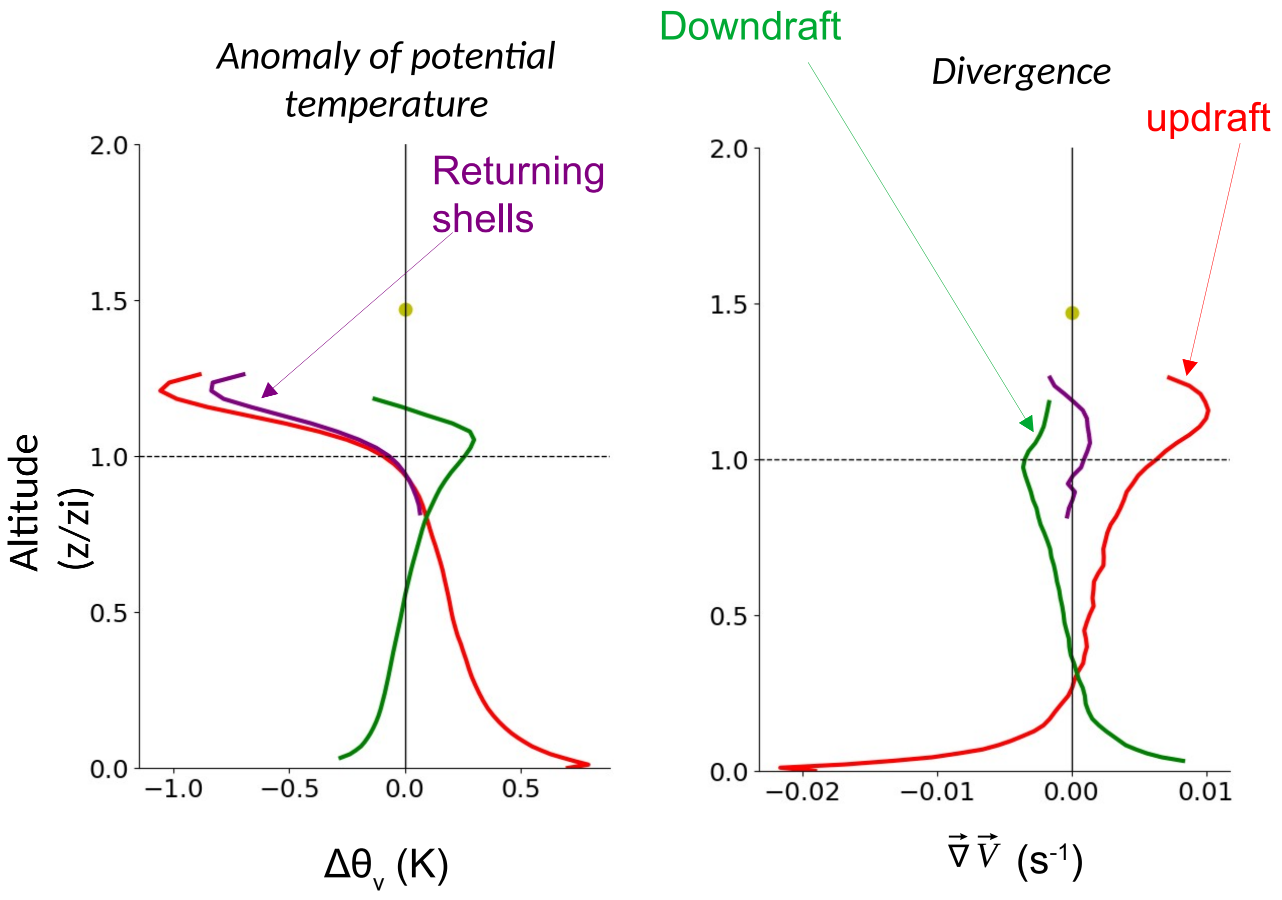


Coherent structures: Dynamics

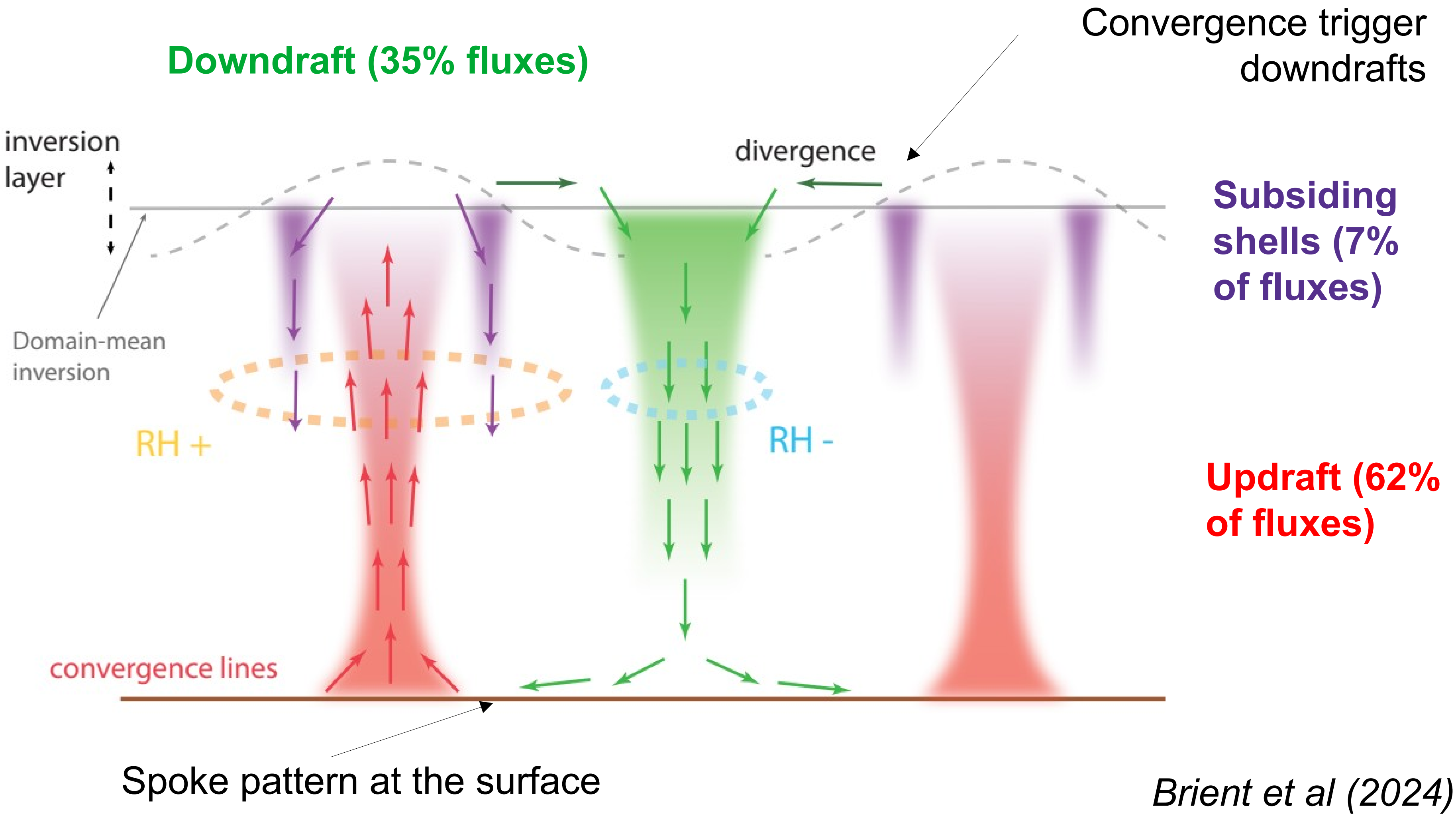


Updrafts start positively buoyant at the surface and overshoot at the inversion.
Returning shells are located atop the boundary layer, and are similar to updrafts

Downdrafts also start **positively buoyancy**, but show **convergence** of air masses
→ Adiabatic triggering

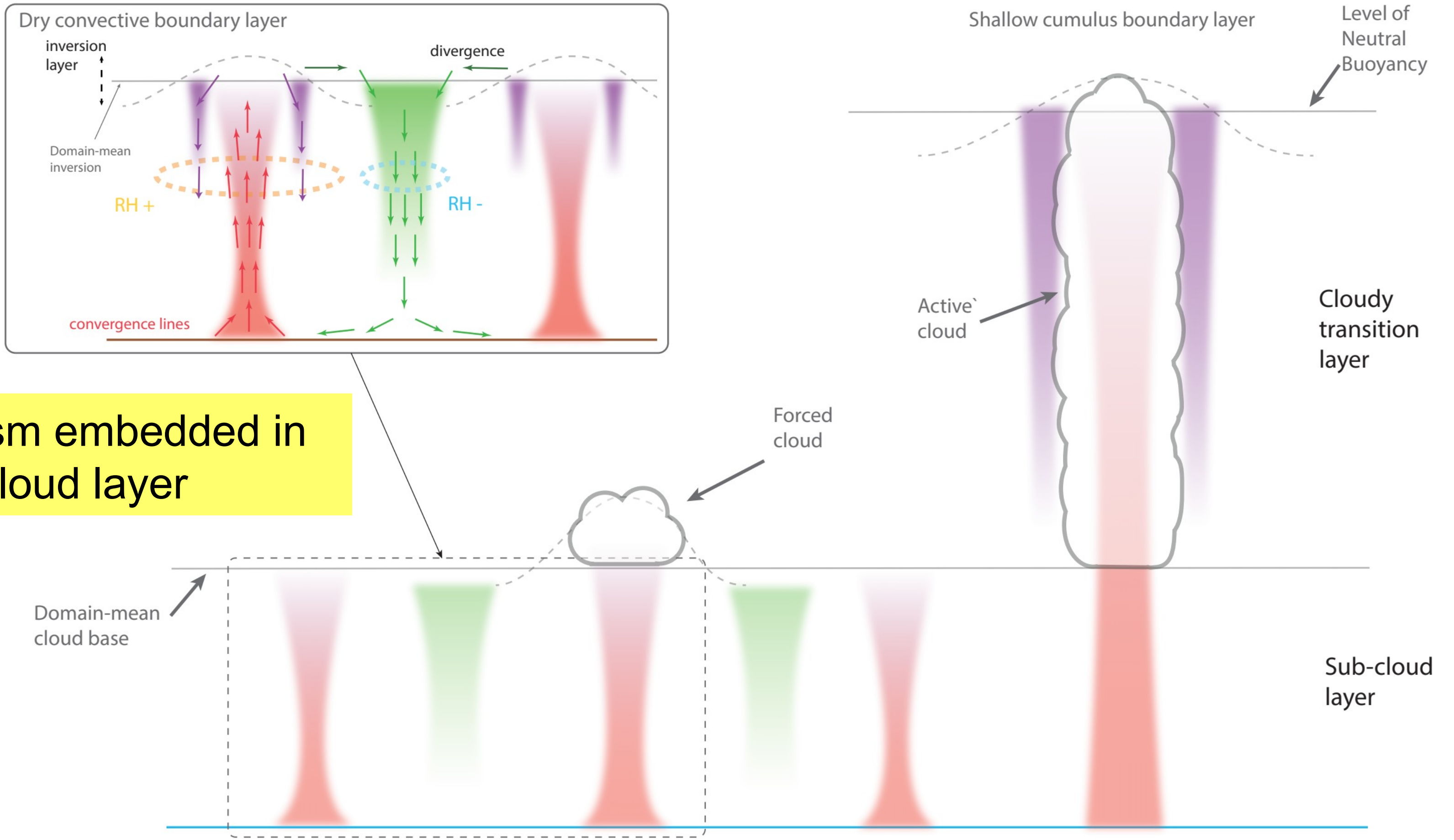


Schematic of the dry convective boundary layer



Brient et al (2024)

Schematic of the cumulus boundary layer



Mechanism embedded in the sub-cloud layer

Spoke pattern at the surface

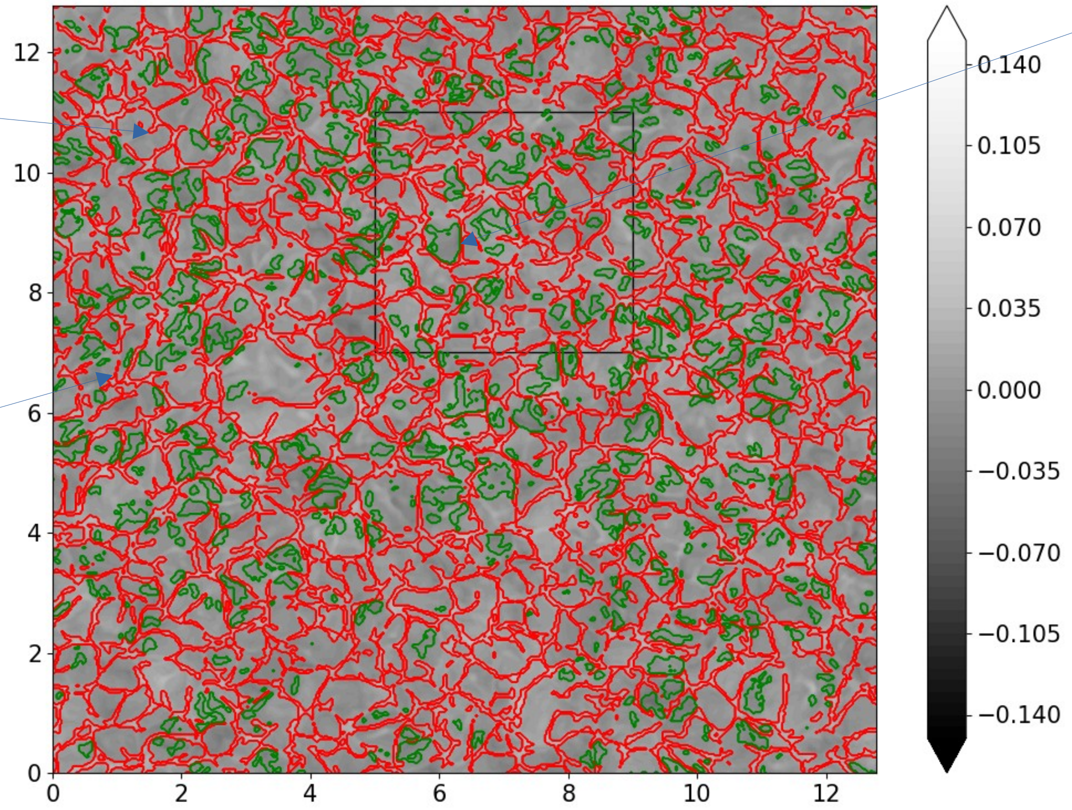
Spoke pattern at the surface

Cumulus simulation
(BOMEX)

Spoke
pattern at
the surface

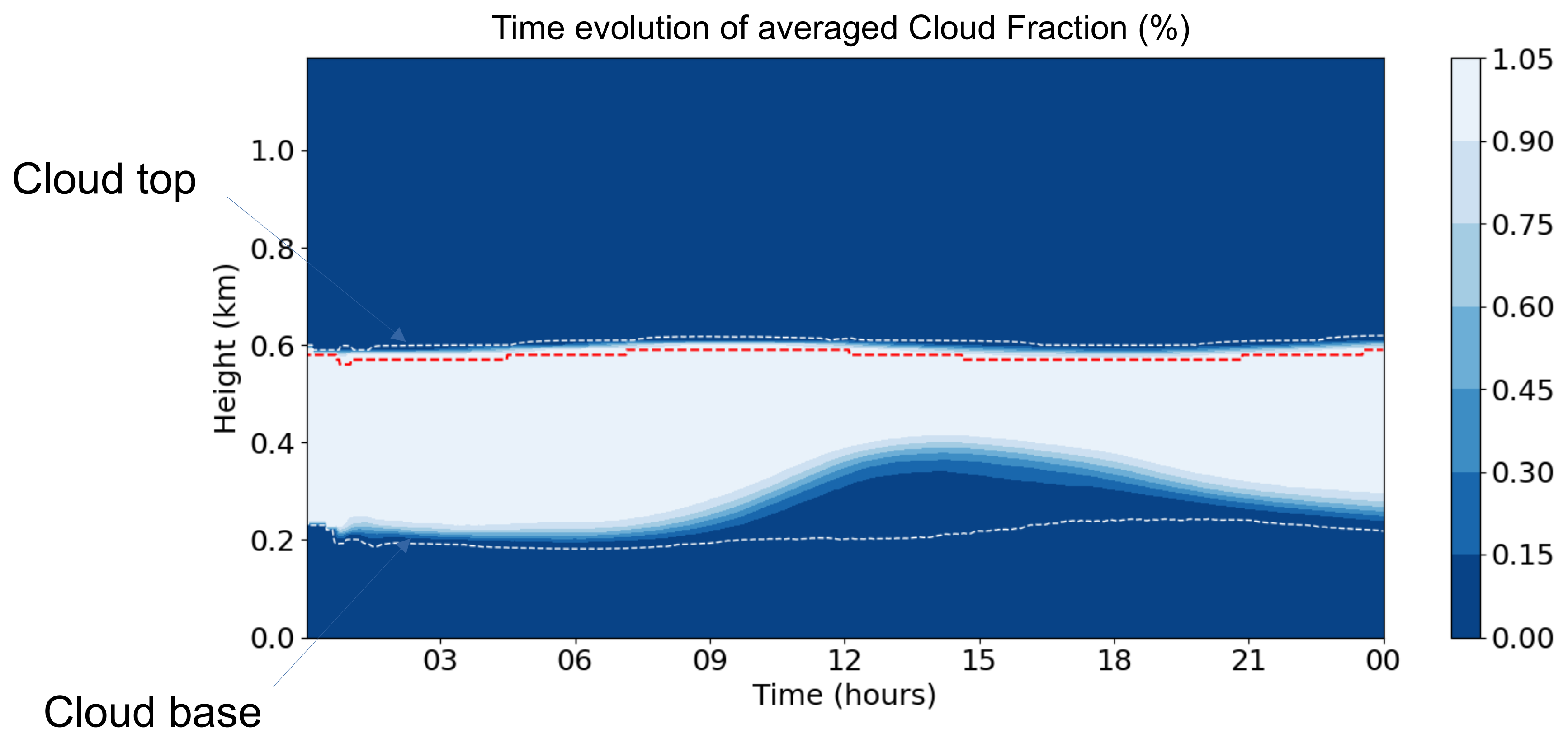
Convergence
lines by
updrafts

Anomaly of relative humidity **at 0.1zi**



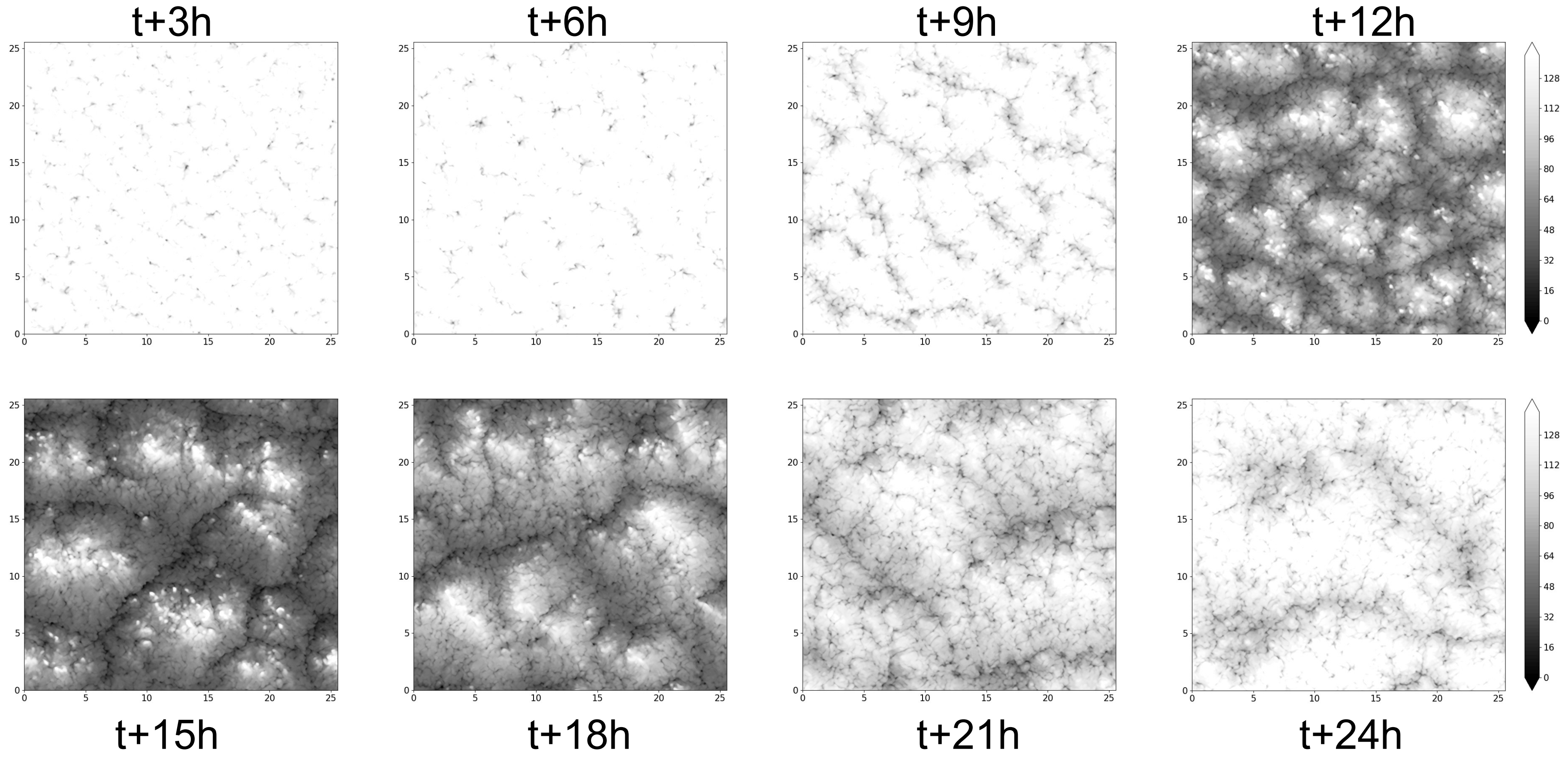
Downdrafts in
the middle of
updrafts' circles

What about stratocumulus?



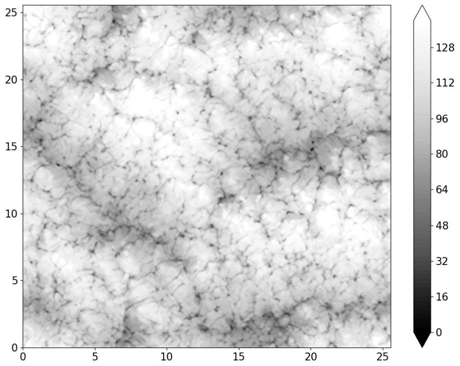
What about stratocumulus?

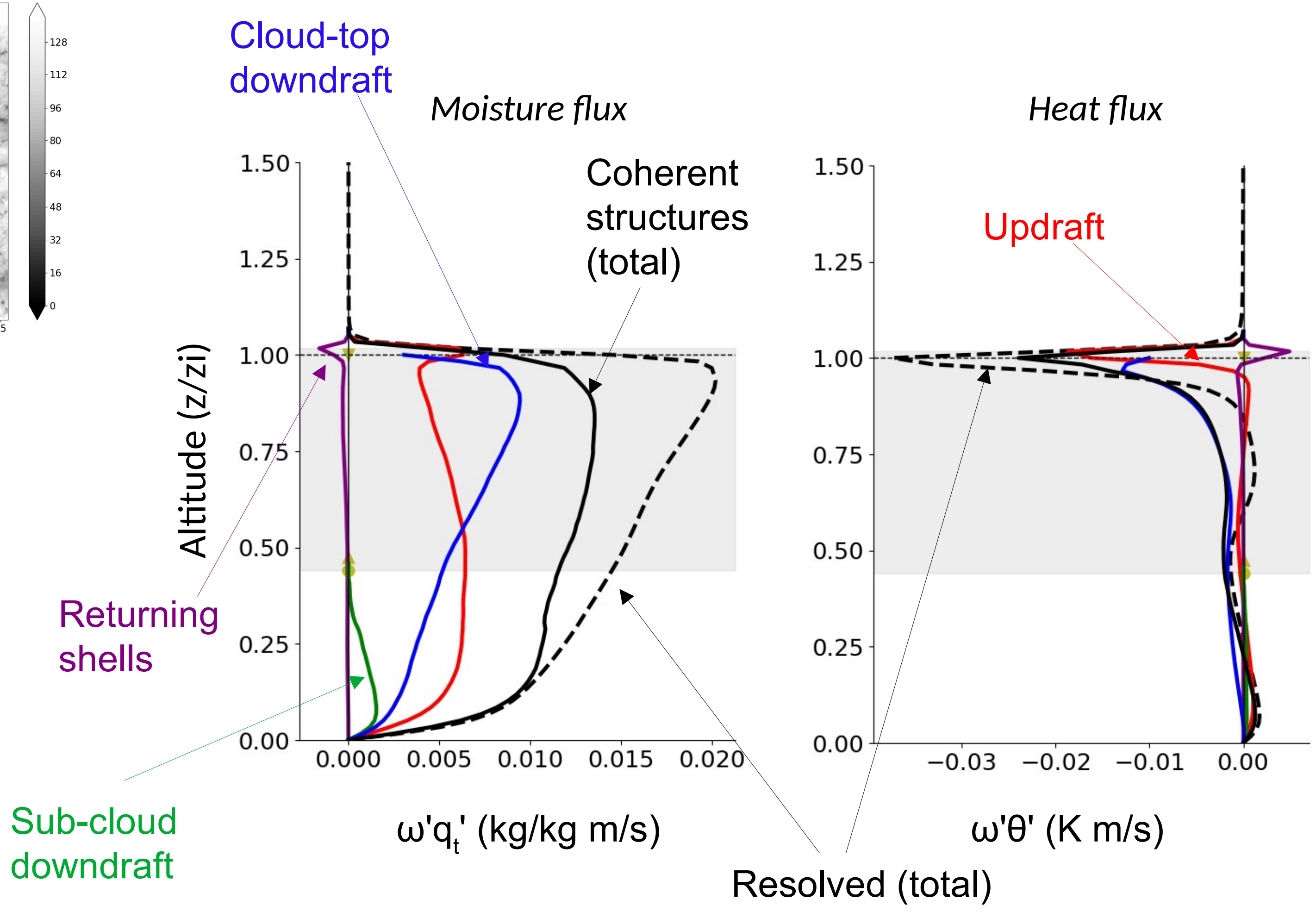
Liquid Water Path (g/m²)



Coherent structures: Fluxes

Nighttime (t+21h)



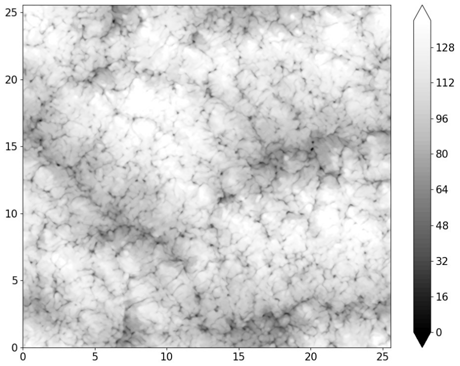


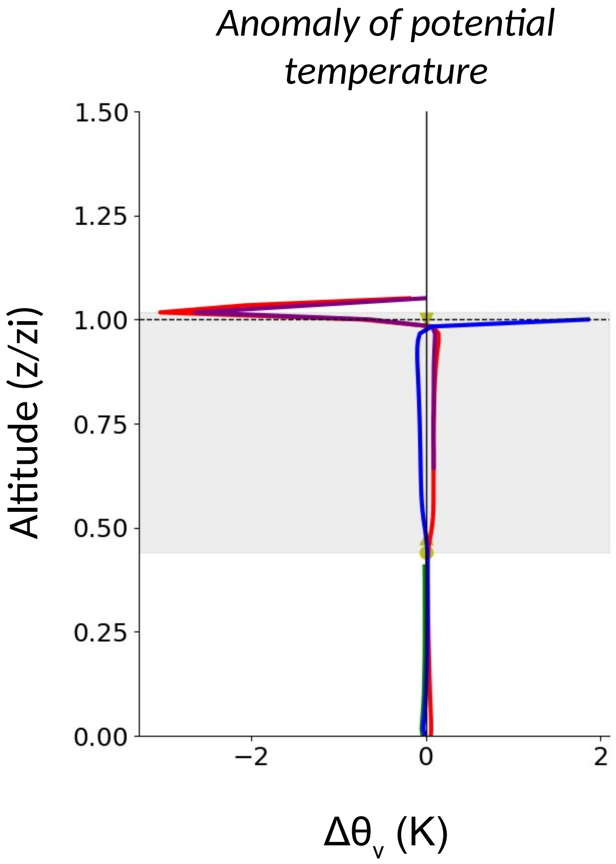
Coherent structures cover **27% of the domain**, but contributes to **78%** of resolved moisture fluxes

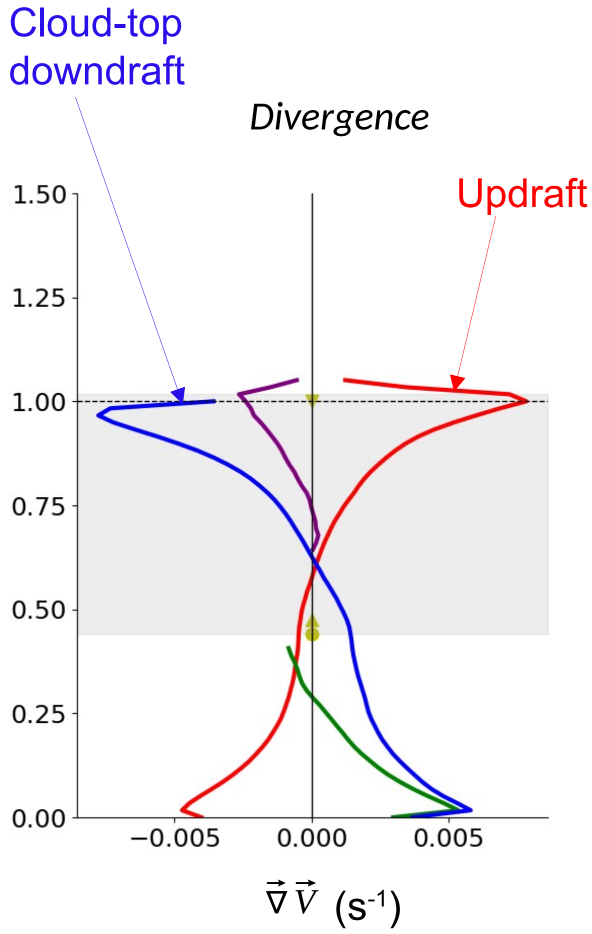
Cloud-top downdrafts to around **40% of resolved fluxes**

Nighttime (t+21h)

Coherent structures: Dynamics



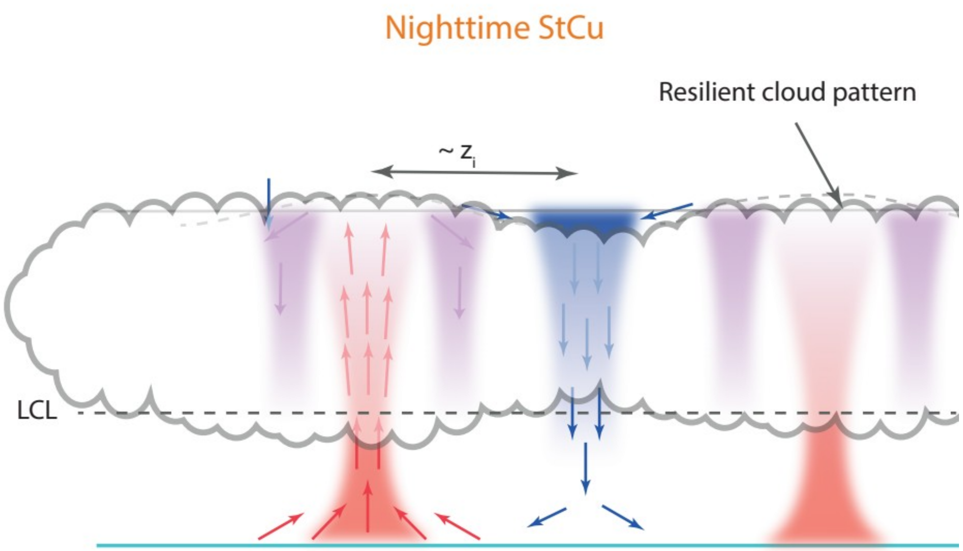




Updrafts and cloud-top downdrafts have opposite characteristics

Despite strong radiative cooling, cloud-top downdrafts start **positively buoyancy** and undergo **convergence** of air masses
→ Similarities with the dry convective boundary layer !

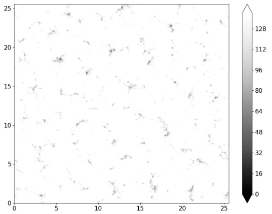
Schematic of the stratocumulus boundary layer

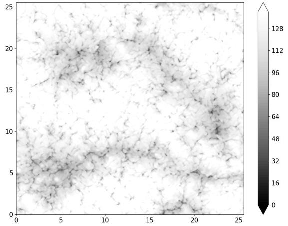


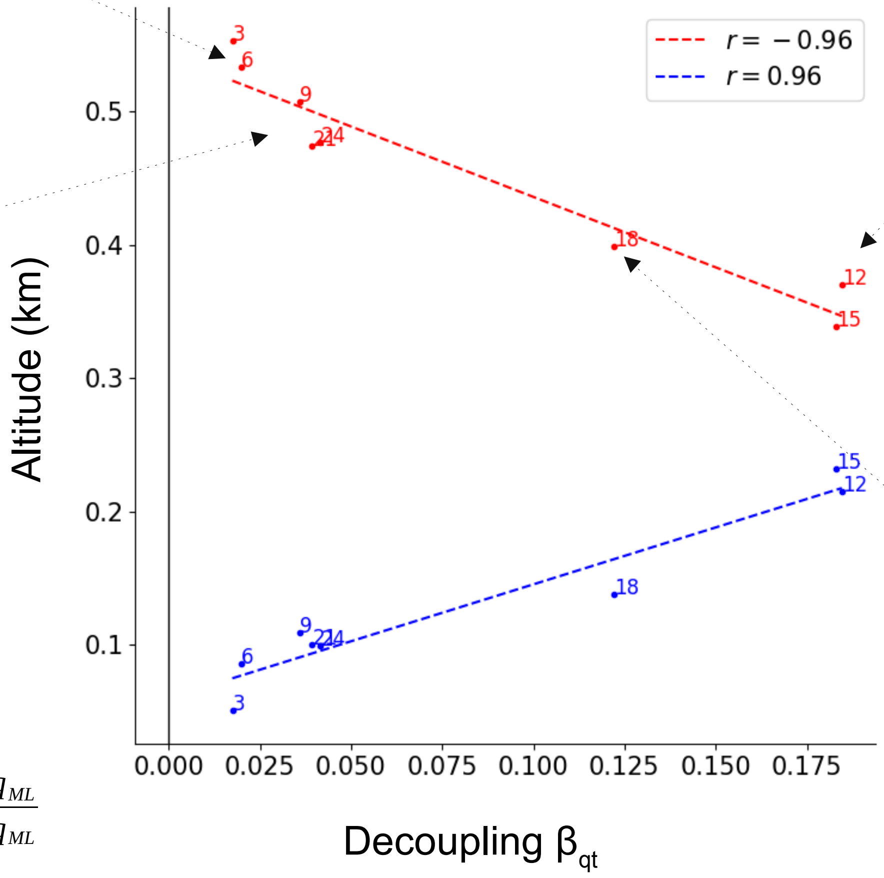
At nighttime

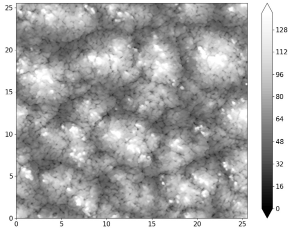
- Boundary layer is coupled
- **Downdrafts contribute to 80% of fluxes**
-

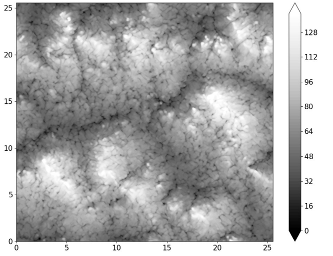
Schematic of the stratocumulus boundary layer











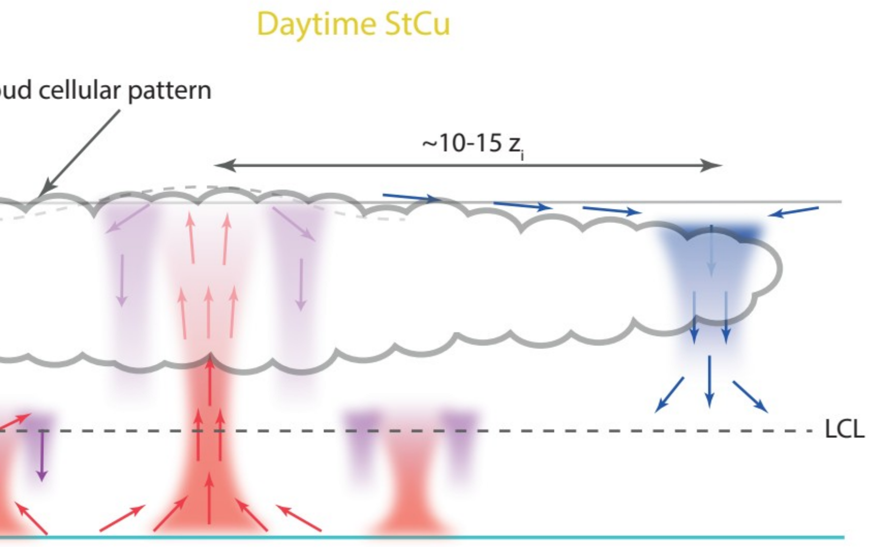
Averaged maximum altitude reached by updrafts

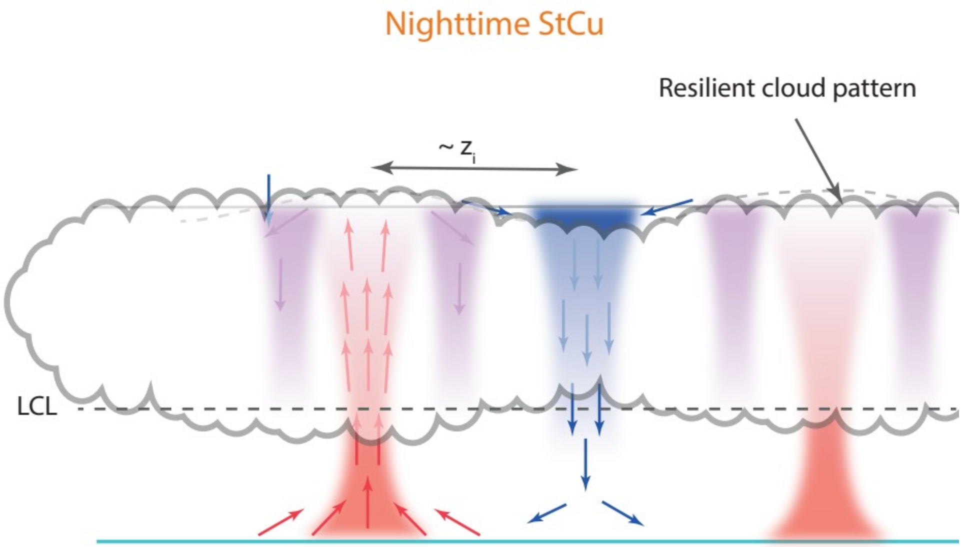
Averaged minimun altitude reached by downdrafts

Decoupling index: simple quantification of stabilization (0 = mixed layer)

$$\frac{q_{cld} - q_{ML}}{q_{inv} - q_{ML}}$$

Schematic of the stratocumulus boundary layer





At daytime

- Most updrafts are located at the center of the cells, most downdrafts at their surroundings
- Updraft contribute to 50% of fluxes.
- **Decoupling** reduces links between surface and cloud top
- **Aspect ratio of 10-30**

At nighttime

- Boundary layer is coupled
- **Downdrafts contribute to 80% of fluxes**
- Resilient cloud pattern of the daytime organization

Intermediate conclusions and remaining questions

Conclusions

- Passive tracer analysis is really efficient to identify and study **coherent structures**, which contribute to **80% of resolved fluxe**s while covering only 25 % of the domain
- Downdrafts are **adiabatically** triggered in all boundary layers. Negative buoyancy is enhanced by radiative/evaporative cooling in stratocumulus
- **Interaction between updrafts and downdrafts** shape the boundary layer organisation

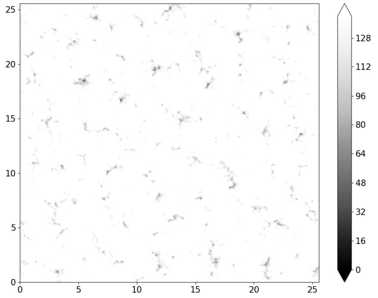
Questions to go further

- Q1: Why have the stratocumulus a so large aspect ratio?
- Q2 :Is there some unified theory for **downdrafts' triggering** in all well-mixed layers?
- Q3: How should we **represent** downdrafts in climate models?
- Q4: Can we identify robust low-cloud feedback mechanisms?

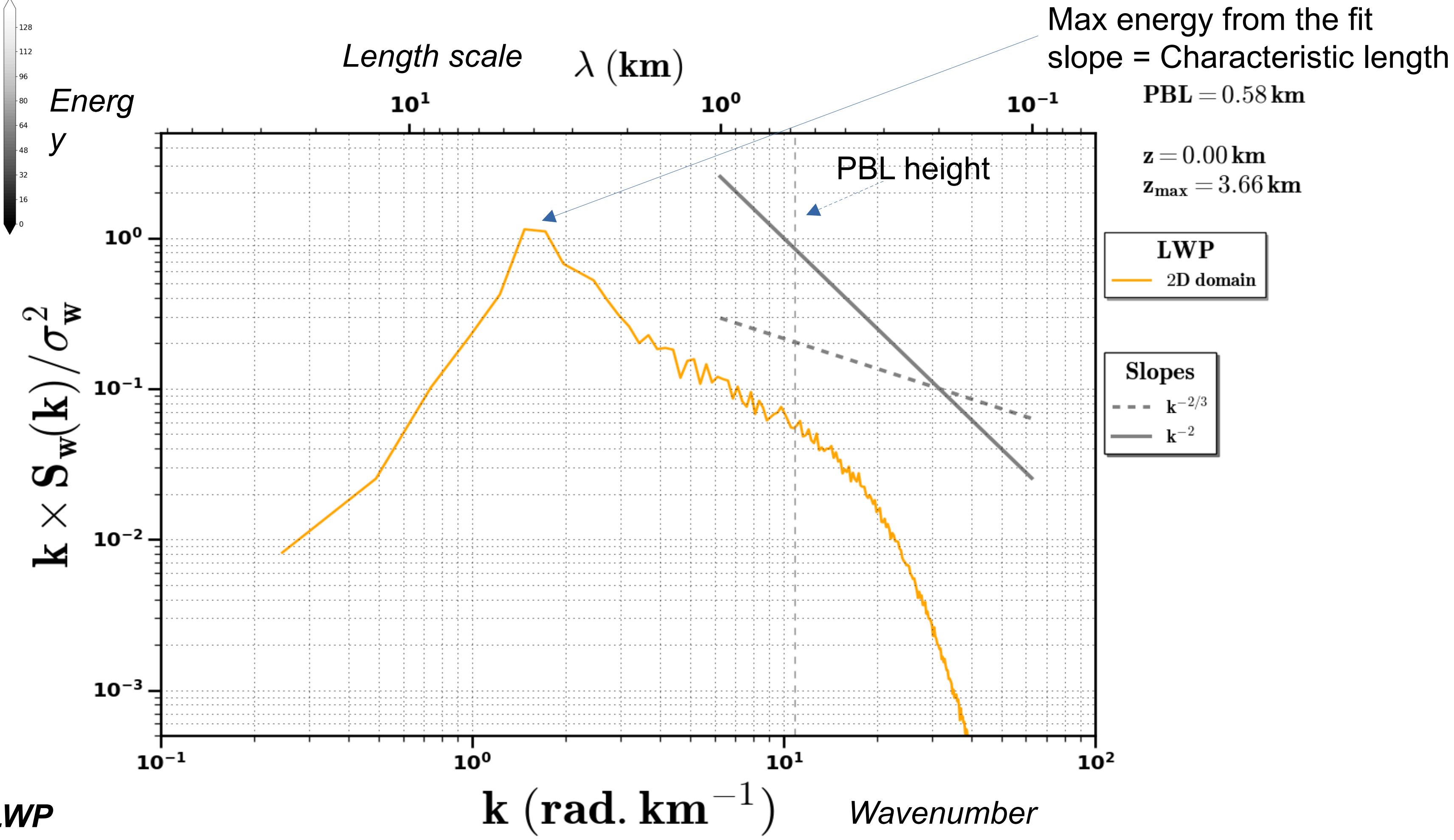
Morphology Of stratocumulus, BoundarY-layer DYnamics, and Climate Change (MOBYDYC) – ANR Project (2023-2027)

anr agence nationale de la recherche

Cloud morphology (Large-eddy simulations)



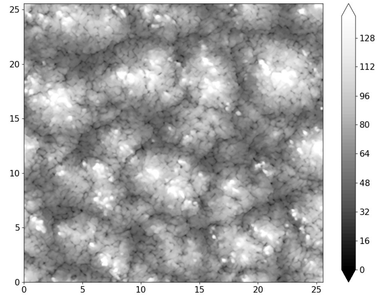
t+6h

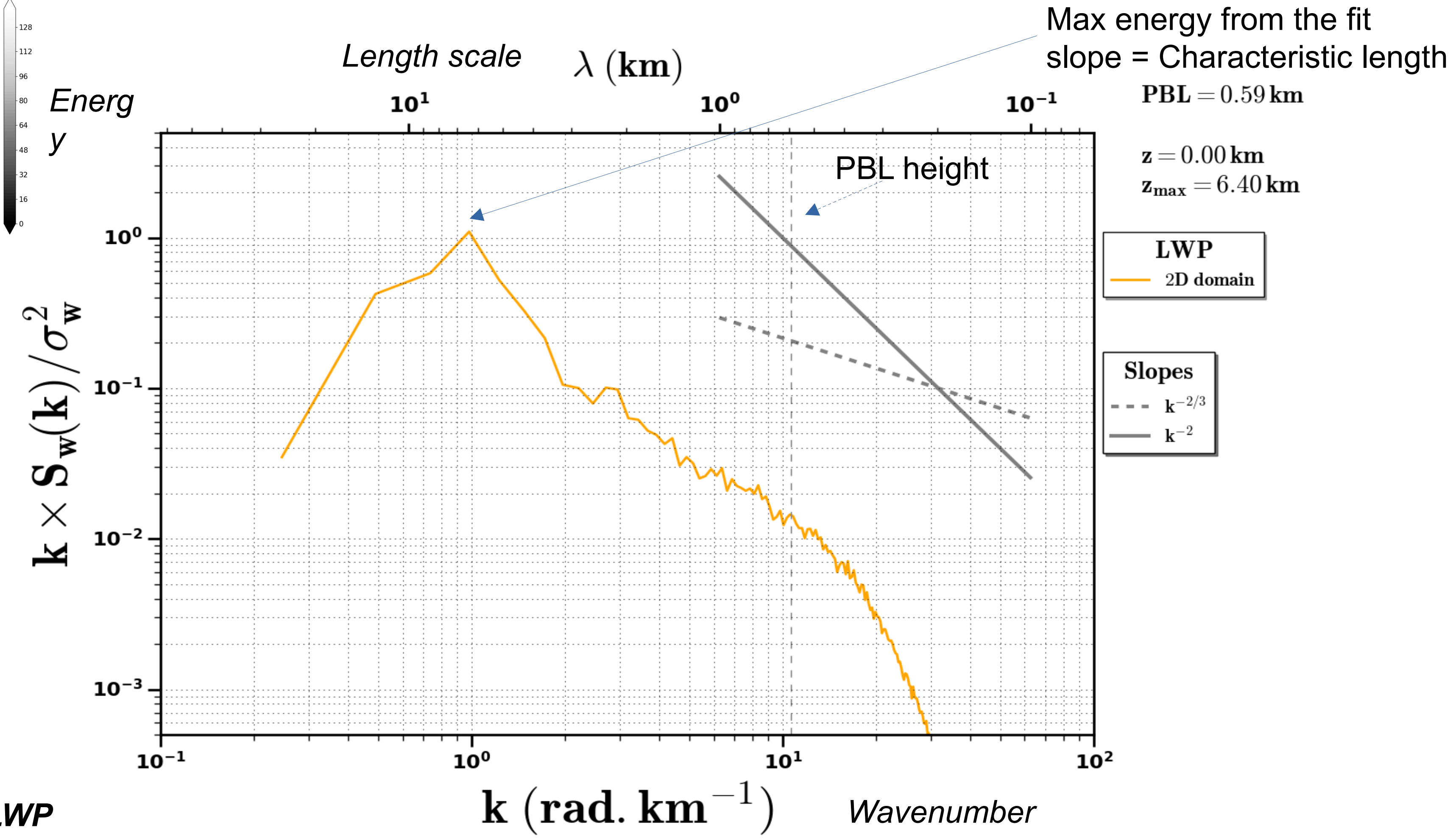


Power spectra of LWP

Cloudmetrics package by Janssens, Denby

Cloud morphology (Large-eddy simulations)



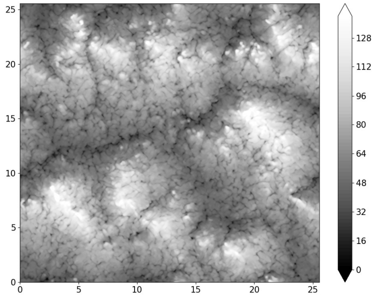


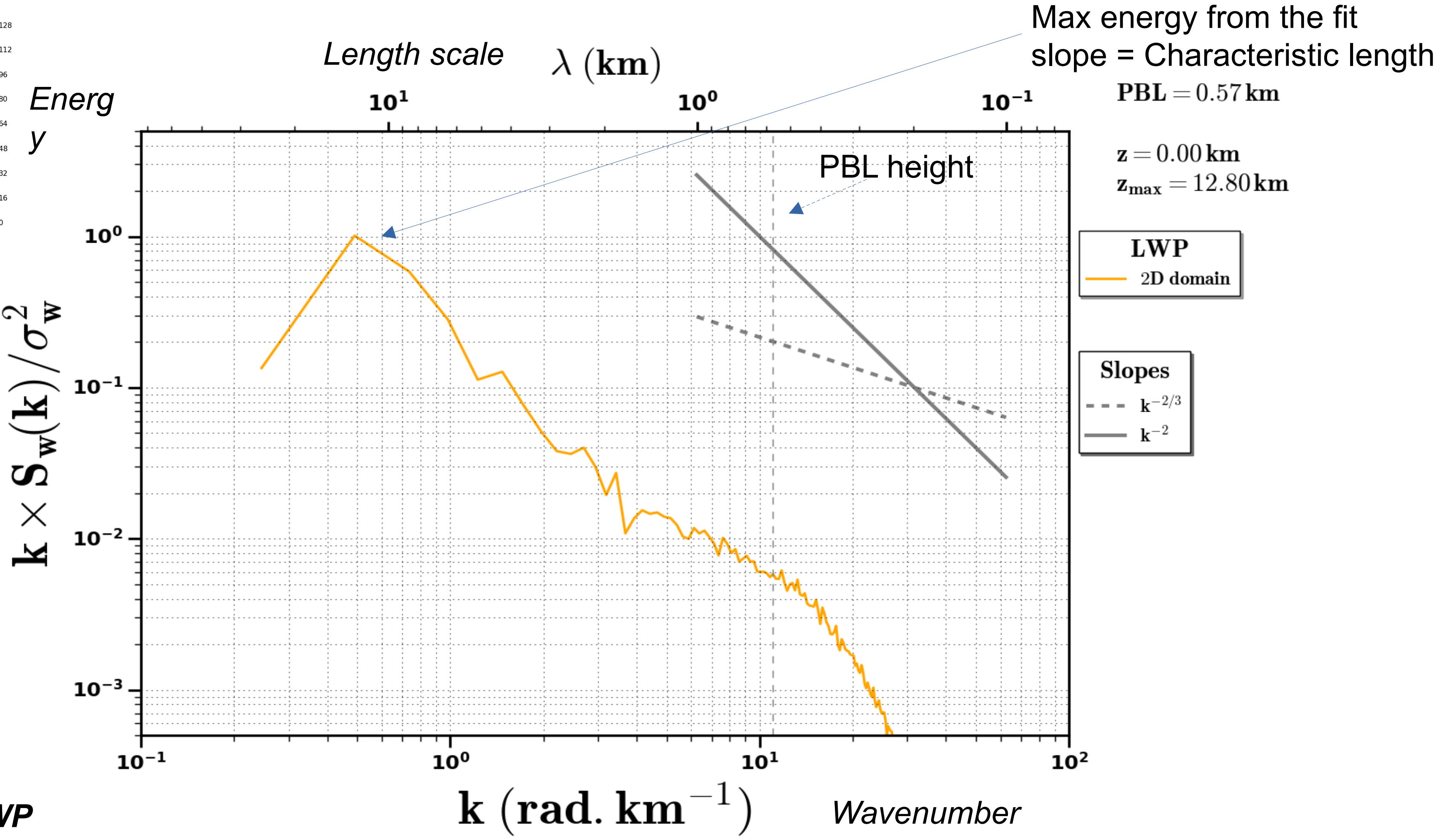
t+12h

Power spectra of LWP

Cloudmetrics package by Janssens, Denby

Cloud morphology (Large-eddy simulations)



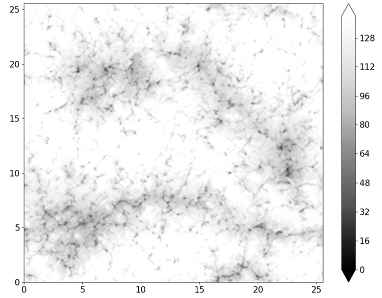


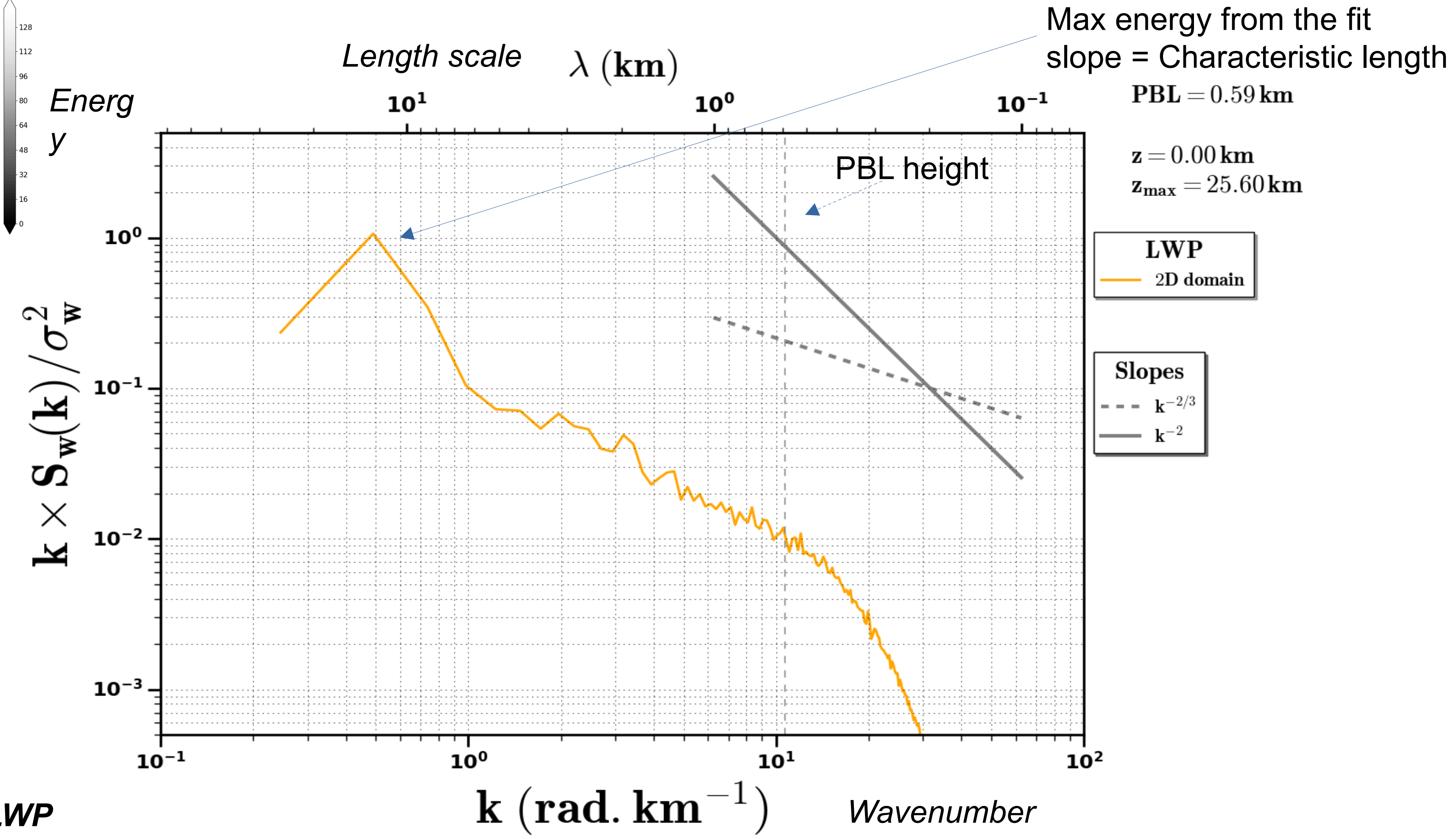
t+18h

Power spectra of LWP

Cloudmetrics package by Janssens, Denby

Cloud morphology (Large-eddy simulations)





t+24h

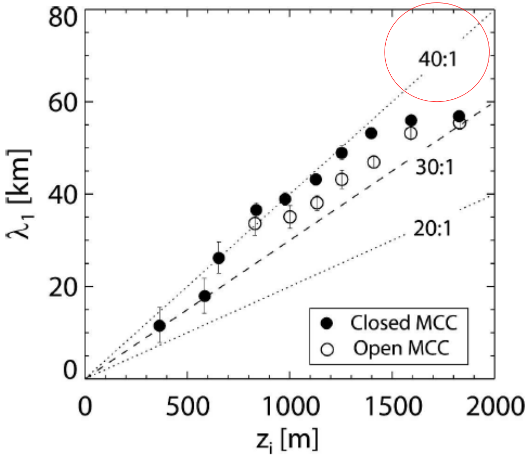
Power spectra of LWP

Cloudmetrics package by Janssens, Denby

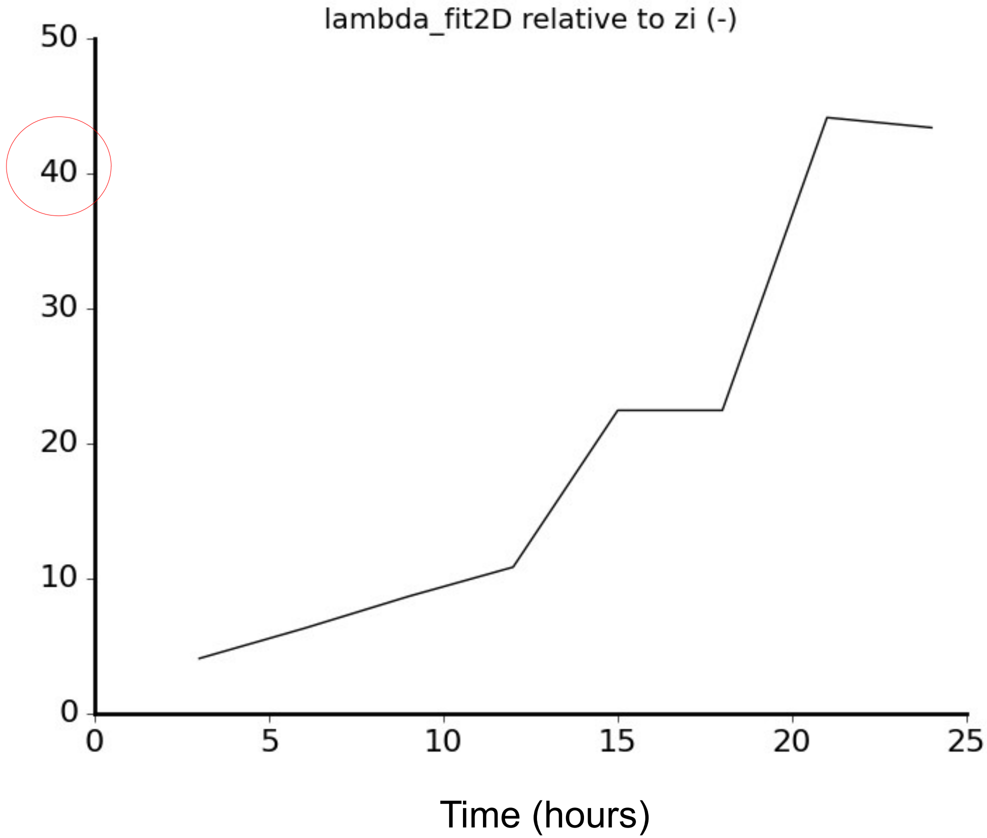
Cloud morphology (Large-eddy simulations)

Aspect ratio (cell size / PBL height) of
the Liquid Water Path field

Satellites
Observations



Wood and Hartmann (2006)



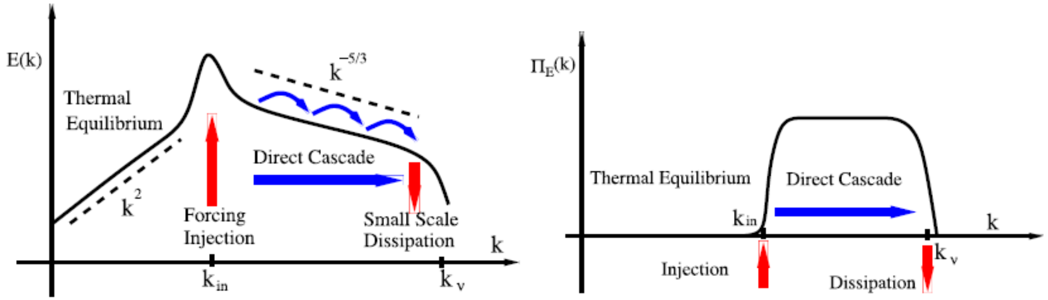
Upscale growth
scale of
structures

Why?

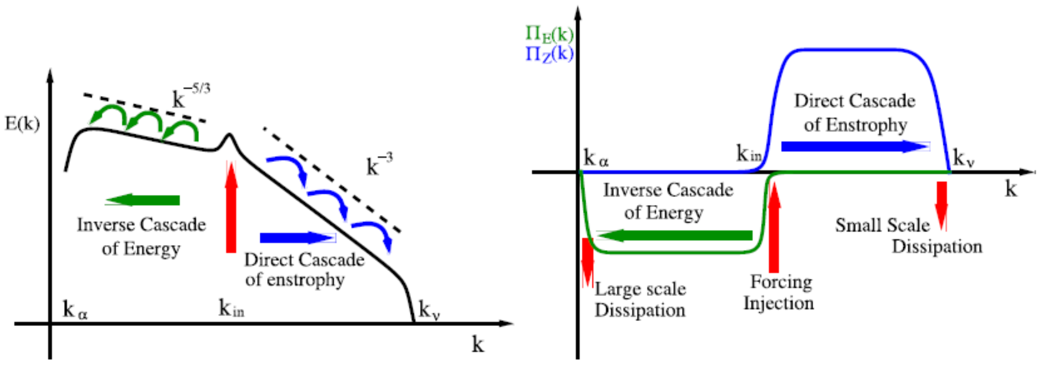
Cloud morphology (theory)

Classic 3D isotropic
Kolmogorov cascade
All vortices lose energy with
surrounding smaller eddies

A. Alexakis, L. Biferale / Physics Reports 767–769 (2018) 1–101



A. Alexakis, L. Biferale / Physics Reports 767–769 (2018) 1–101

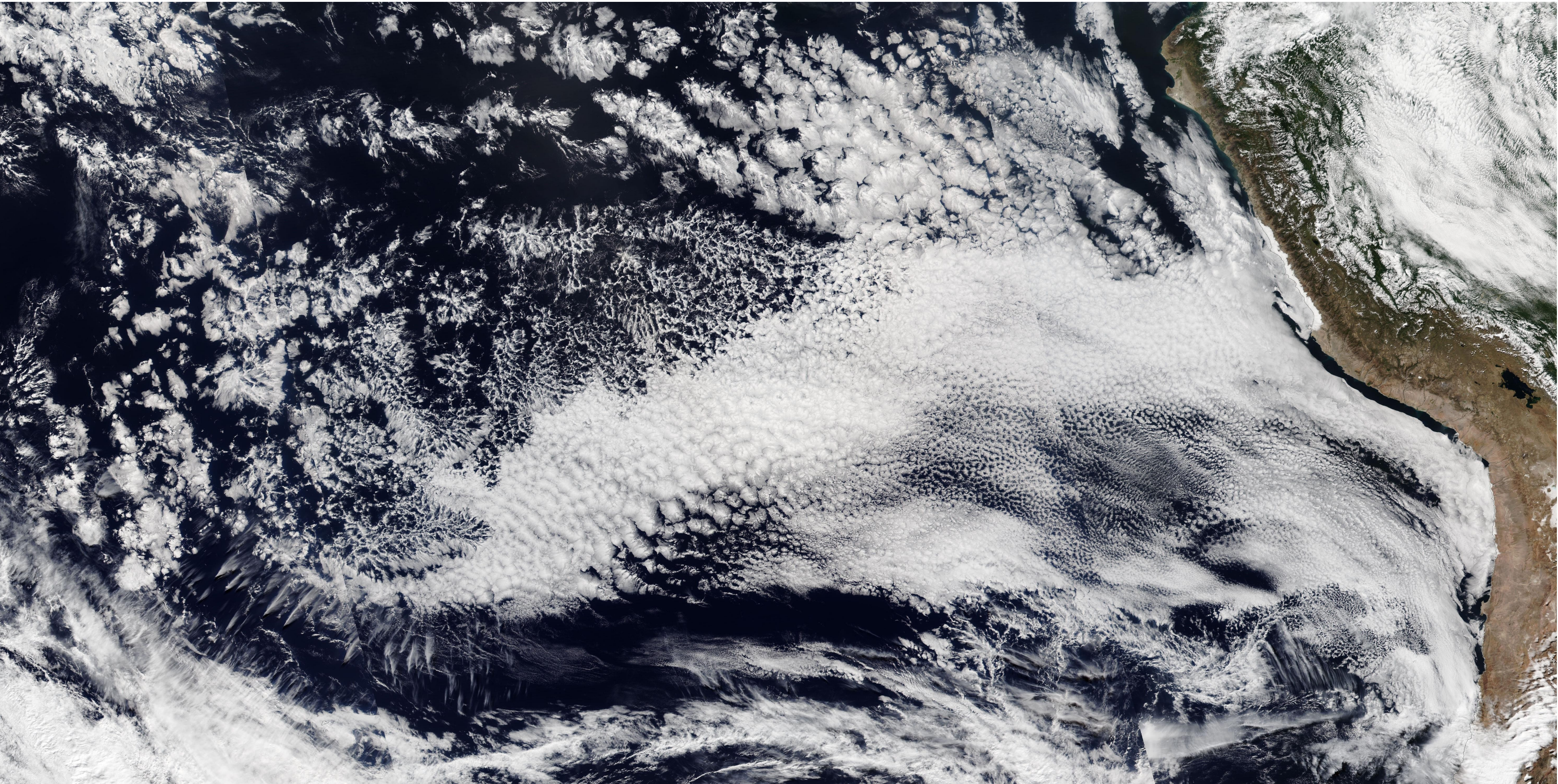


2D double cascade of energy.
Inverse energy cascade
suggest upscale growth above
the length of energy injection

Work in progress

My StCu LES

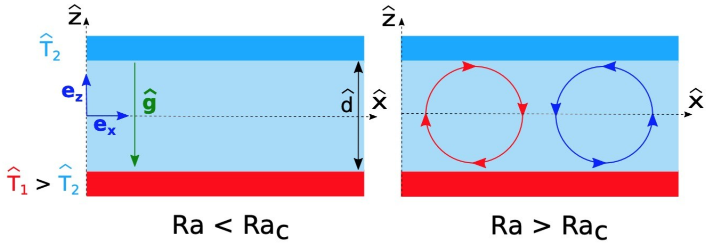
Cloud morphology (observations)

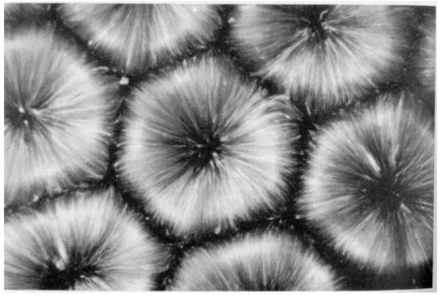


An unified theory for atmospheric boundary layer organisation?

- Definition of the Rayleigh Bénard convection (RBC):

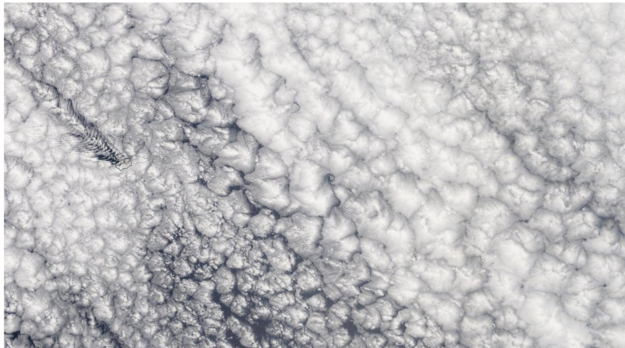
"A horizontal fluid layer of height d is confined between two thermally well conduction, parallels plates. When the difference DT = Tb - Tt between the bottomplate temperature and the top-plate temperature exceeds a critical value, the conductive motionless state is unstable and convection sets in. The simplest pattern which can occur is that of straight, parallel convection rolls" (Bodenschatz et. al, 10)





- **Similarities** between RBC and the Atmospheric Boundary Layer?
  - Fluid with high Rayleigh number (convection)
  - Warmer surface, colder troposphere (vertical T gradient)
  - Strong inversion as top plate?
  - Sensitivity of fluid proprieties to T and P solved by taking into account Non-Oberbeck-Boussinesq (NOB) effects (hexagons)

- **Differences** between RBC and the atmospheric BL?
  - The top-plate is **not rigid** (entrainment occur)
  - **Phase change** can modify RBC inside the convective layer and/or above (cumulus layer)
  - The **aspect ratio** of cells is larger than the RBC theory (30-50 for StCu >> 1-2).



Conclusions

- Questions to go further
  - *Q1: Why has the stratocumulus a so large aspect ratio? Can we explain the upscale growth during the day? What is the exact role of decoupling in this evolution?*
    - **Power spectra** show an upscale growth of structures in clear-sky and stratocumulus
  - *Q2 :Is there some unified theory to understand downdrafts' triggering in all well-mixed layers?*
    - Structural organisation suggest that **Rayeigh-Bénard convection** is a good candidate
    - Still need to figure what are the exact role of entrainment, condensation, heterogeneities in modifying the canonical RBC
  - *Q3: How should we represent downdrafts in climate models?*
    - **Coherent subsiding structures** need to be represented, compensating subsidence not enough
  - *Q4: Can we highlight robust low-cloud feedback mechanisms?*
    - Not yet

2026 Workshop idea:
"Theoretical advances in understanding the organization of atmospheric (oceanic?) boundary layers" (or something like that) - Link with GDR Defis théoriques, DEPHY, GASS, Annual Workshop Organisation Convection


Thank You
SORBONNE UNIVERSITÉ
IPSL
LMD
anr agence nationale de la recherche