On the role of clouds in climate: New research perspectives

Sandrine Bony

Laboratoire de Météorologie Dynamique, CNRS
Académie des Sciences

Académie des Sciences, 9 Septembre 2025

Earth's radiation budget & climate

V. Ramanathan was pivotal in quantifying

how different atmospheric constituents

impact Earth's radiation budget, such as

trace gases (CFCs), aerosols, water vapor and clouds

1989: First measurements of the cloud impact on Earth's radiation budget

Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment

V. Ramanathan, R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, E. Ahmad, D. Hartmann

6 JANUARY 1989 SCIENCE, VOL. 243

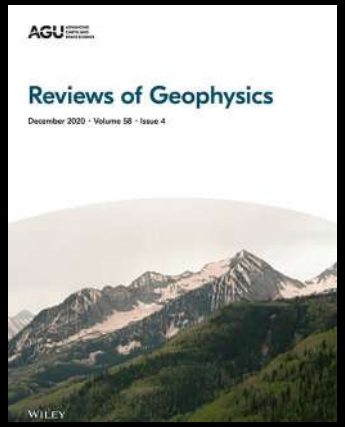
- Clouds exert two antagonist effects on Earth's energy balance.

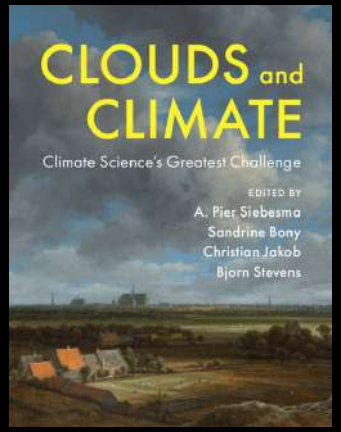
- Satellite observations reveal that on average over the Earth, clouds exert a large cooling effect (-20 W/m^2)

- May exert a powerful climate feedback under climate change

→ A turning point in cloud and climate research

Where do we stand today?





Much has been learned since 1989

Clouds respond to warming in several ways that

- amplify global warming
- influence many other aspects of weather and climate:

e.g. atmospheric circulations, rainfall, extreme events

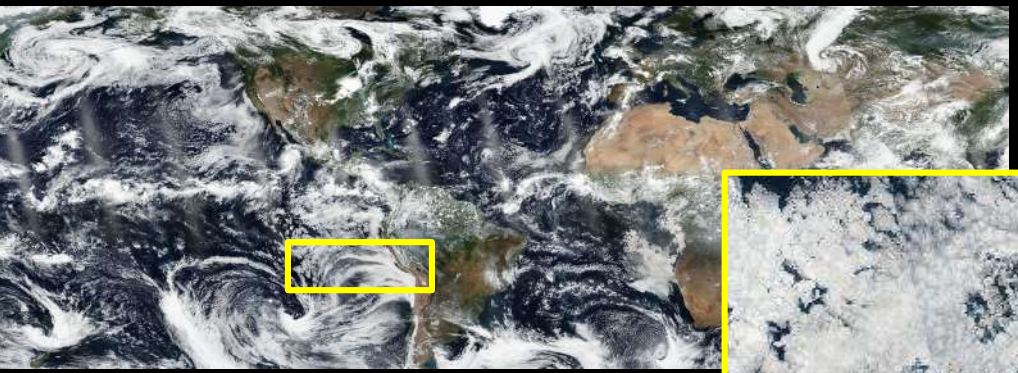
Uncertainties remain:

- global scale (quantitative uncertainties)
- regional scale (both qualitative and quantitative uncertainties)

Puzzles linked to knowledge gaps at the mesoscale

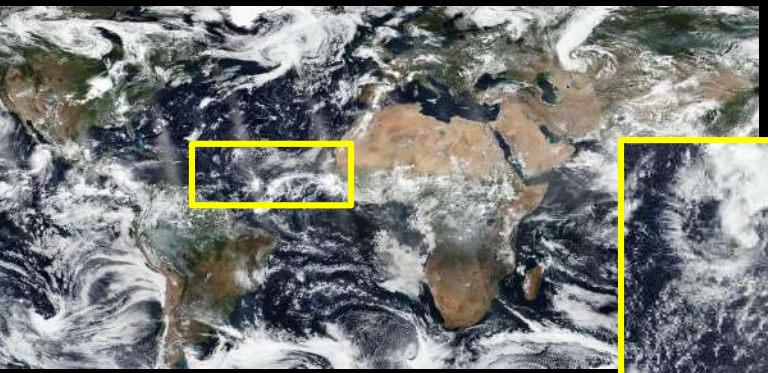
(Mesoscale: from a few km to a few hundred km)

Mesoscale puzzles

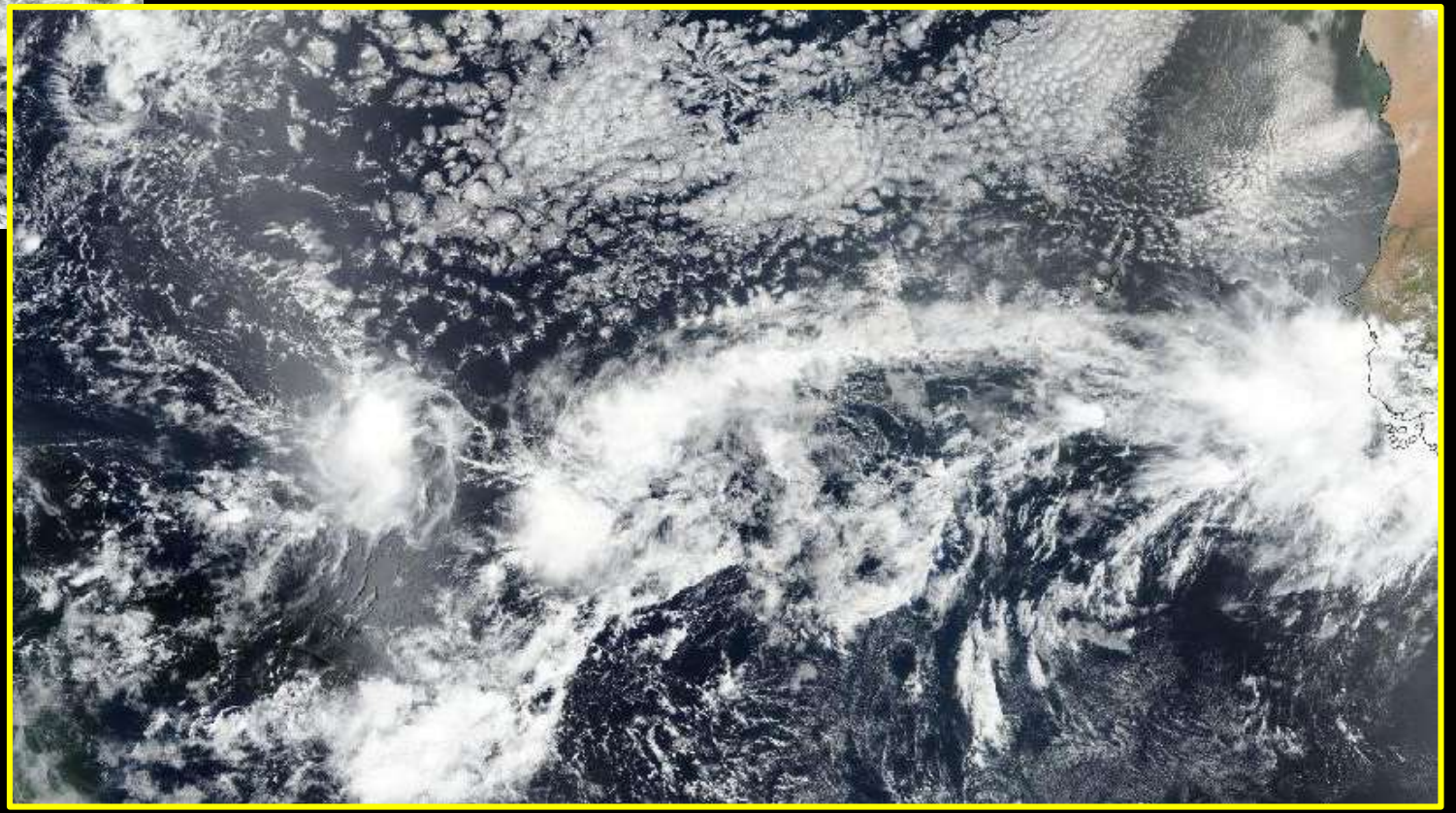


Morphology and albedo of Stratocumulus

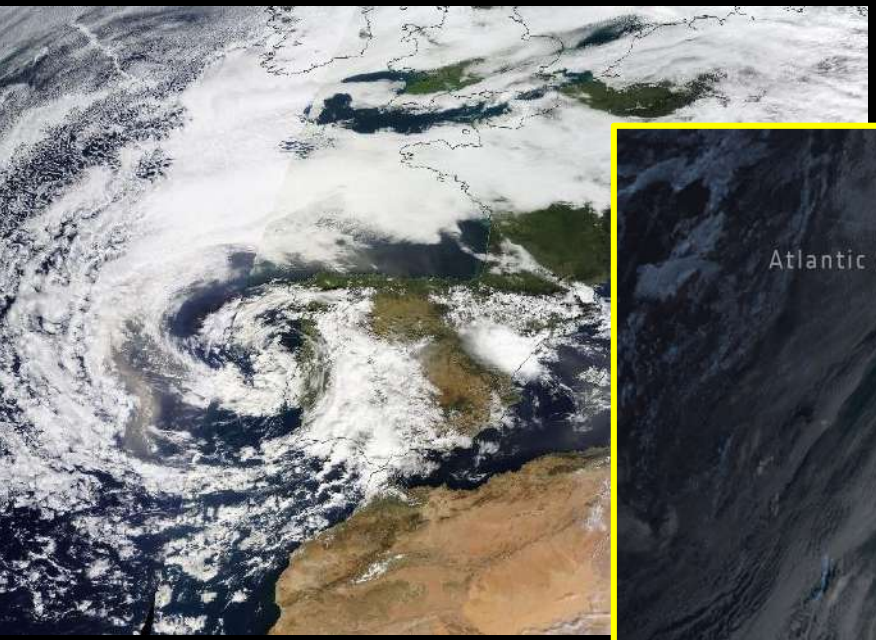
Mesoscale puzzles



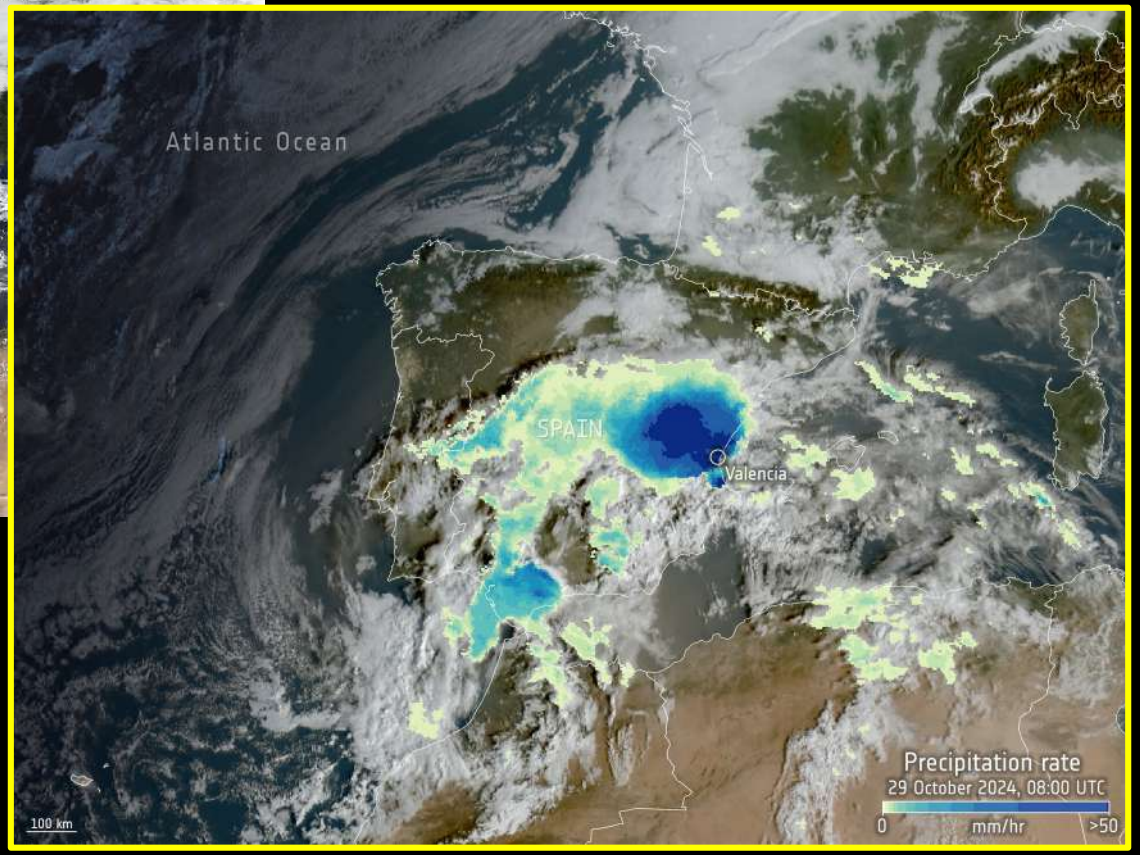
Shallow and deep clouds ; Cloud clustering



Cloud clustering matters



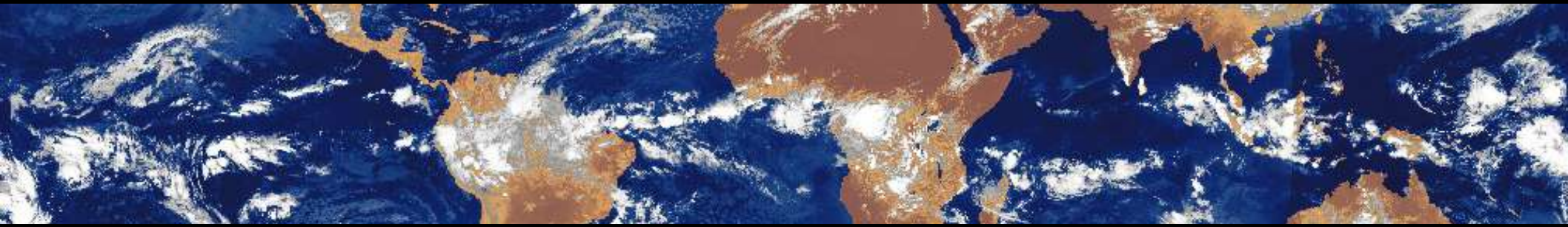
Intensity of heavy precipitation

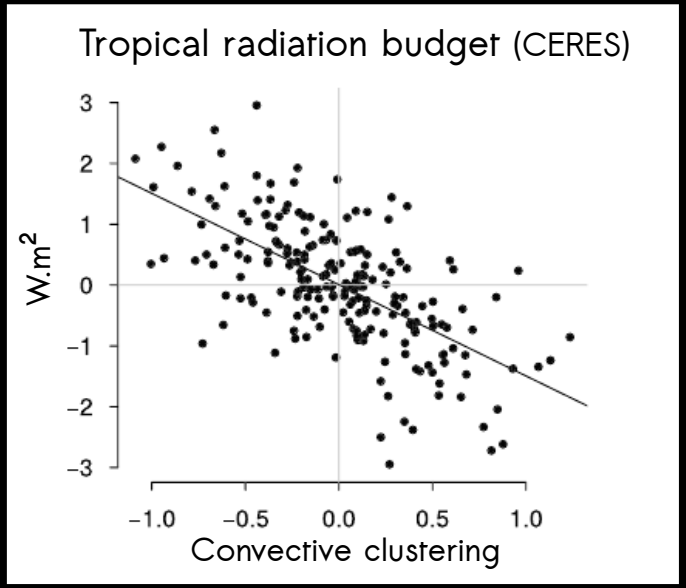


Valencia, Spain, Oct 2024

Cloud clustering matters

Influence on Earth's radiation budget





Enhanced clustering
of deep clouds

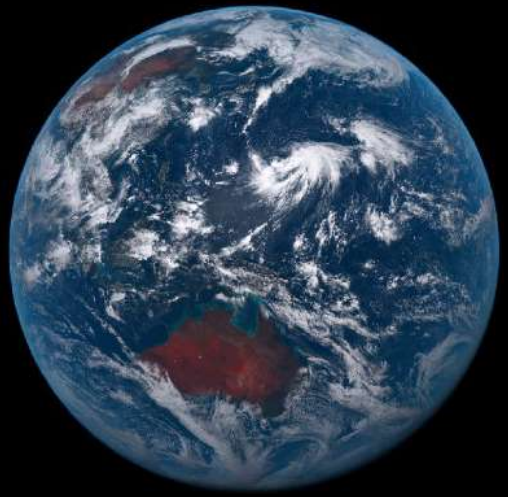
↓

Drier tropics
&
Enhanced
radiative cooling to space

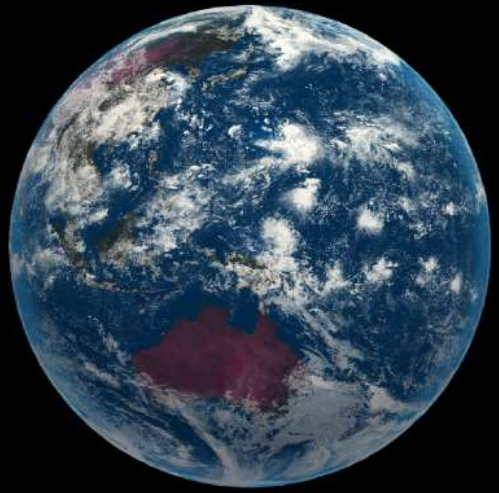
Bony et al. (2020a)

Cloud clustering matters

Satellite observations



Simulations at km-scale



A challenge for
weather and climate modeling
at the km-scale

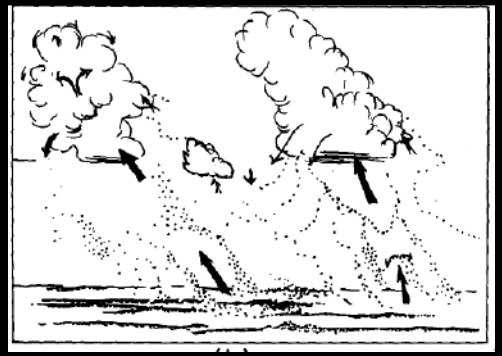
Stevens et al. (2019)

What causes clouds to organize at the mesoscale?

What causes clouds to organize at the mesoscale?

Can be spontaneous (“self-aggregation”) and result solely from cloud-cloud and cloud-environment interactions

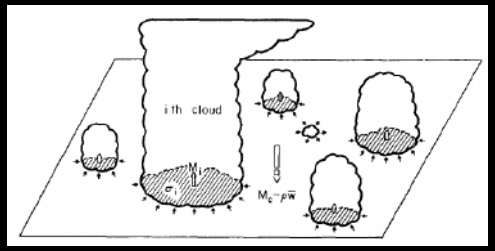
Sub-cloud thermals



Le Mone and Pennell (1976)

Photograph: V. Douet (ATR)

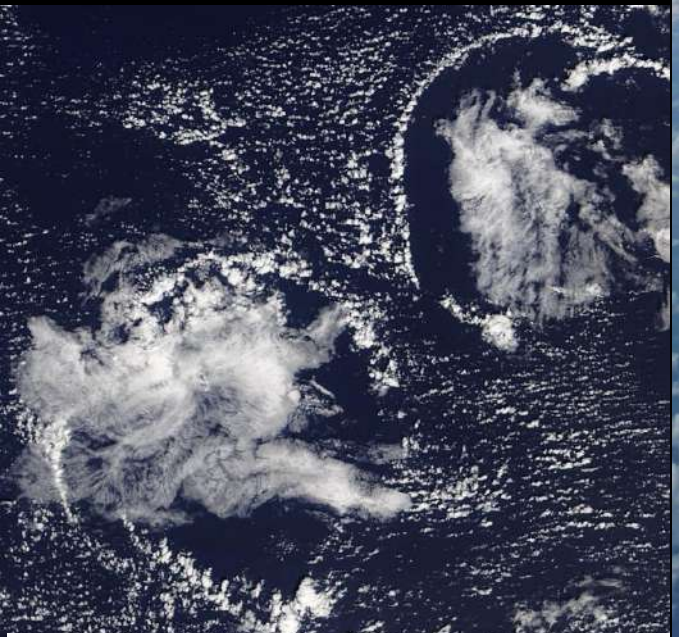
Cloud growth

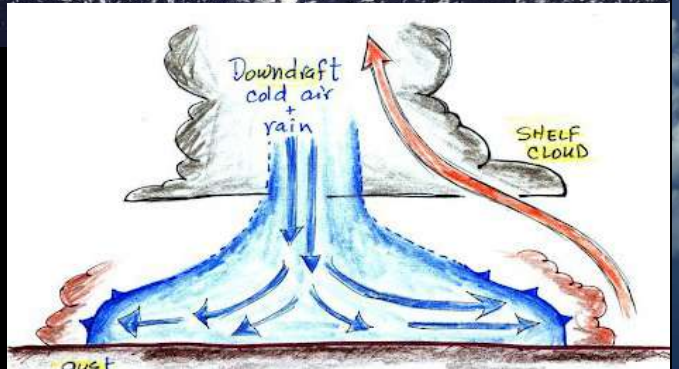


Arakawa and Schubert (1974)

Photograph: B. Stevens (HALO)

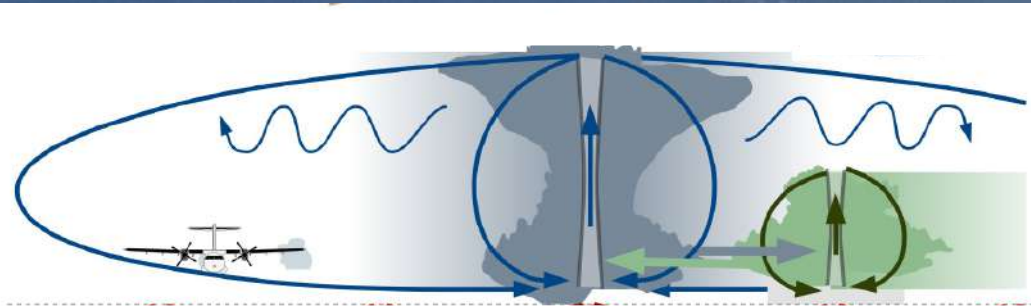
Cold pools





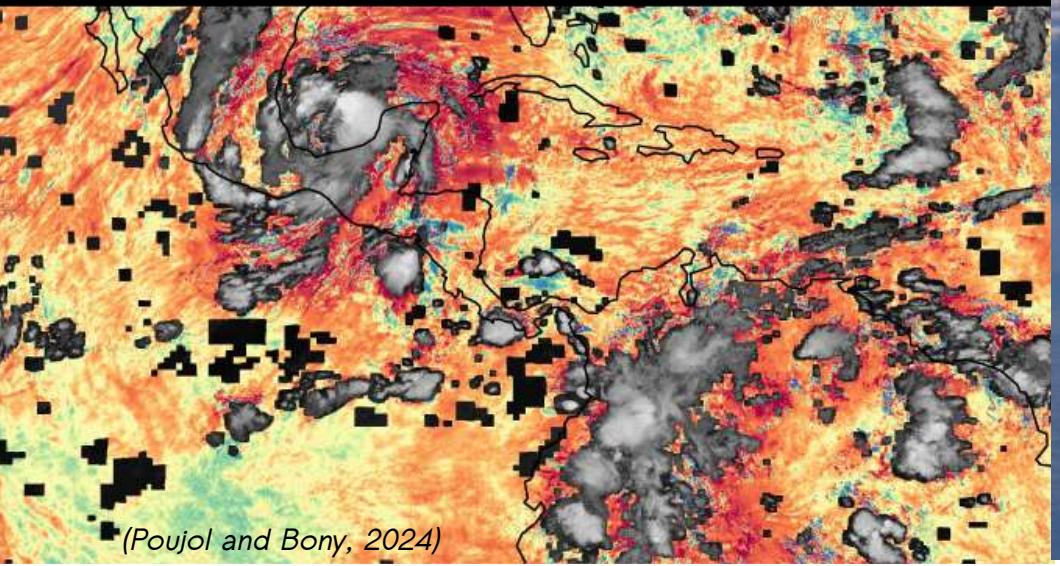
Photograph: S. Bony (HALO)

Mesoscale circulations



Mesoscale circulations

- First satellite measurements of clear-sky vertical velocities



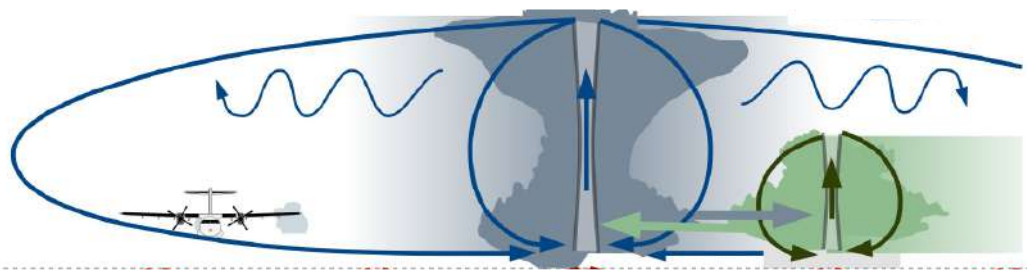
(Poujol and Bony, 2024)

- Theoretical interpretation of measurements:

$$\omega \approx f(z)\frac{\mathcal{M}g}{2H\sqrt{(r+R)H}}e^{-\frac{\pi(r+R)}{2H}} + \omega_{inf}$$

→ decreases with the distance from cloud

→ controlled by cloud width, depth and mass flux



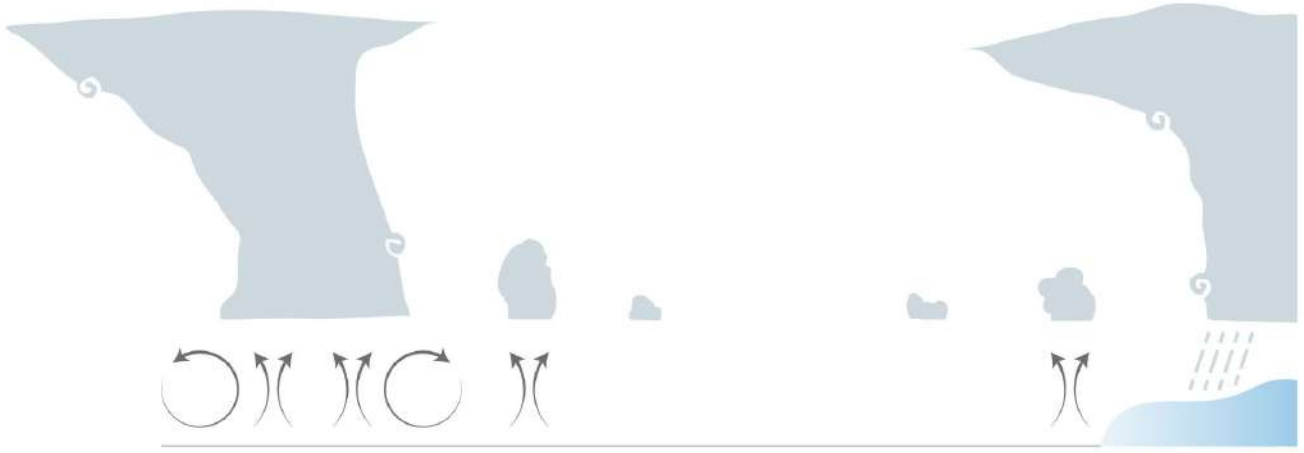
Basile Poujol (PhD thesis, 2025)

Interplay between all these processes?

Photograph: R. Vogel (HALO)

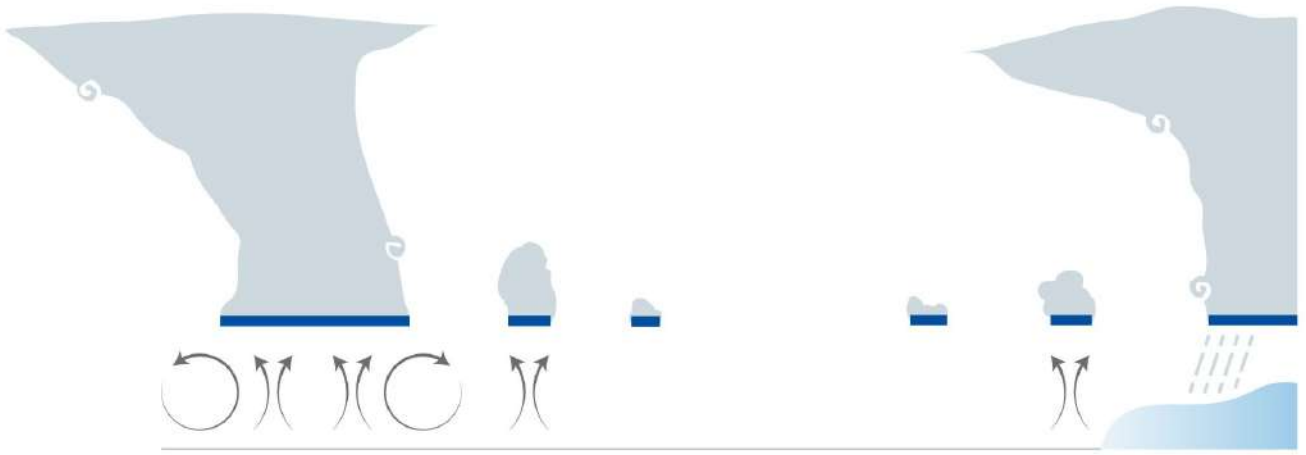
Physical processes controlling the mesoscale organisation of convection

Coherent structures

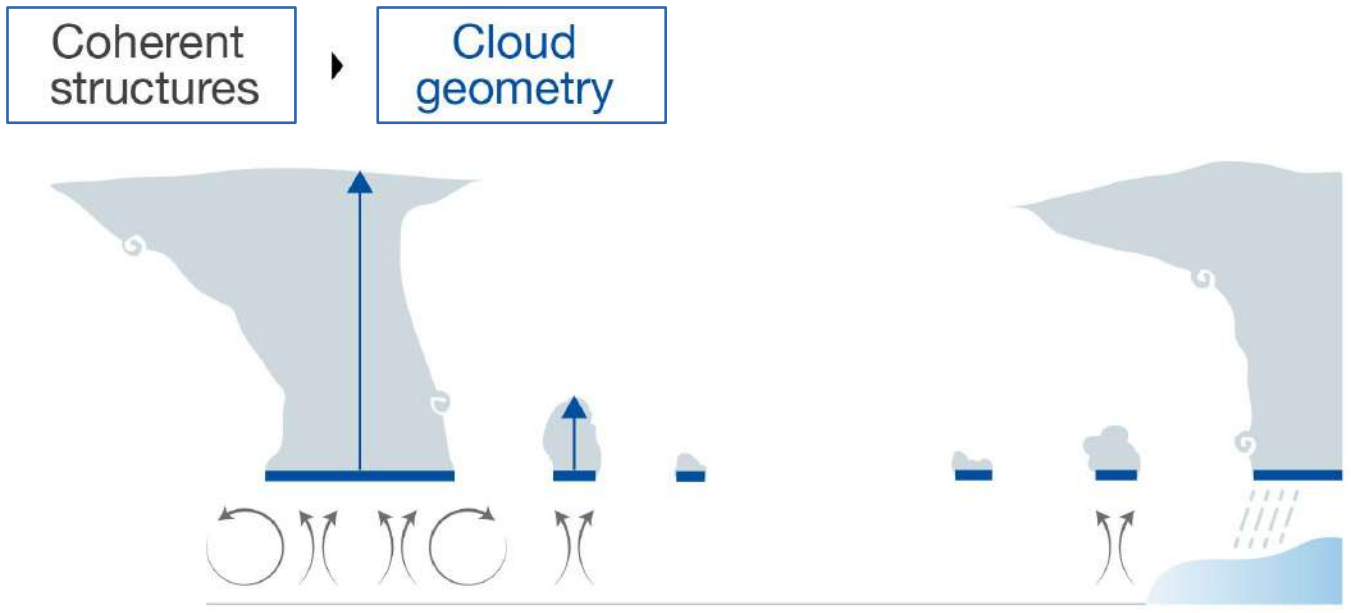


Physical processes controlling the mesoscale organisation of convection

Coherent structures ▸ Cloud geometry

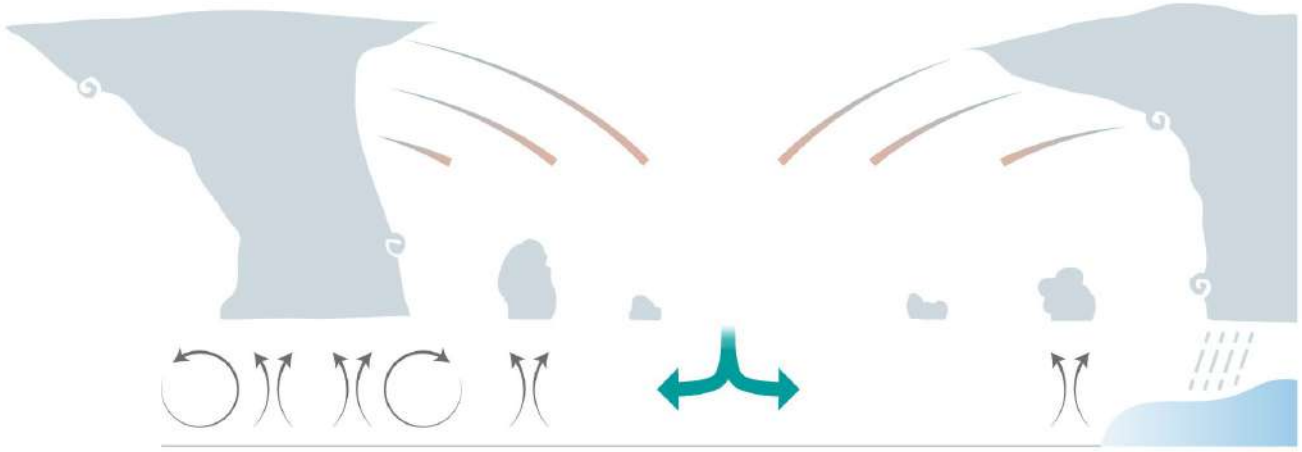


Physical processes controlling the mesoscale organisation of convection



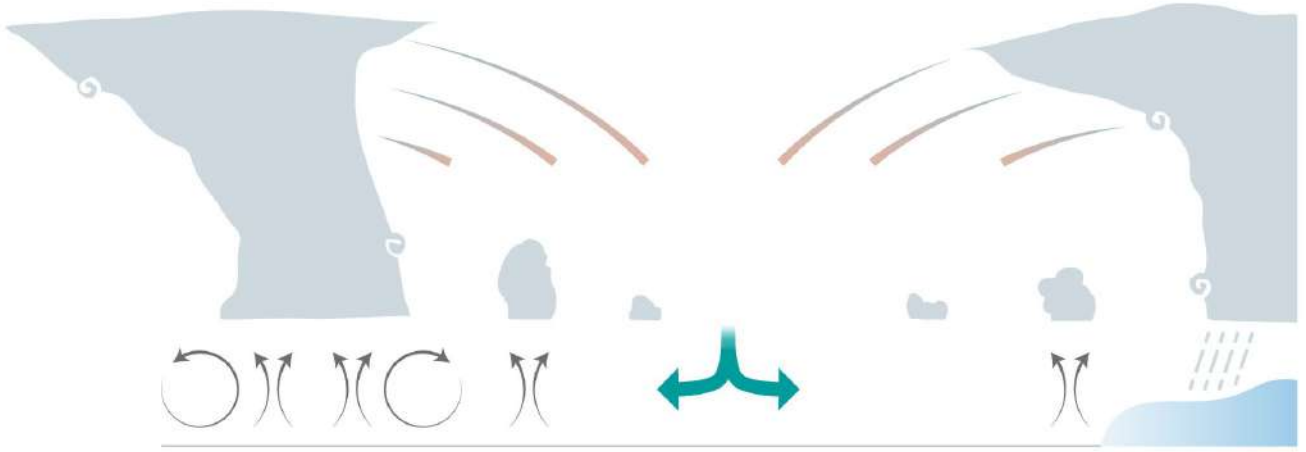
Physical processes controlling the mesoscale organisation of convection

Coherent structures ▸ Cloud geometry ▸ Mesoscale circulation



Physical processes controlling the mesoscale organisation of convection

Coherent structures ▸ Cloud geometry ▸ Mesoscale circulation & Water vapour



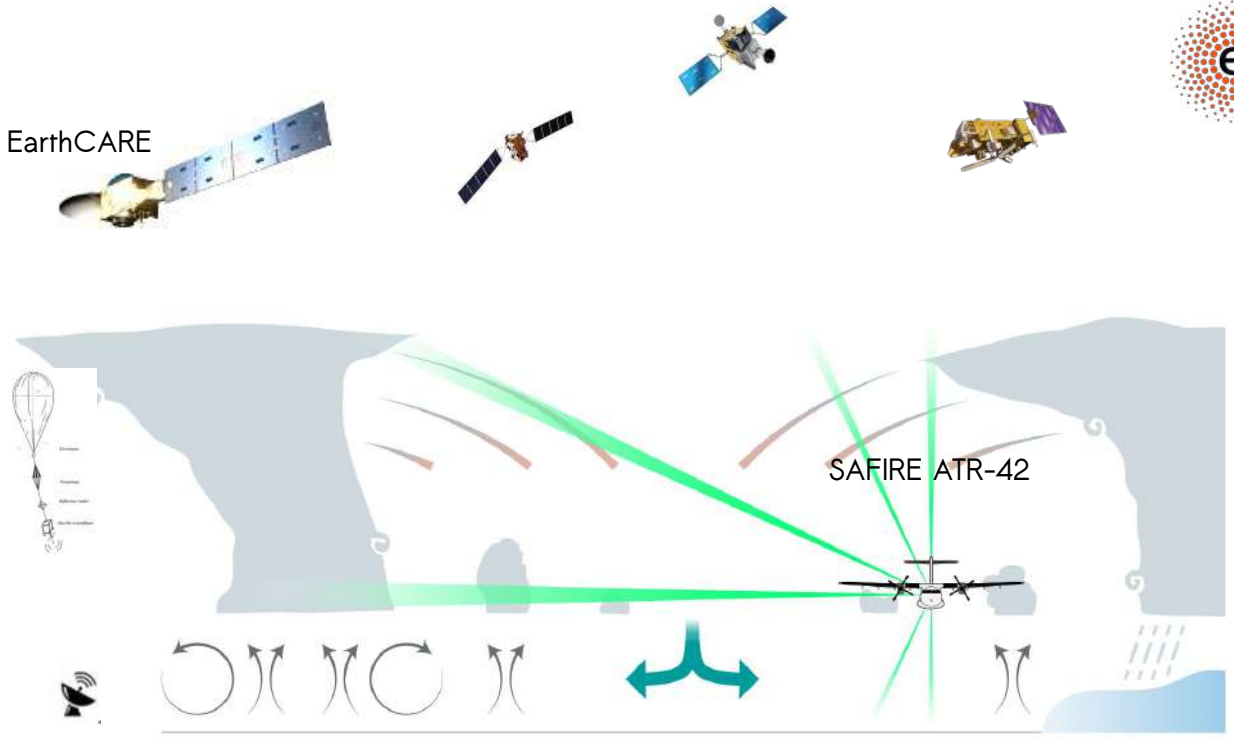
Until now: insights mostly from modeling or individual process observations

Missing: observations of this interplay

MAESTRO/ORCESTRA field campaign

(Mesoscale organisation of tropical convection)

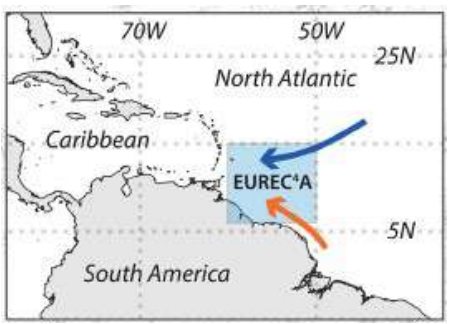
Cape Verde, Aug-Sep 2024

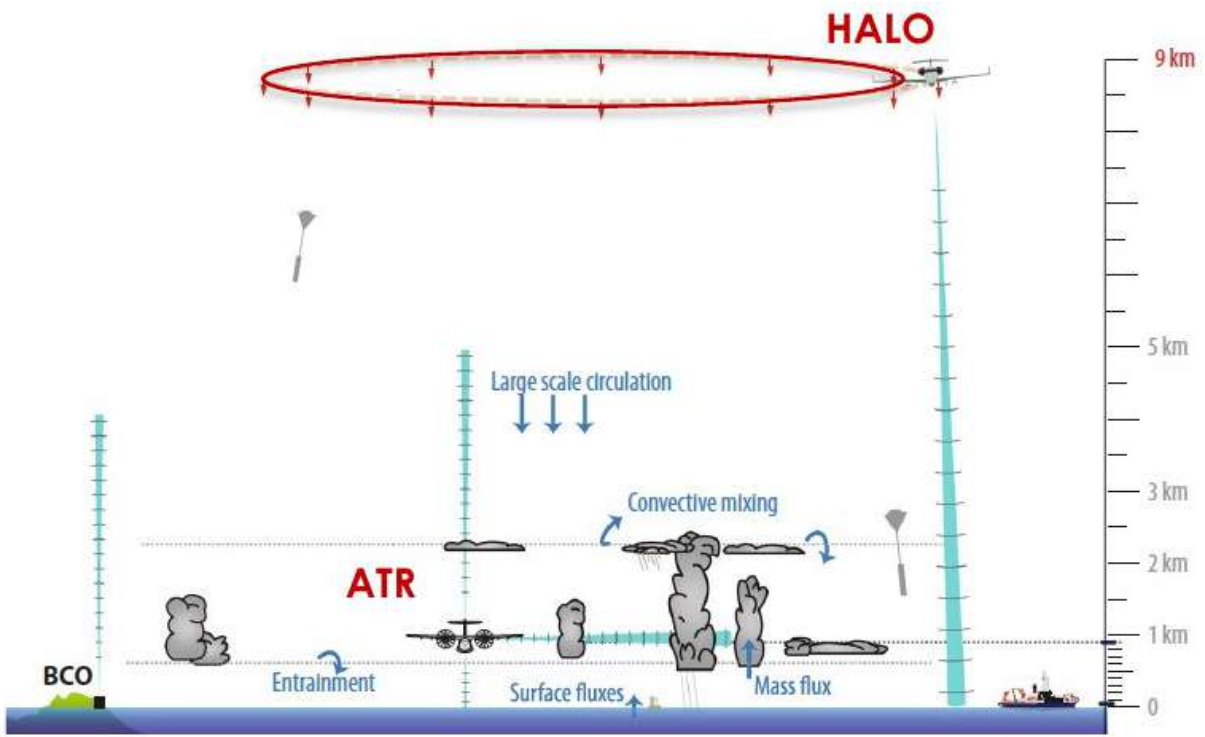


EUREC⁴A field campaign

(Elucidating the role of couplings between clouds, convection and climate)

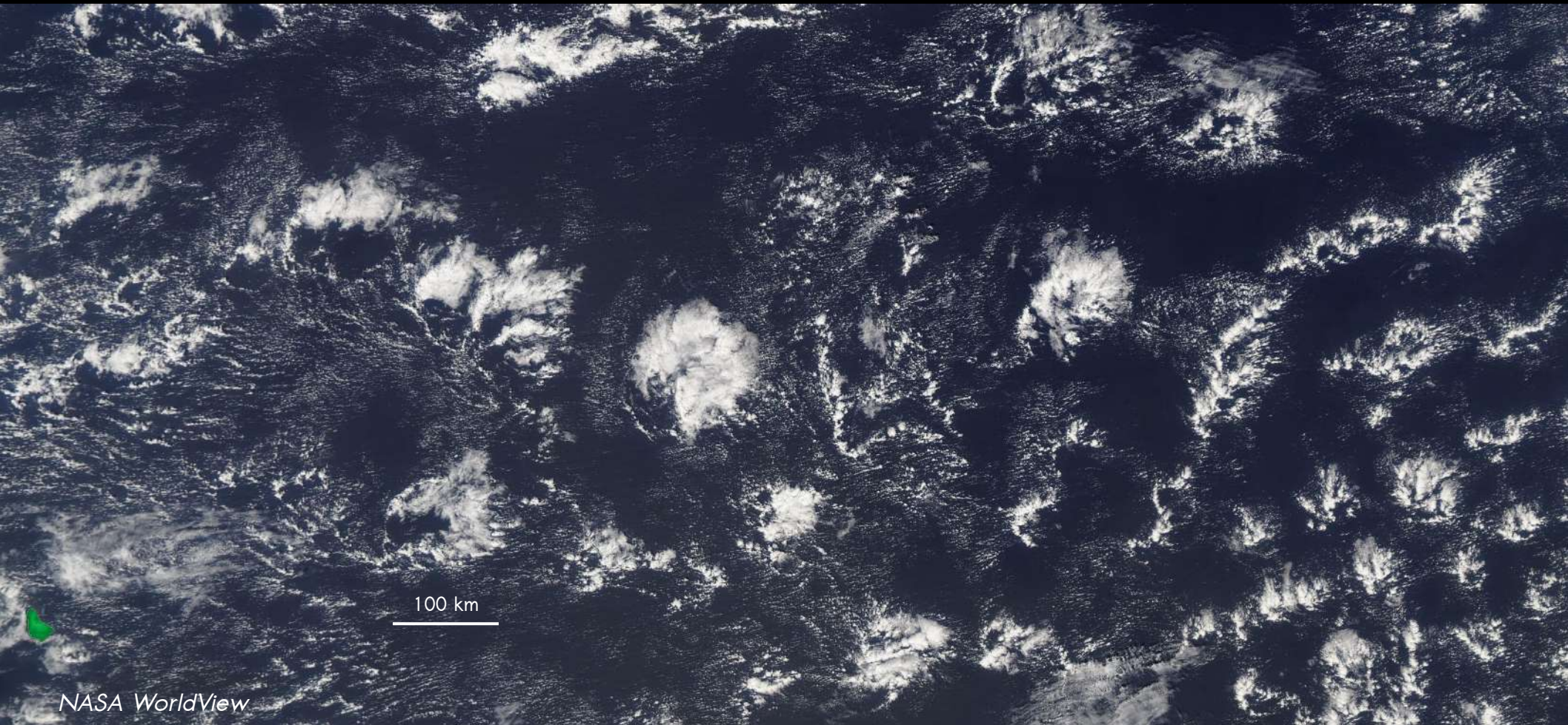
Barbados, Jan-Feb 2020



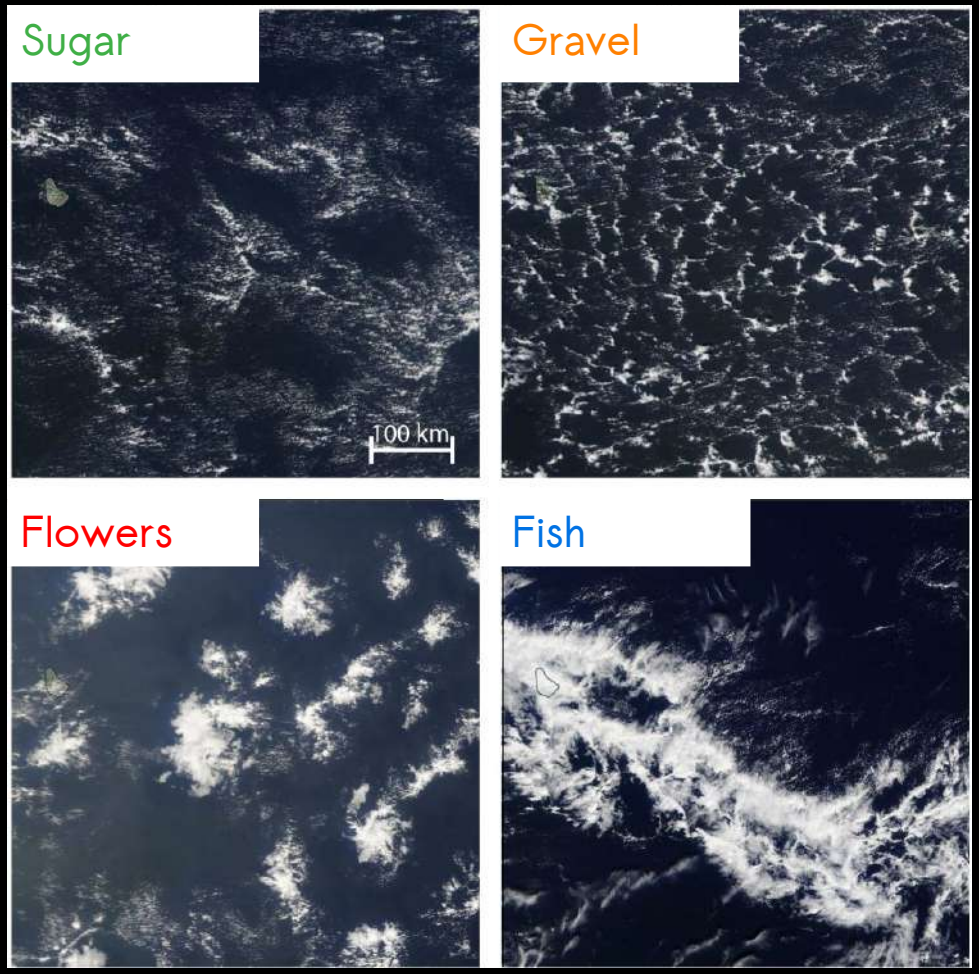


Bony et al. (2017), Stevens et al. (2021), Bony et al. (2022)

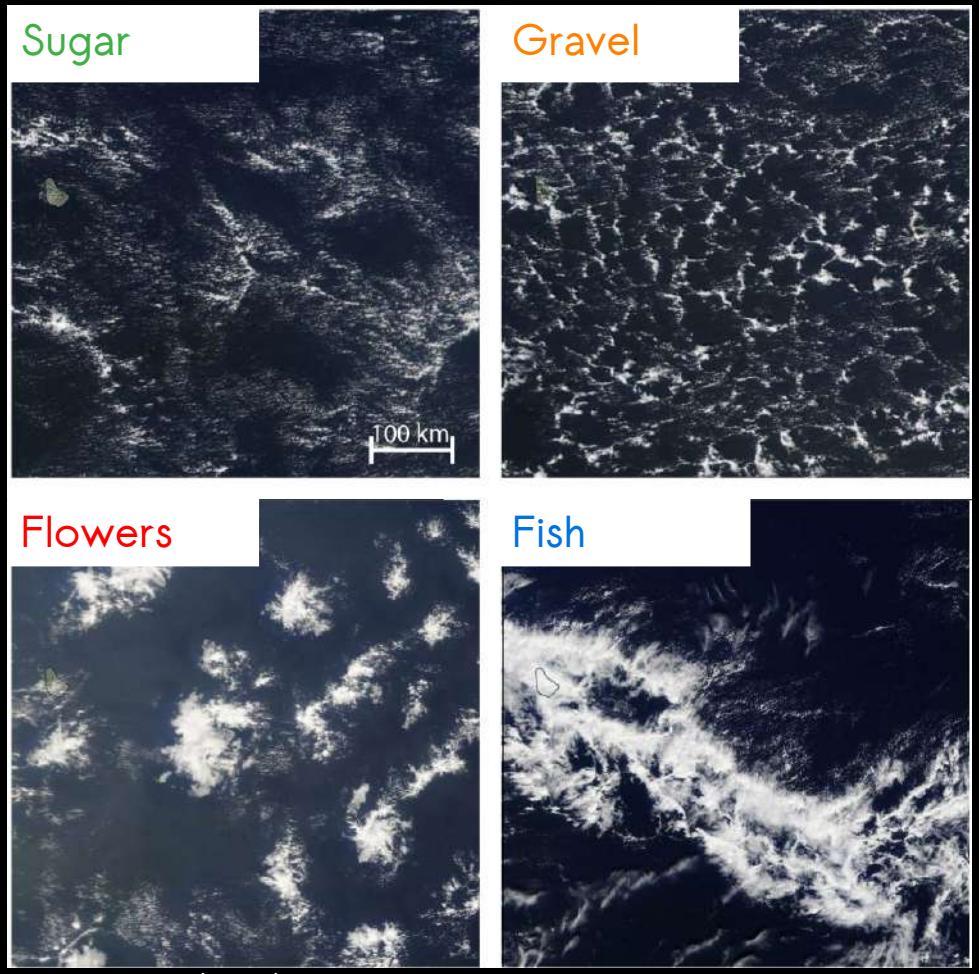
Mesoscale patterns of trade-wind clouds over the tropical Atlantic



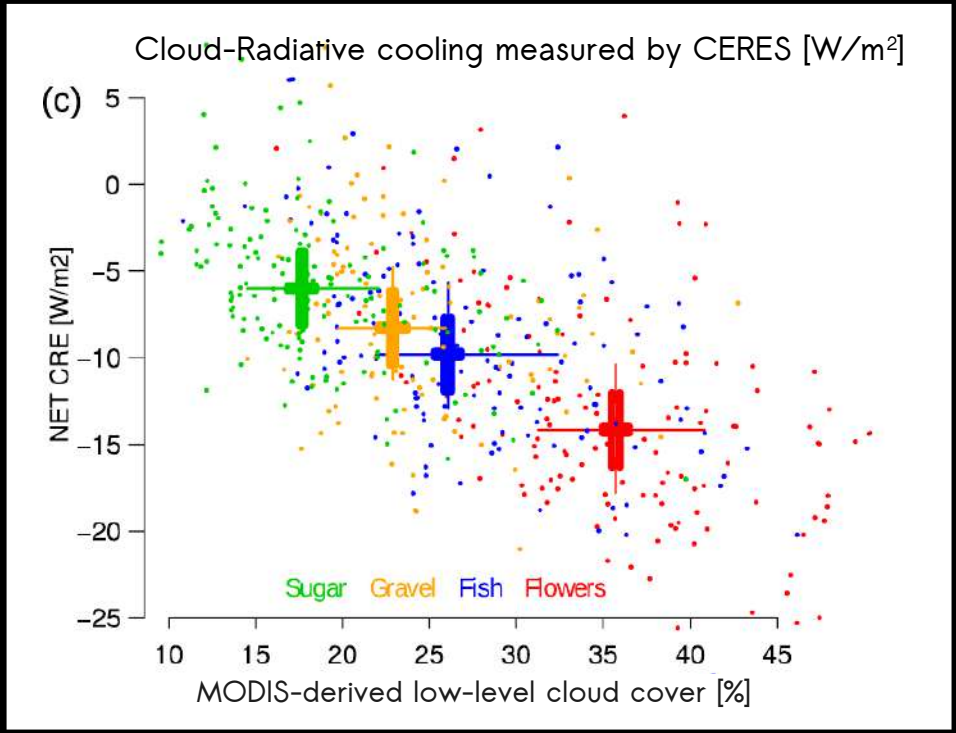
Impact on Earth's radiation budget



Impact on Earth's radiation budget

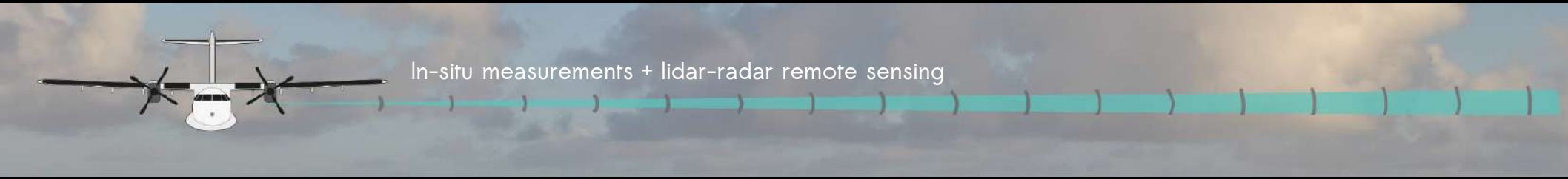


Stevens et al. (2020)

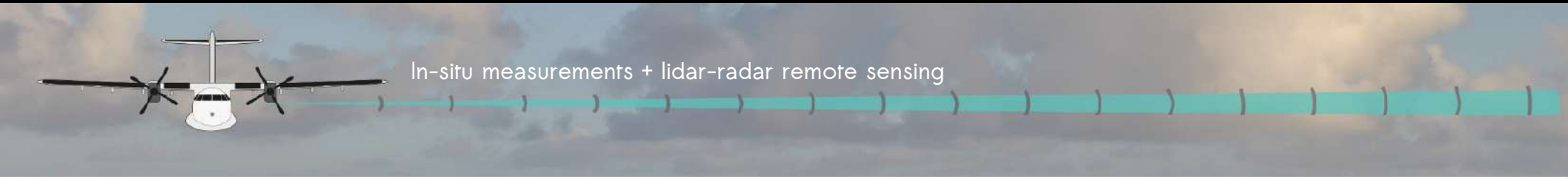


Bony et al. (2020a)

Exploring the processes controlling mesoscale dynamics



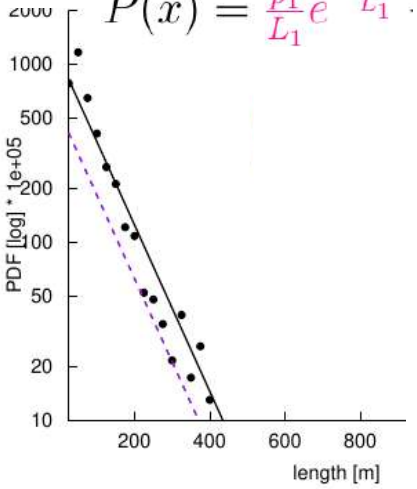
Exploring the processes controlling mesoscale dynamics



Size distribution of thermals

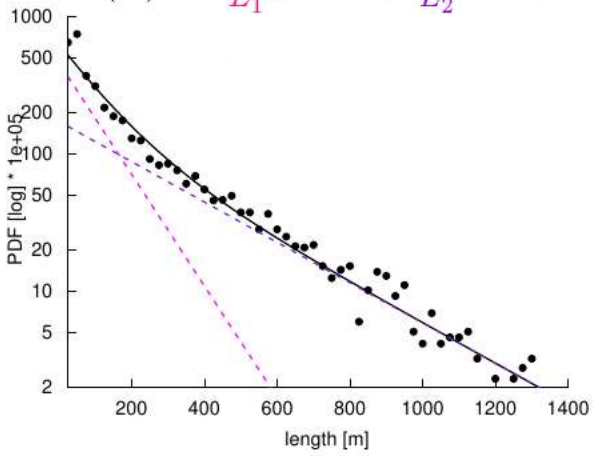
near the surface

$$P(x) = \frac{p_1}{L_1} e^{-\frac{x}{L_1}}$$

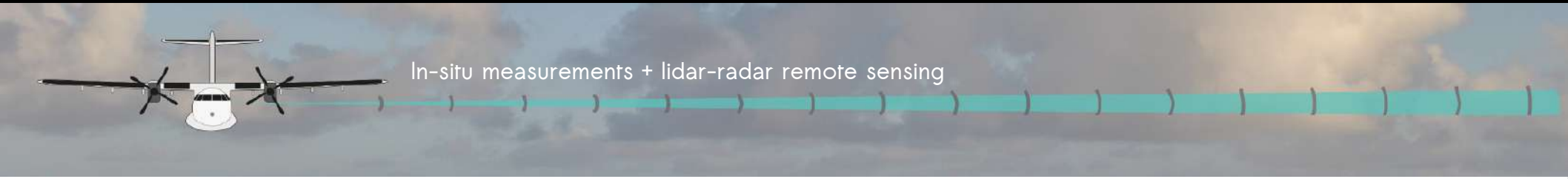


near the cloud base level

$$P(x) = \frac{p_1}{L_1} e^{-\frac{x}{L_1}} + \frac{p_2}{L_2} e^{-\frac{x}{L_2}}$$

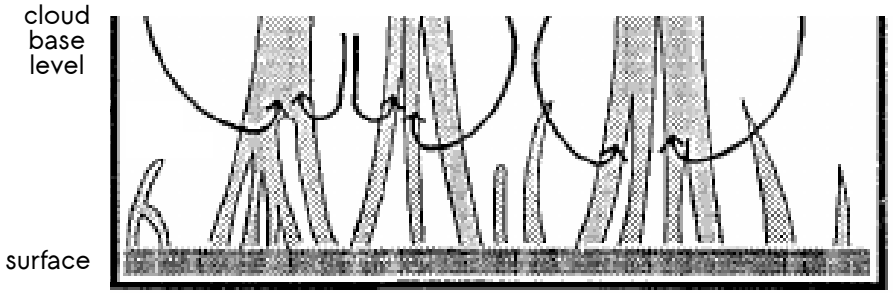


Exploring the processes controlling mesoscale dynamics



Interpretation (supported by mathematical calculations and statistical simulations) :

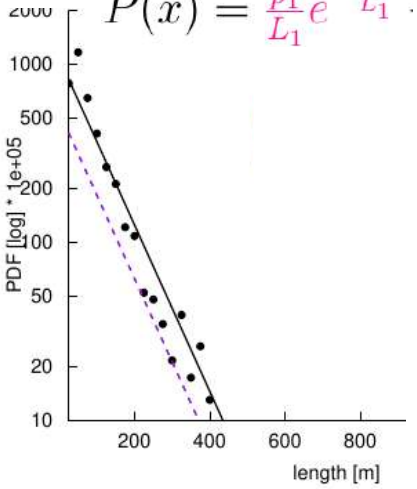
Merging of thermals
across the depth of the subcloud layer



Size distribution of thermals

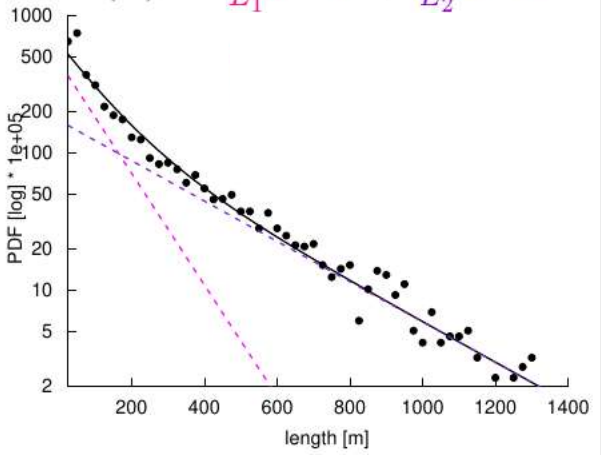
near the surface

$$P(x) = \frac{p_1}{L_1} e^{-\frac{x}{L_1}}$$

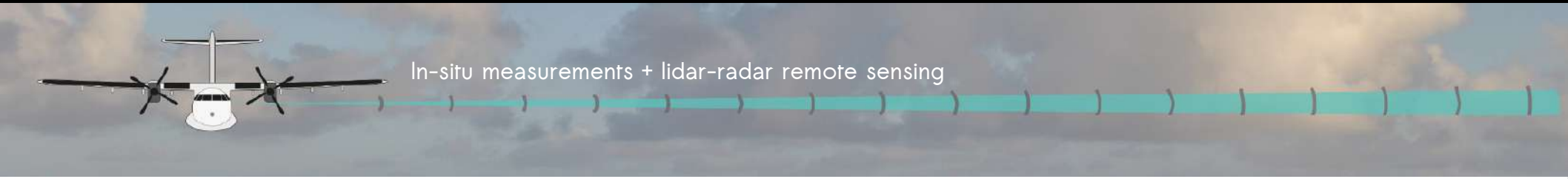


near the cloud base level

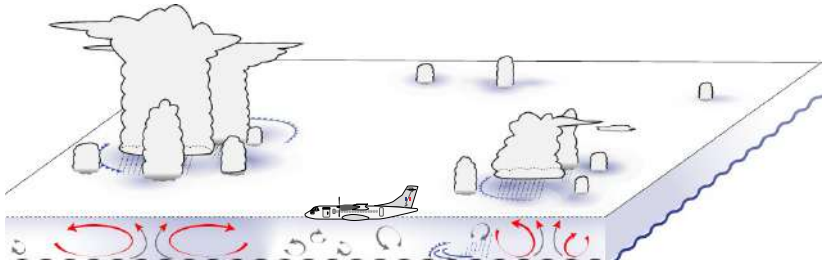
$$P(x) = \frac{p_1}{L_1} e^{-\frac{x}{L_1}} + \frac{p_2}{L_2} e^{-\frac{x}{L_2}}$$



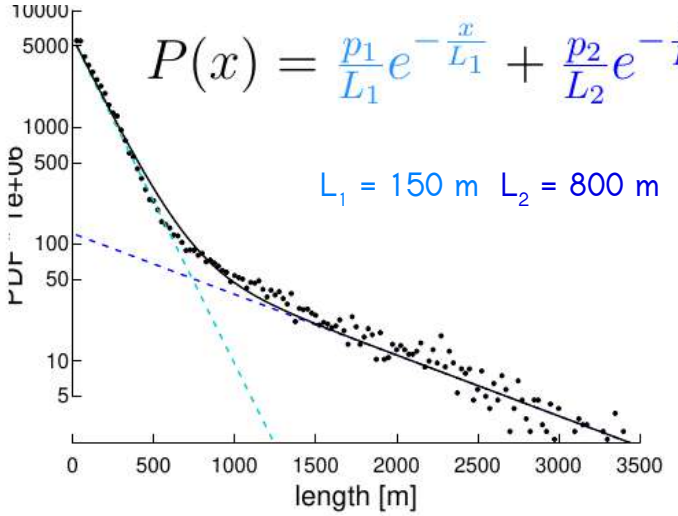
Exploring the processes controlling mesoscale dynamics



- Evidence for cloud merging too
- Related to the thermal characteristics (size, density)

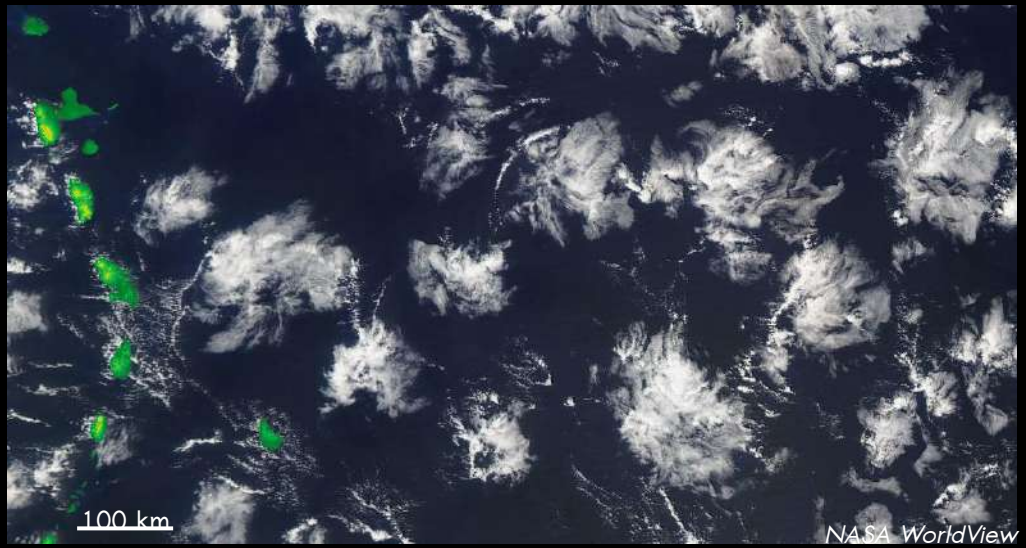


Size distribution of cloud base widths



Mesoscale patterns of cloudiness shaped by thermal & cloud merging

Weak thermal merging → *High density of thermals*
→ *Strong cloud aggregation* → *Large cloud bases* → *Strong mass flux*



Strong thermal merging → *Large but widely spaced thermals*
→ *Weak cloud aggregation but longer lifetime*
→ *Extended cloud anvil*

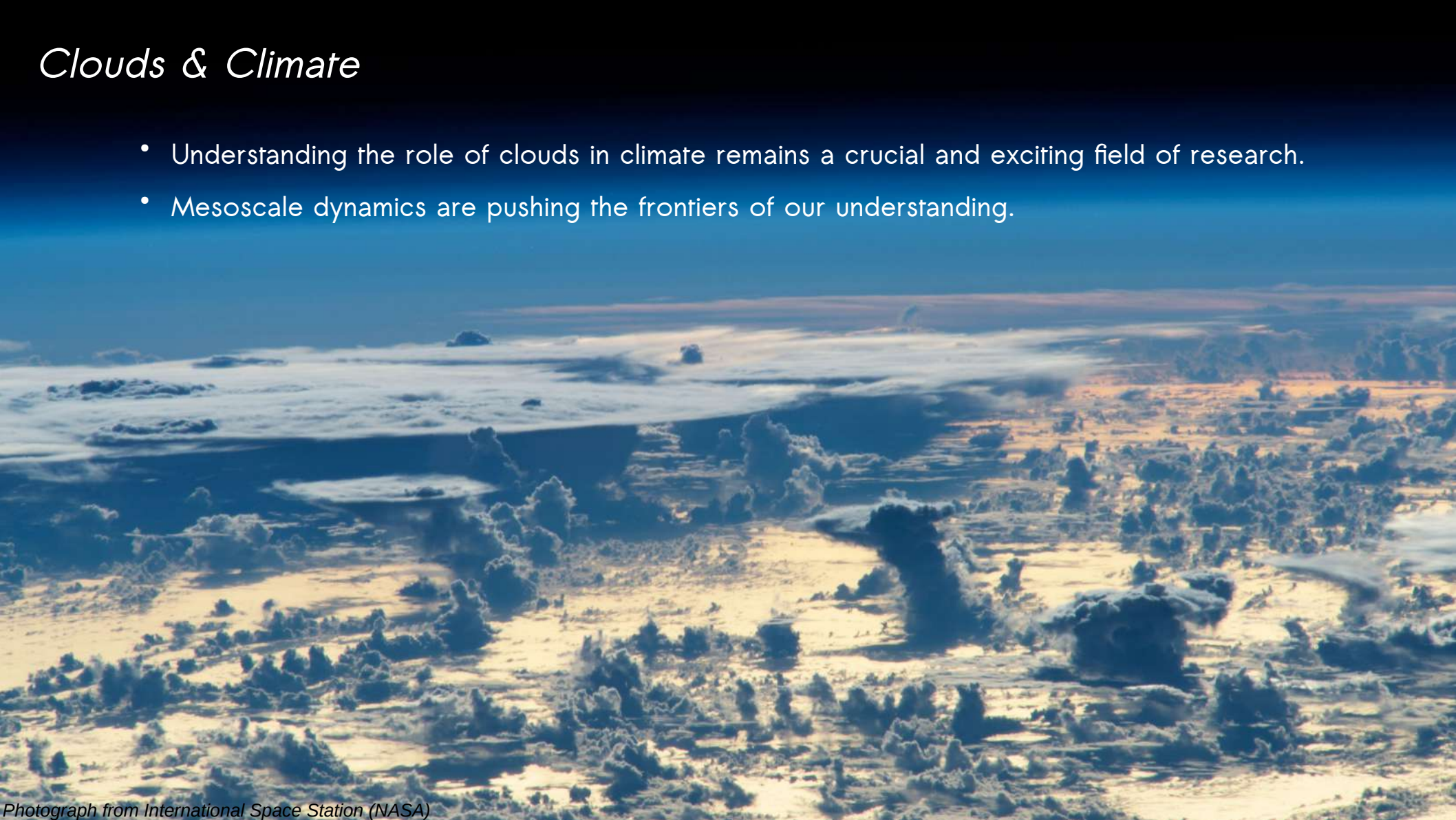
→ A key role in the control of cloud width, depth and coverage, cloud clustering and mesoscale circulations

→ One should now understand how it might change with global warming

Bony et al. (2025)

Clouds & Climate

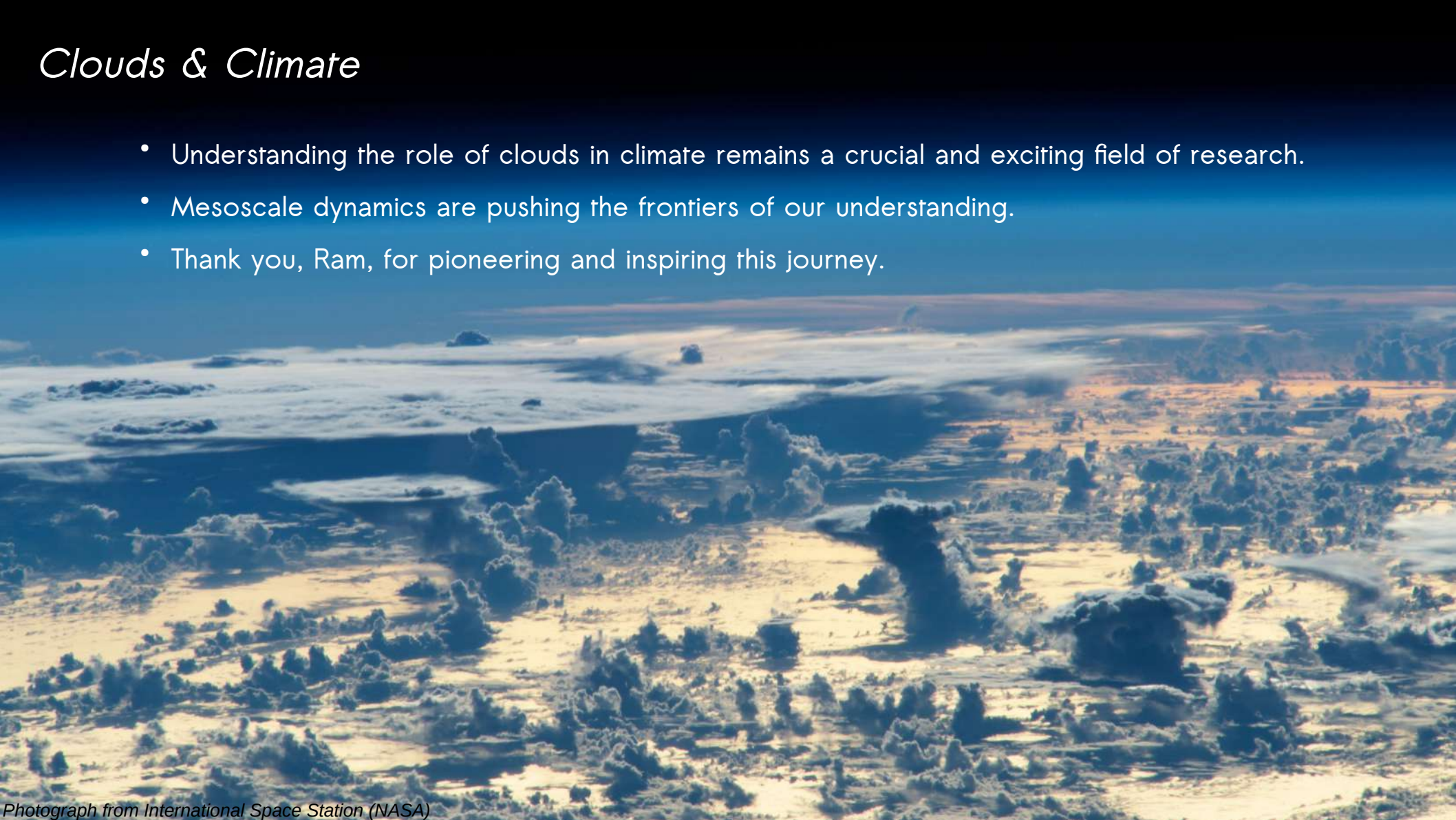
- Understanding the role of clouds in climate remains a crucial and exciting field of research.
- Mesoscale dynamics are pushing the frontiers of our understanding.



Photograph from International Space Station (NASA)

Clouds & Climate

- Understanding the role of clouds in climate remains a crucial and exciting field of research.
- Mesoscale dynamics are pushing the frontiers of our understanding.
- Thank you, Ram, for pioneering and inspiring this journey.



Photograph from International Space Station (NASA)