Observations needed to advance understanding of the role of clouds in climate

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With contributions from Bjorn Stevens (MPI-M, Hamburg),
the WRCP Grand Chalenge on Clouds, Circulation and Climate Sensitivity,
and participants of the Feb 2016 ISSI workshop

GCOS conference on Global Climate Observations, Amsterdam, 2-4 Mar 2016

Big questions have been answered

- Is the atmospheric composition changing?
- Is climate warming?
- Are human activities responsible for it?

Recognized by the COP21

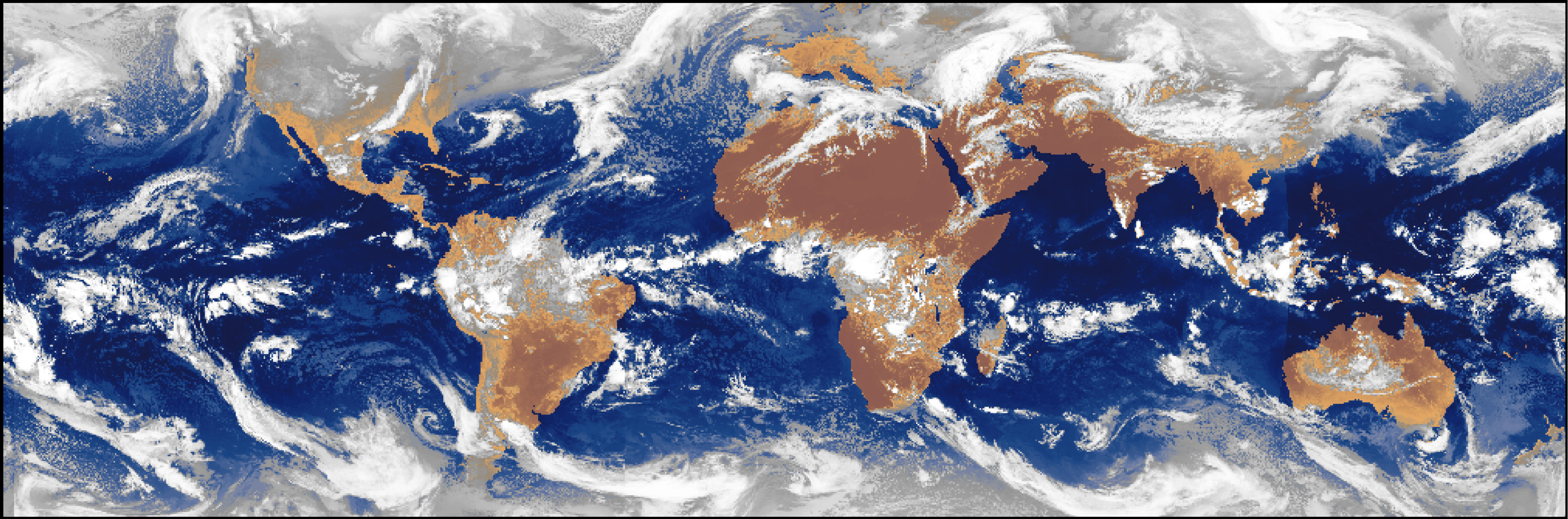
New questions are emerging

- How much will we have to cut CO2 emissions to reach a particular temperature target?
- What will be the pace and pattern of warming, over the next decades and beyond?
- How will climate change in specific regions? (rainfall, extreme events, etc)
- Etc

Requires a solid understanding of how the climate system works!

Clouds & climate

Our inability to provide robust assessments of
global and regional climate changes, including changes in extreme events,
stems to a large extent from our limited understanding of
how clouds control circulation and climate sensitivity



http://www.wcrp-climate.org/index.php/gc-clouds

Clouds, Circulation and Climate Sensitivity

A **Grand Science Challenge**
of the World Climate Research Programme

Outline:

- Key science questions
- Observations needed to advance this Grand Challenge

Clouds, Circulation and Climate Sensitivity

4 QUESTIONS

Bony, Stevens, Frierson, Jakob, Kageyama, Pincus, Shepherd, Sherwood, Siebesma, Sobel, Watanabe and Webb, 2015 :
Clouds, Circulation and Climate Sensitivity, *Nature Geoscience*, 4, 261-268

1

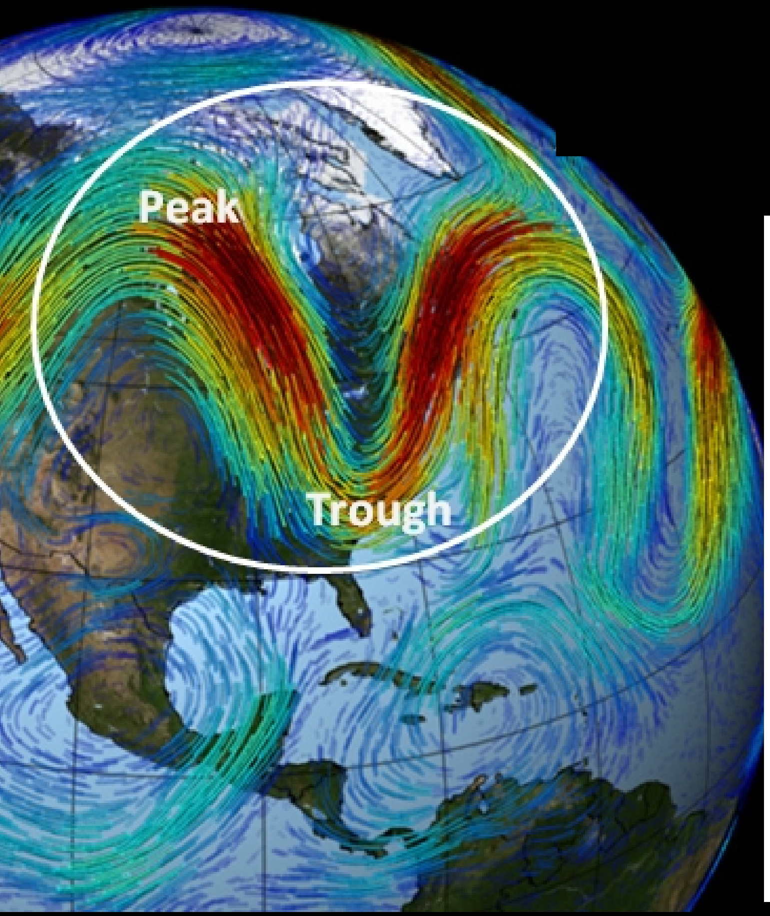
What controls the position, strength and variability of extra-tropical storm tracks?

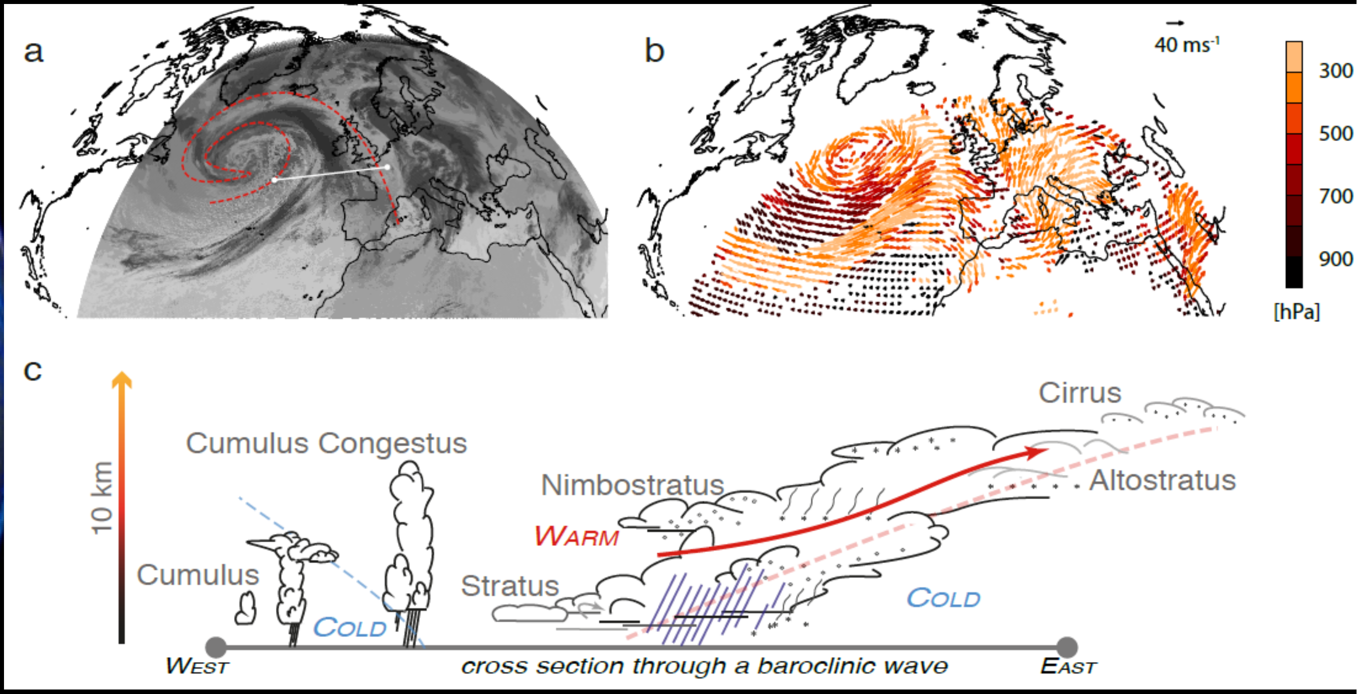
What controls the position, strength and variability of storm tracks?

Most of the extra-tropical storms develop, organize and decay in localized regions known as “storm tracks”.

They organize clouds and precipitation, and control weather-related climate impacts.

There is increasing evidence that clouds play an active role in storm tracks.

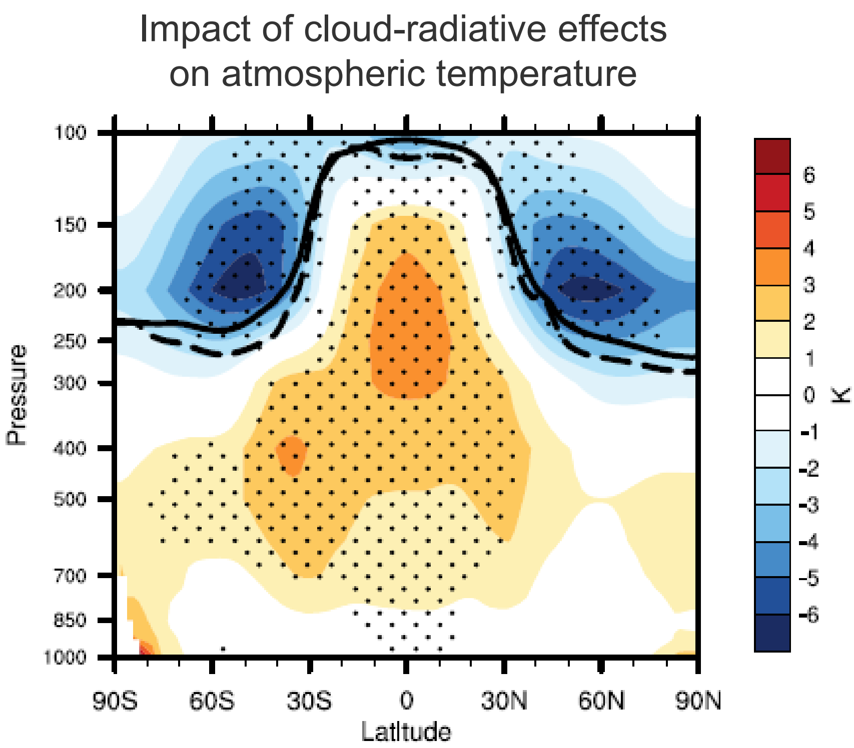


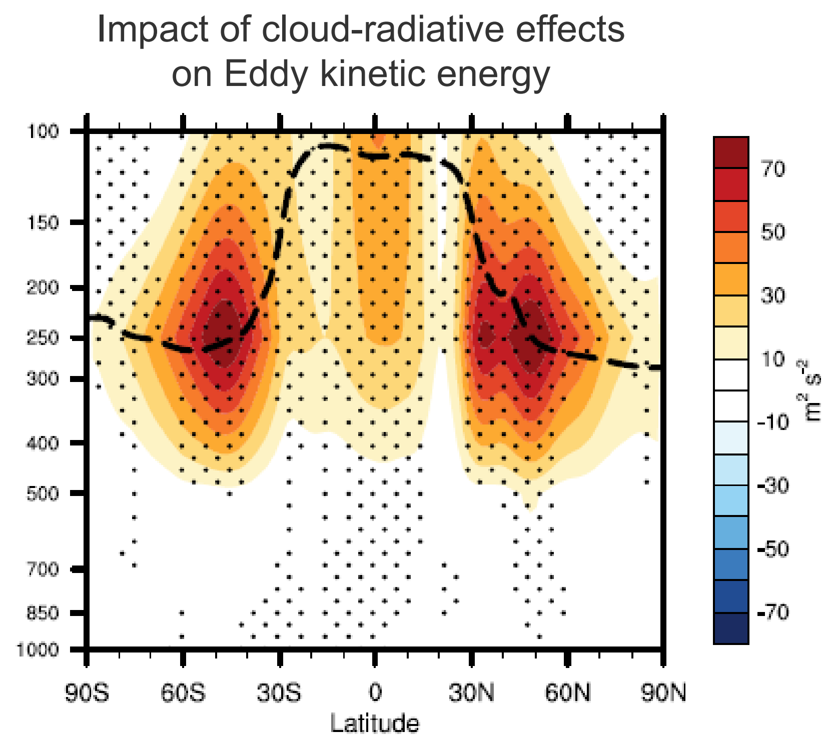


Bony et al. Nature Geosci., (2015)

Impact of atmospheric cloud-radiative effects on the extra-tropical circulation

By modulating the radiative cooling of the atmosphere, clouds affect the thermal structure of the atmosphere and its baroclinicity. It has a strong impact on the strength of atmospheric eddies.





Li, Thompson and Bony, J. Climate (2015)

2

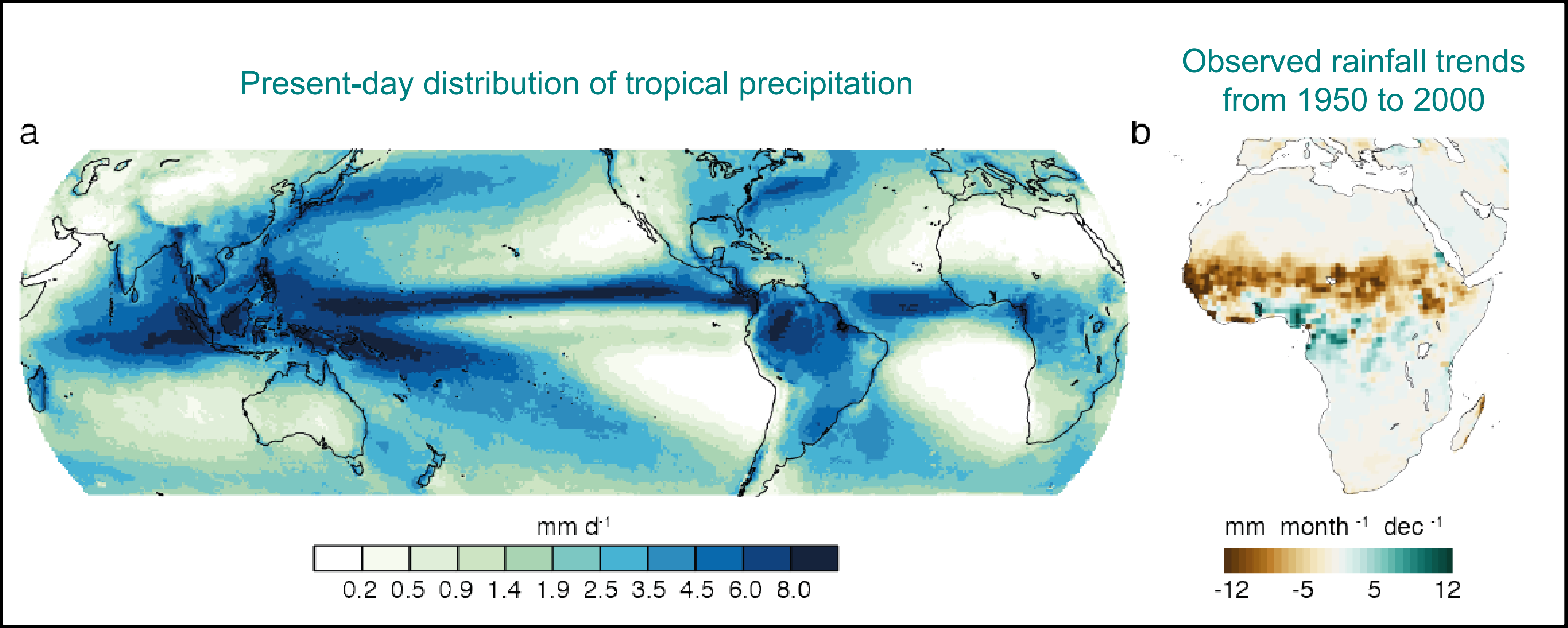
What controls the position, strength and variability of tropical rain belts?

What controls the position, strength and variability of tropical rain belts?

Large-scale convergence zones largely control the distribution of tropical rainfall at the regional scale.

Shifts of rain belts responsible for severe droughts (*e.g.* in the Sahel)

How will rain belts (ITCZ, monsoon..) respond to anthropogenic forcings?

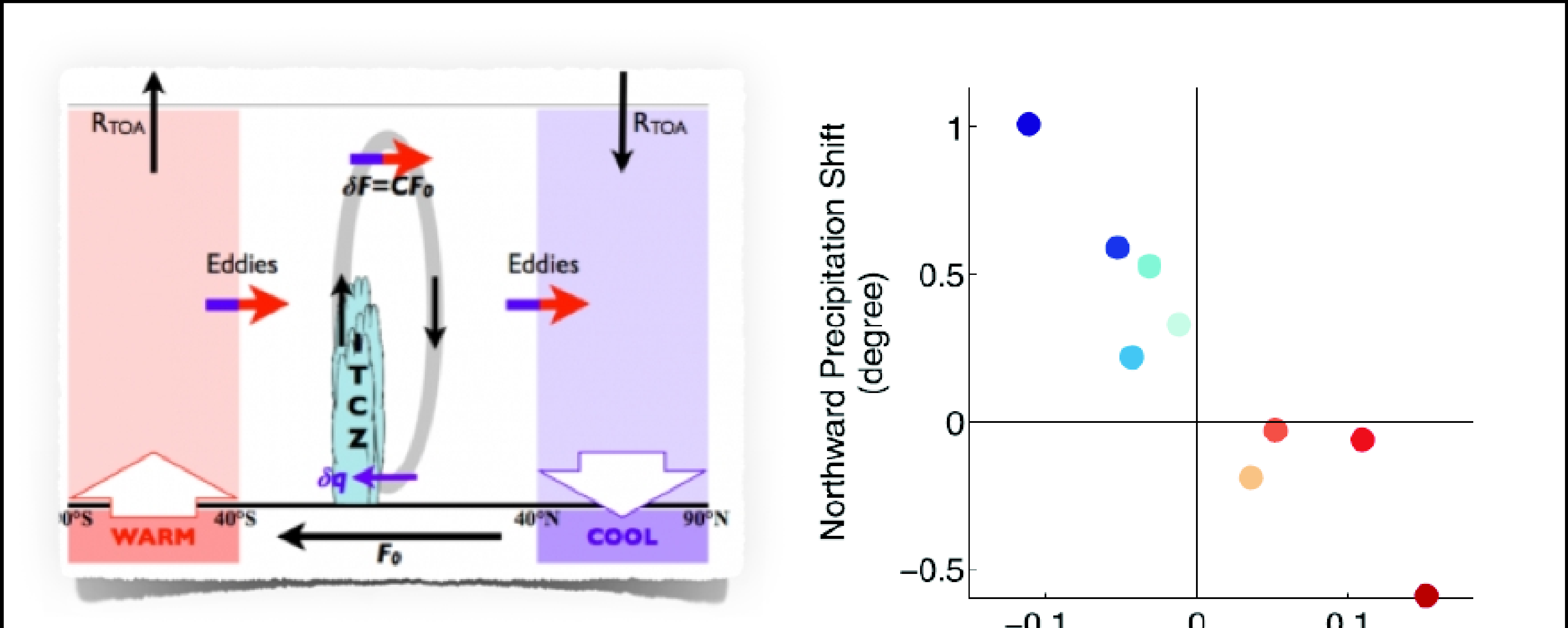


Bony et al. *Nature Geosci.,* (2015); Held et al., *PNAS* (2005)

What controls the position, strength and variability of tropical rain belts?

Energetic frameworks are being developed to interpret the rain belts position and shifts

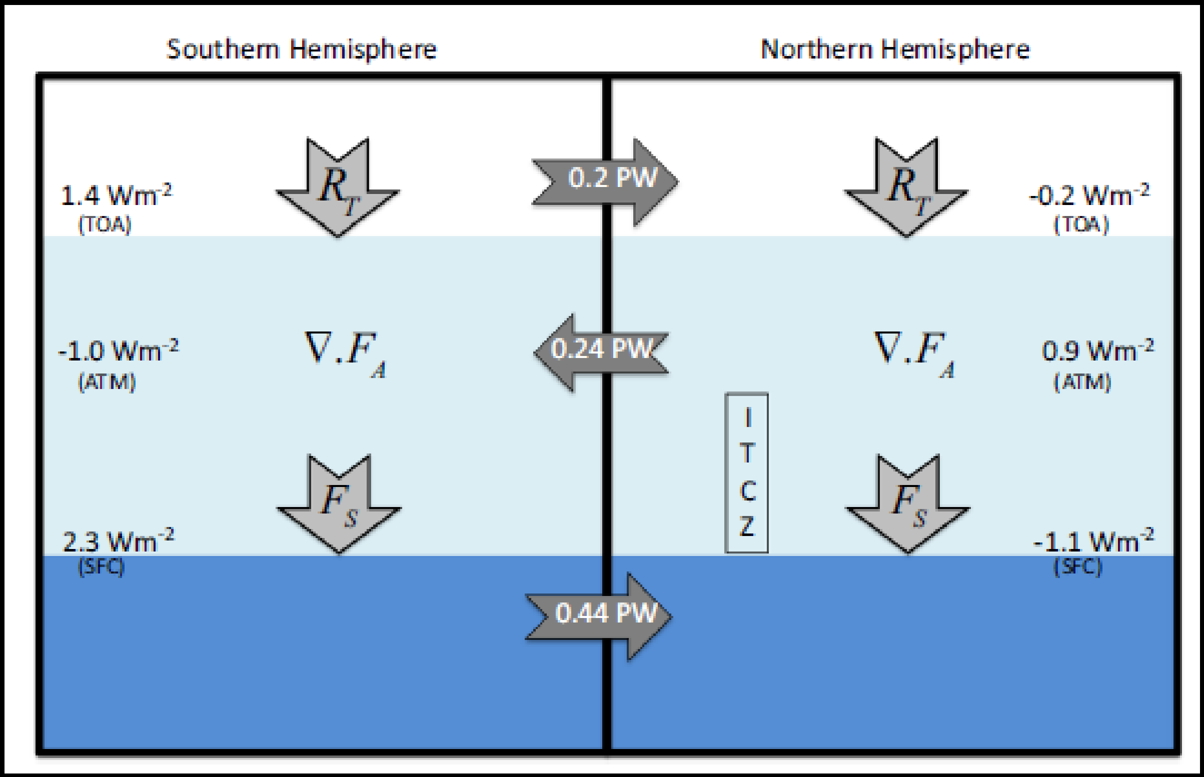
The large-scale circulation in the tropics and position of the ITCZ are intricately linked with the large-scale distribution of the energy budget (inter-hemispheric gradients).



inter-hemispheric energy transport

Kang et al., *J. Atmos Sci*, 2009; Frierson and Hwang, *J. Climate*, 2012; Frierson et al., *NGS,* 2013; Loeb et al. *Clim. Dyn.*, 2015

Clouds critically influence equatorial energy transports, and therefore the position of the ITCZ



Estimates of equatorial energy transports can be derived from observations (Loeb et al 2015).

Observations suggest that the hemispheric asymmetry in the vertical distribution of clouds (more low-clouds in SH) contributes to the northern location of the ITCZ.

In climate models, the position (and shifts) of the ITCZ also critically depends on cloud-radiative effects.

Loeb et al. Clim. Dyn., 2015

3

What role does convective aggregation play in climate?

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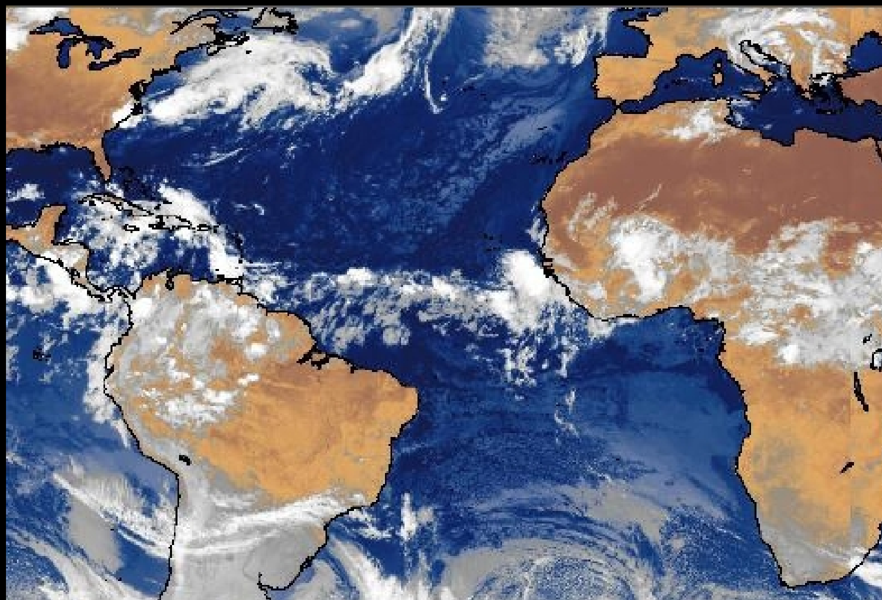
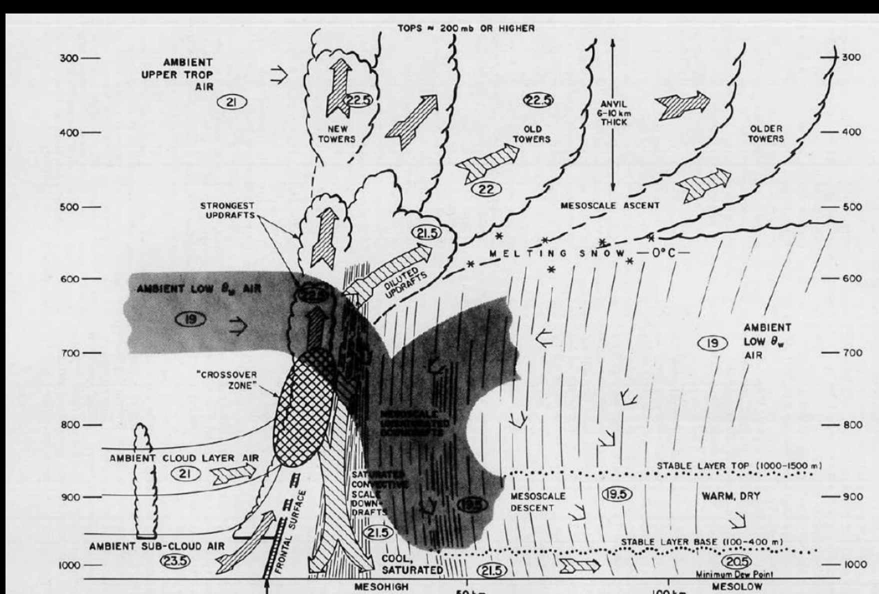
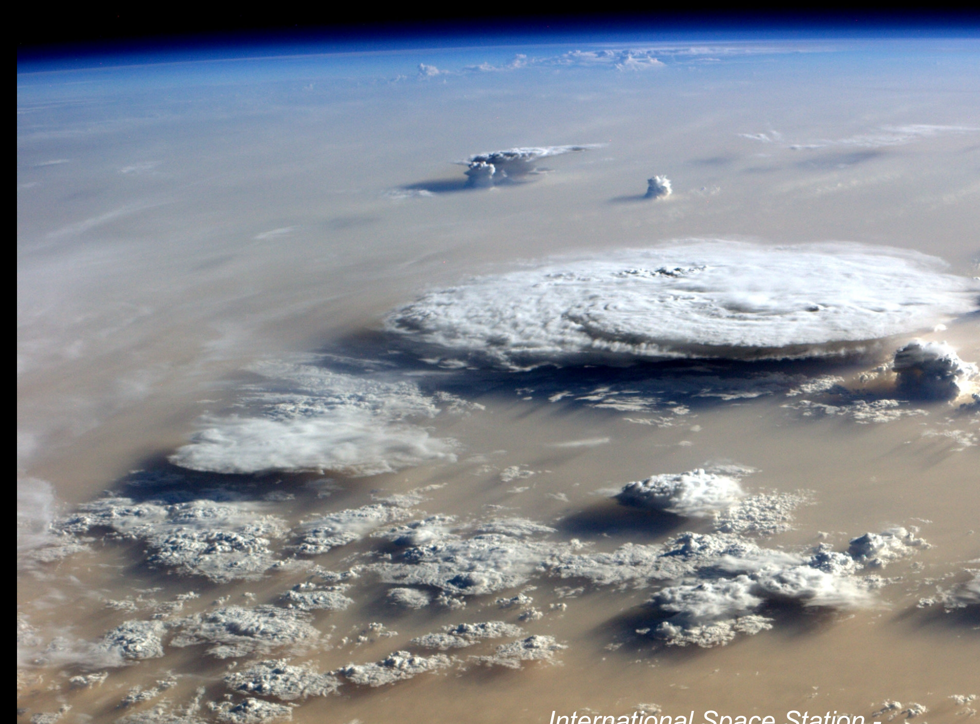


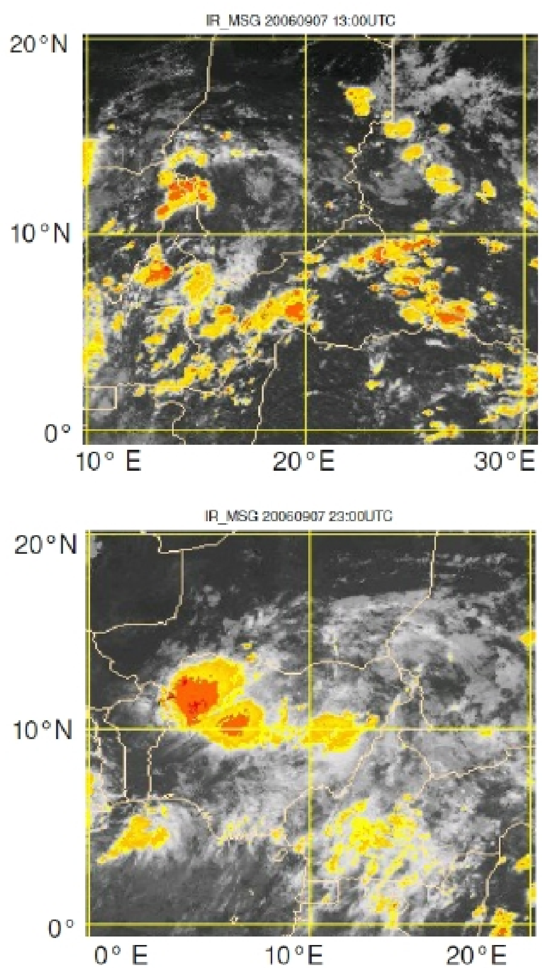


- On the storm scale, organization/aggregation matters for weather and extreme events.
- How much does it matter for climate?



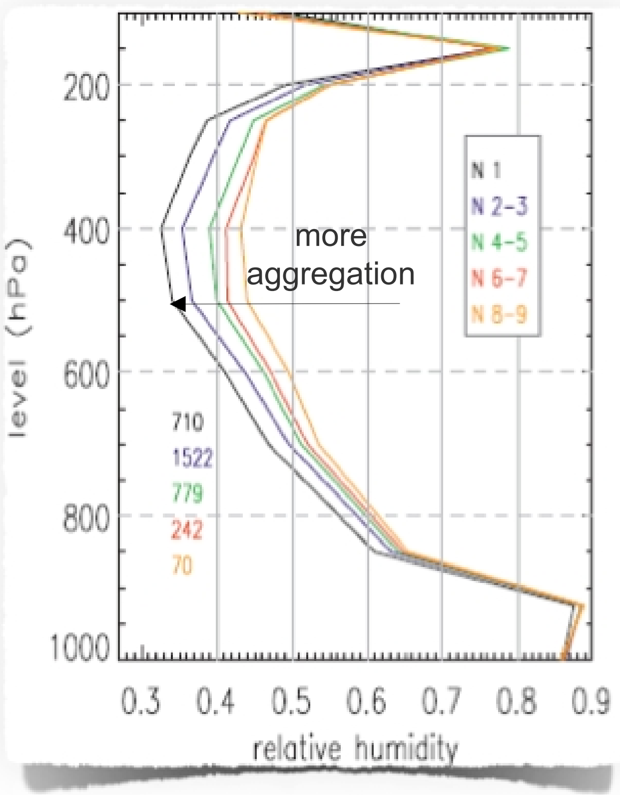
International Space Station -

Observations (and models) suggest that convective aggregation considerably affects the large-scale atmospheric state

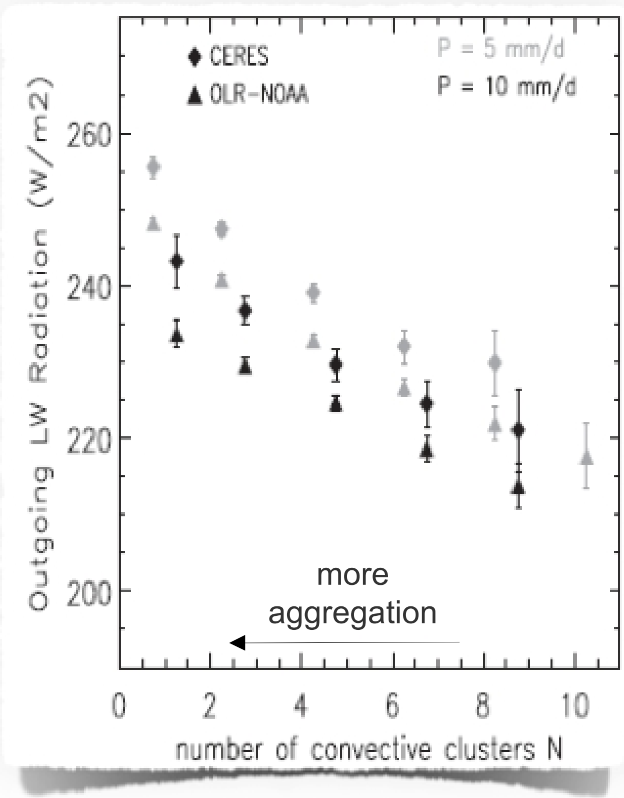


Satellite observations (Geostationnary + HOAPS + AIRS + CERES)

troposphere is drier, clearer
(RH, AIRS data)

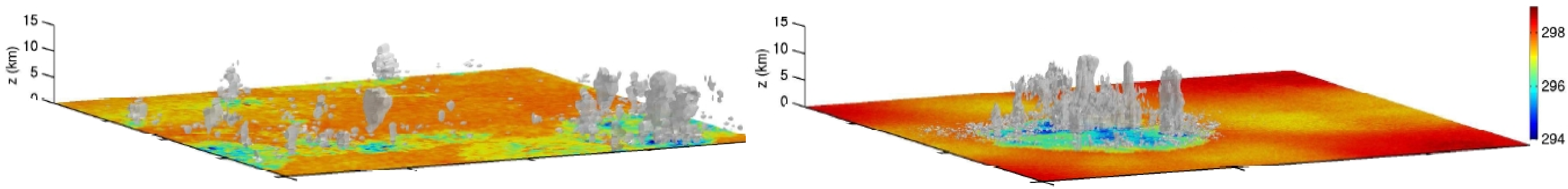


radiatively cools more efficiently
(OLR, CERES data)



Tobin, Bony and Roca, J. Climate (2012); Tobin et al, JAMES (2013); Stein et al. (submitted)

Numerical and theoretical studies suggest that convective aggregation becomes easier and stronger as surface temperature increases



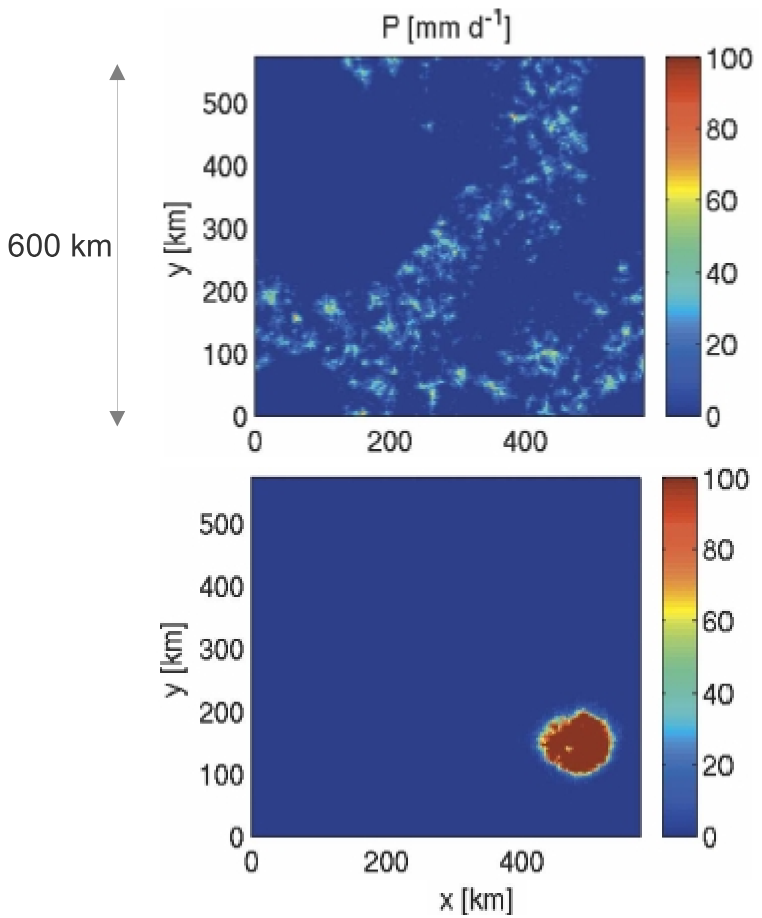
low SST *high SST*

More convective aggregation at high temperatures → Atmospheric drying and enhanced OLR → Impact on Climate Sensitivity and Hydrological Sensitivity?

Khairoutdinov and Emanuel, AMS (2010); Khairoutdinov and Emanuel, JAMES (2013); Wing and Emanuel, JAMES (2014); Emanuel et al., JAMES (2014); Wing and Cronin, QJRMS (2015); Coppin and Bony, JAMES (2015); Mauritsen and Stevens (2015); Bony et al. (submitted); Fig adapted from Muller and Held, J. Climate (2012)

What controls convective aggregation? A renewed interest

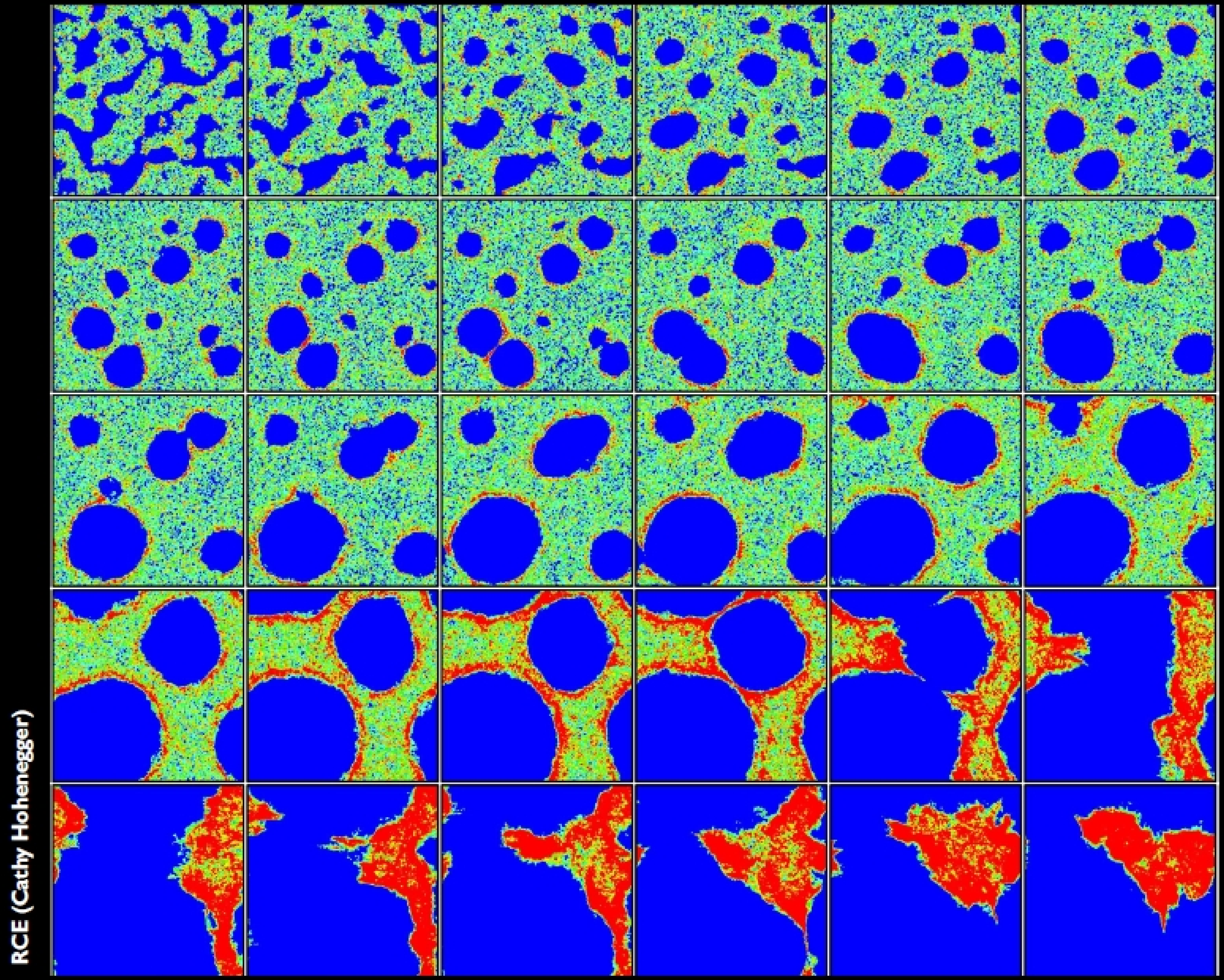
Idealized Cloud-Resolving Model simulations (non-rotating RCE)



Numerical studies show that even in the absence of external drivers (e.g. rotation, shear, Ts gradients), <u>convection can aggregate spontaneously</u> :
"self-aggregation"

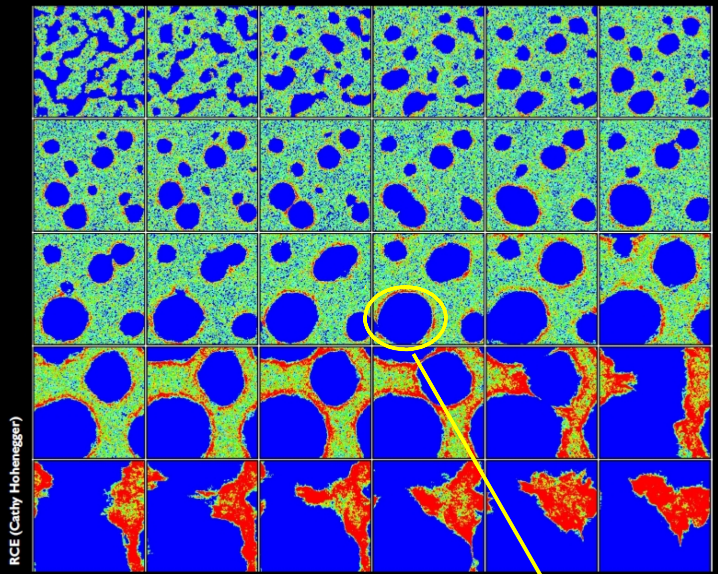
Bretherton, Blossey and Khairoutdinov, JAS (2005)

Self-aggregation of convection in a Cloud-Resolving model

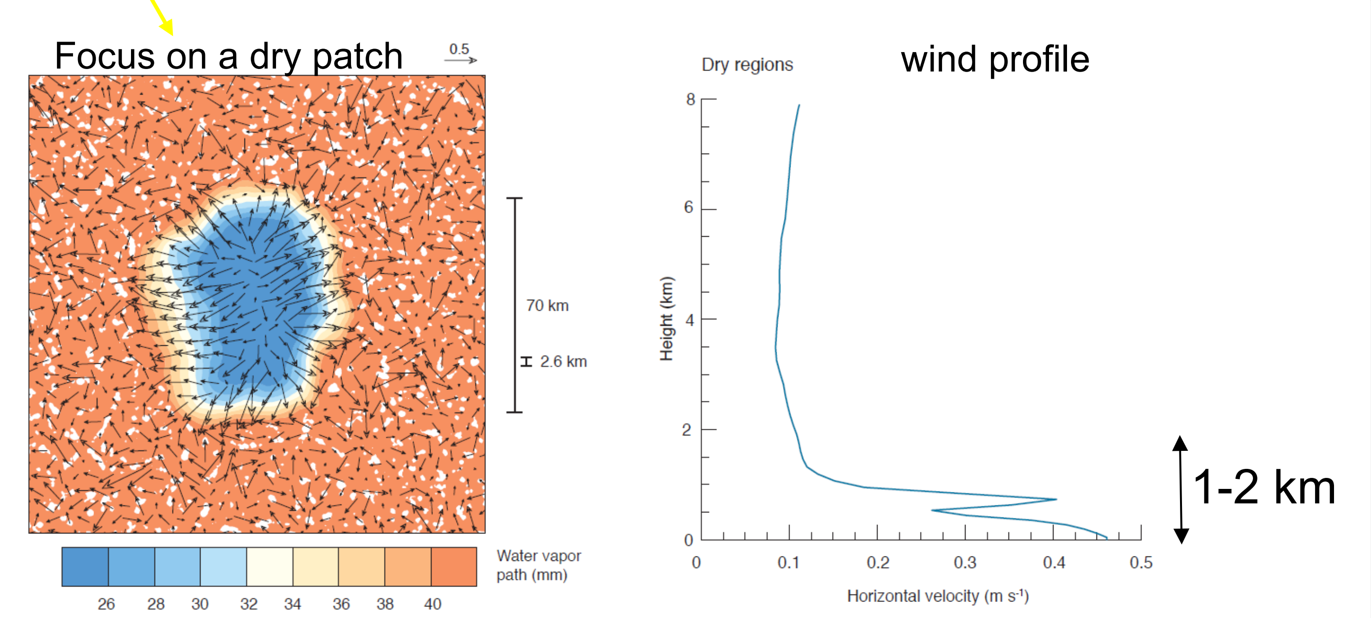


Courtesy Cathy Hohenegger (MPI-M)

What triggers convective self-aggregation?



In models, convective self-aggregation is triggered by the expansion of dry patches driven by a strong radiative cooling, and the development of a shallow <u>circulation within the first few km of the atmosphere</u>.



Courtesy Cathy Hohenegger (MPI)

Bretherton et al., JAS (2005); Wing and Emanuel, JAMES (2014); Muller and Held, JAS (2012); Coppin and Bony, JAMES (2015)

4

What role does convection play in cloud feedbacks?

Primary contributor to the uncertainty in Climate Sensitivity: shallow cumulus clouds

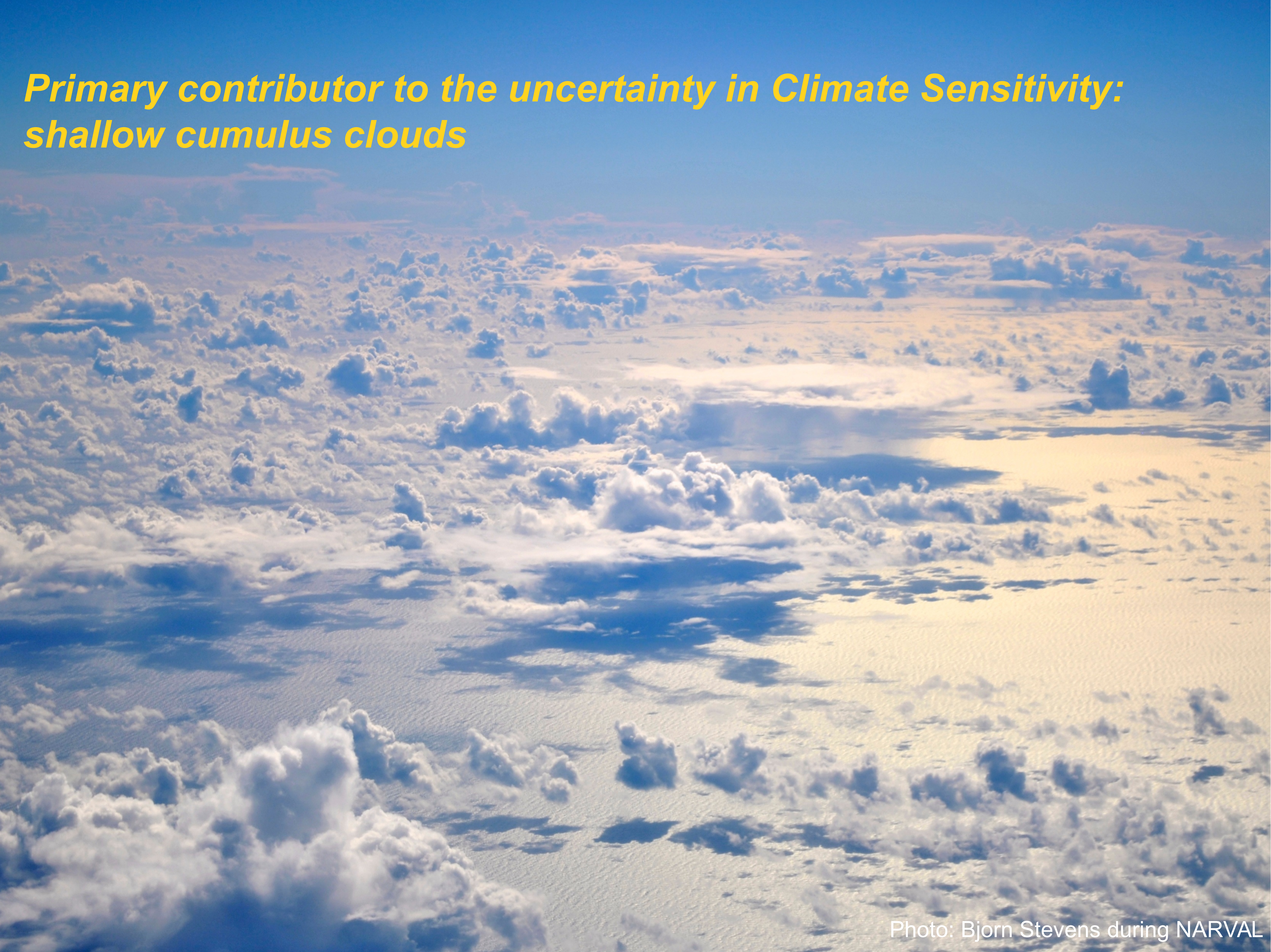
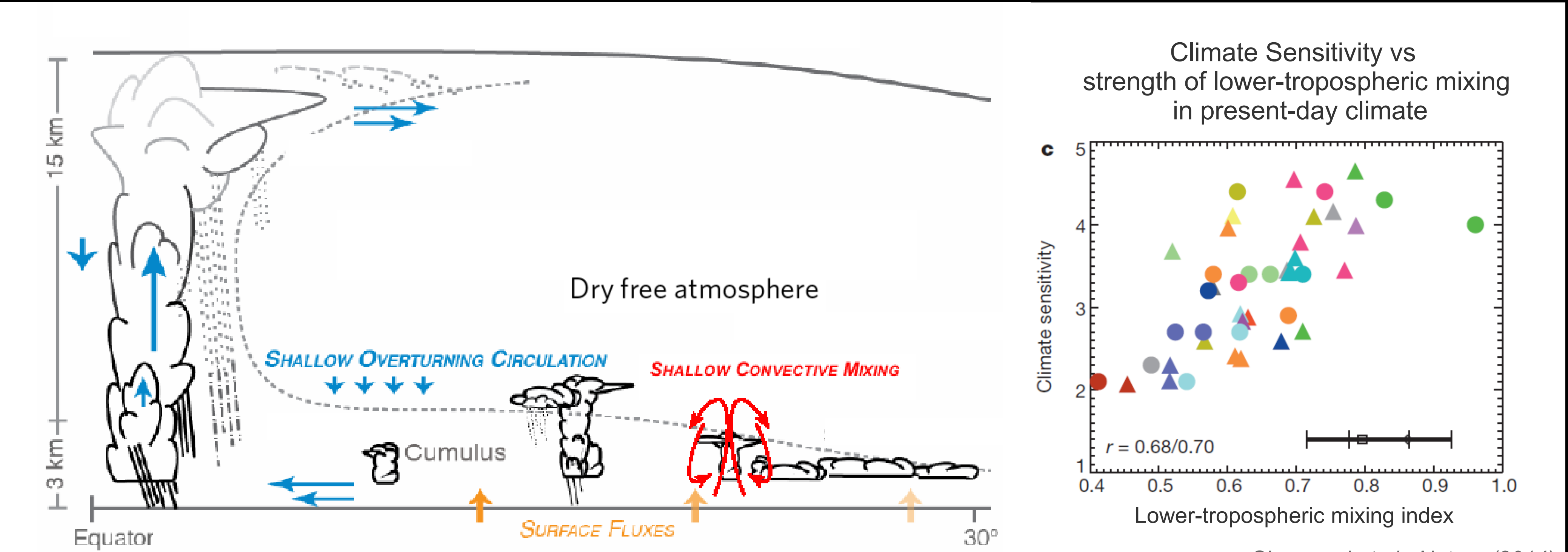


Photo: Bjorn Stevens during NARVAL

Low-cloud feedbacks depend on lower-tropospheric mixing

Most of the inter-model spread in climate sensitivity results from differing low-cloud feedbacks.

Current understanding suggests that the strength of low-cloud feedbacks
strongly depends on the vertical mixing of the lower troposphere
by shallow convection and shallow large-scale circulations.



Sherwood et al., Nature (2014)

Sherwood et al., Nature (2014); Rieck et al., JAS (2012); Zhang et al., JAMES (2013); Zhao (2014)
Tomassini et al., QJRMS (2014); Brient et al., Clim. Dyn. (2015); Stevens et al., BAMS (2016); Vial et al. (submitted)

Clouds, Circulation and Climate Sensitivity

Four questions:

1. What controls the position, strength and variability of extra-tropical storm tracks?
2. What controls the position, strength and variability of extra-tropical storm tracks?
3. What role does convective aggregation play in climate?
4. What role does convection play in cloud feedbacks?

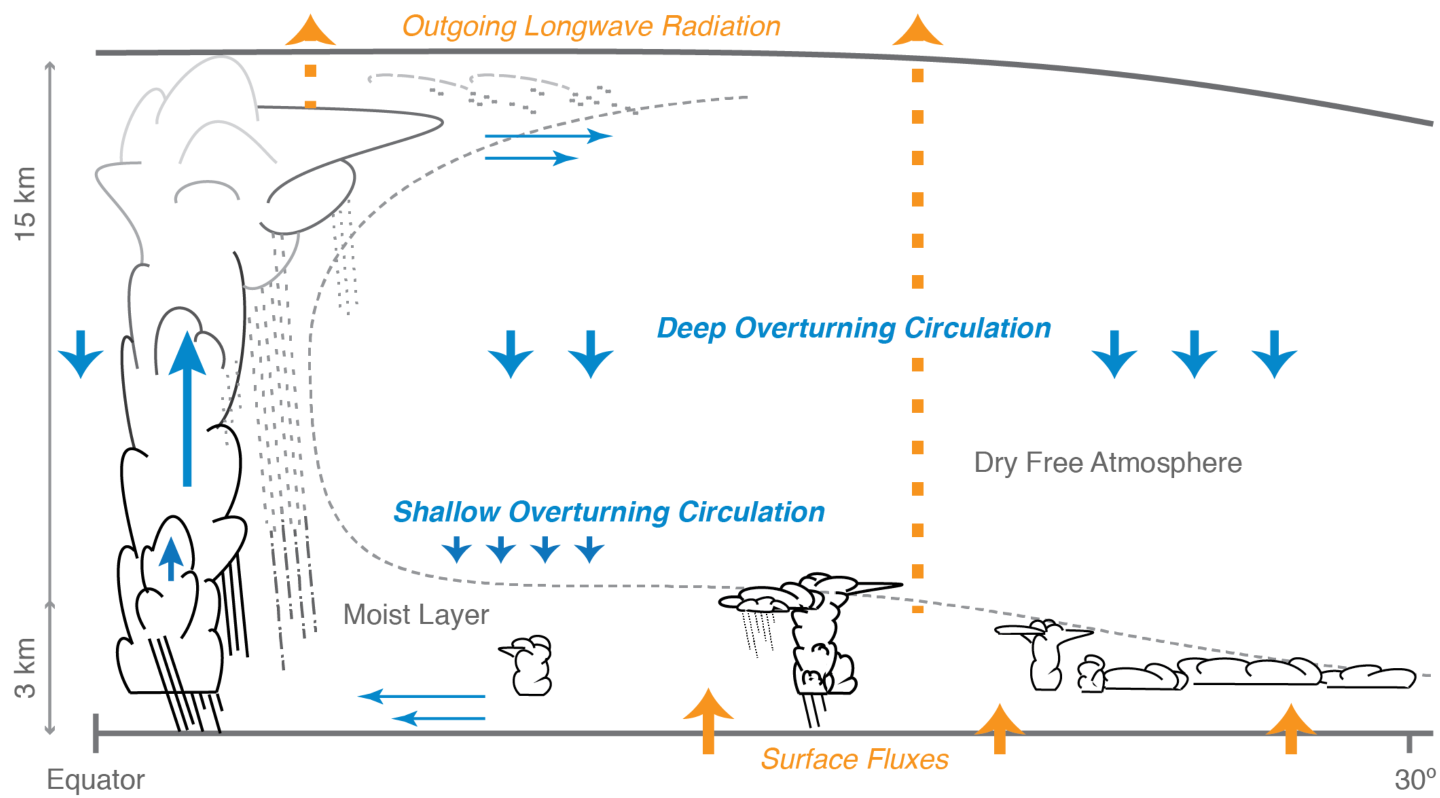
What observations would help answer these questions?

What observations would help answer these questions?

Key climate phenomena such as extratropical storms, rain belts or convective clusters, as well as climate sensitivity, **critically depend on the interaction between water (vapor, clouds), atmospheric heating (e.g. radiation, sfce evaporation) and atmospheric circulations.**

Advancing the understanding and prediction of the role of clouds in climate requires observations of:

Water – Heating - Winds



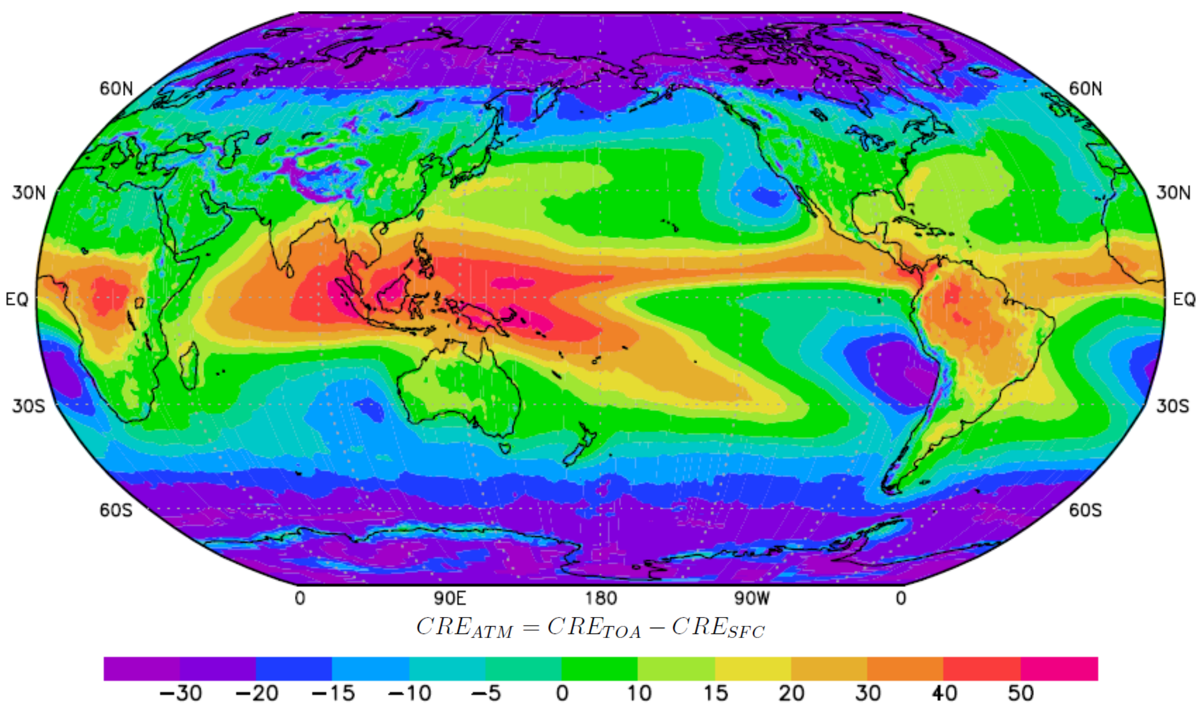
More specifically…

Vertical profiles of atmospheric cloud radiative effects

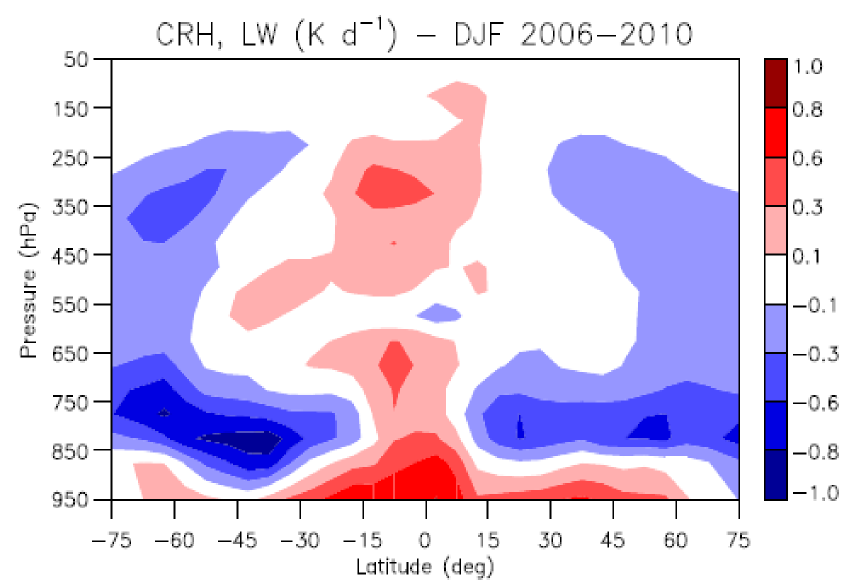
Requires <u>Earth energy budget measurements</u> like CERES, but also <u>atmospheric profiling</u> (vertical cloud information from lidar and radar, microwave, IR sounders) so that radiative transfer can be used to reconstruct surface radiation budget and <u>vertical profiles of radiative cooling</u>.

Long time series of measurements needed to interpret decadal circulation changes.

CERES EBAF observations
vertically-integrated cloud-radiative heating
[W/m²]



Zonally-averaged vertical profile of
LW cloud-radiative heating
derived from CloudSat/CALIPSO
[K/day]

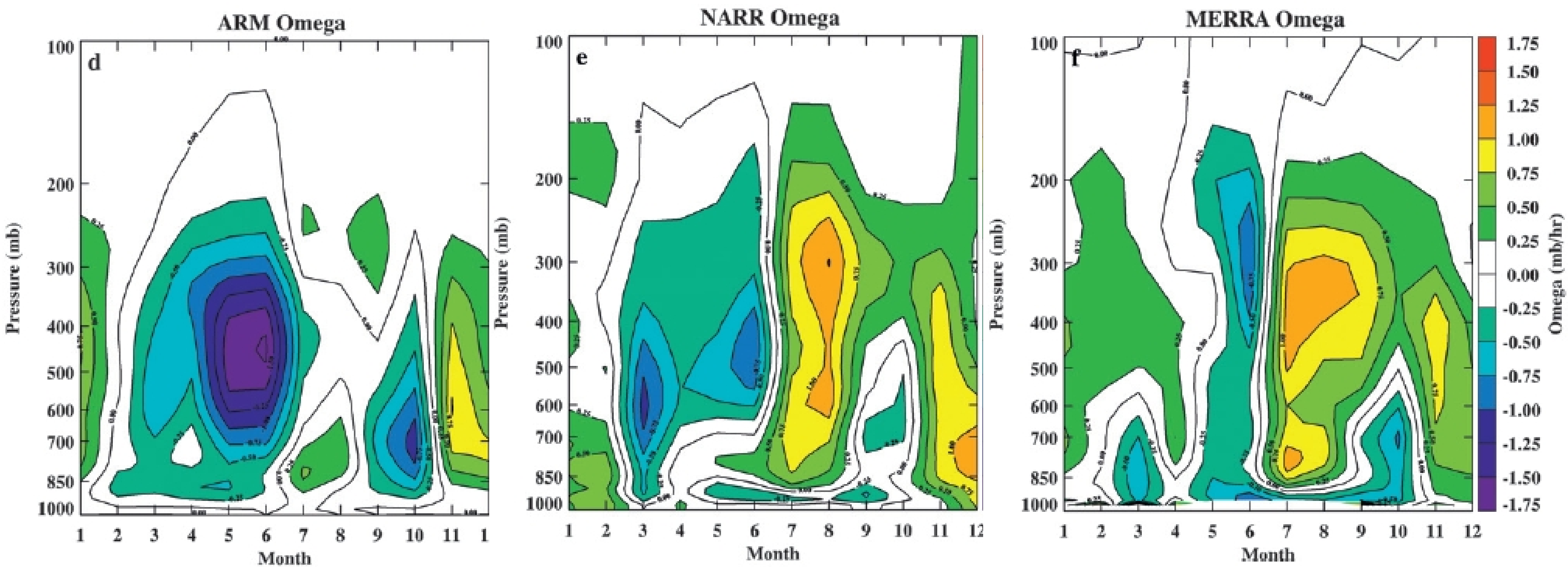


Loeb et al, NGS, 2012; Kato et al., J. Climate, 2013; Haynes et al., GRL, 2013

Vertical profiles of winds and large-scale vertical velocity ω

Large-scale vertical velocity is probably the most critical field for the thermodynamic budgets of the atmosphere, and for understanding the regional distribution of rainfall and almost every tropical phenomenon (mean circulation, MJO, tropical cyclones, etc).

There are prospects for wind profiling along one direction (ADM-Aeolus); a two-component wind lidar would revolutionize the observing system.



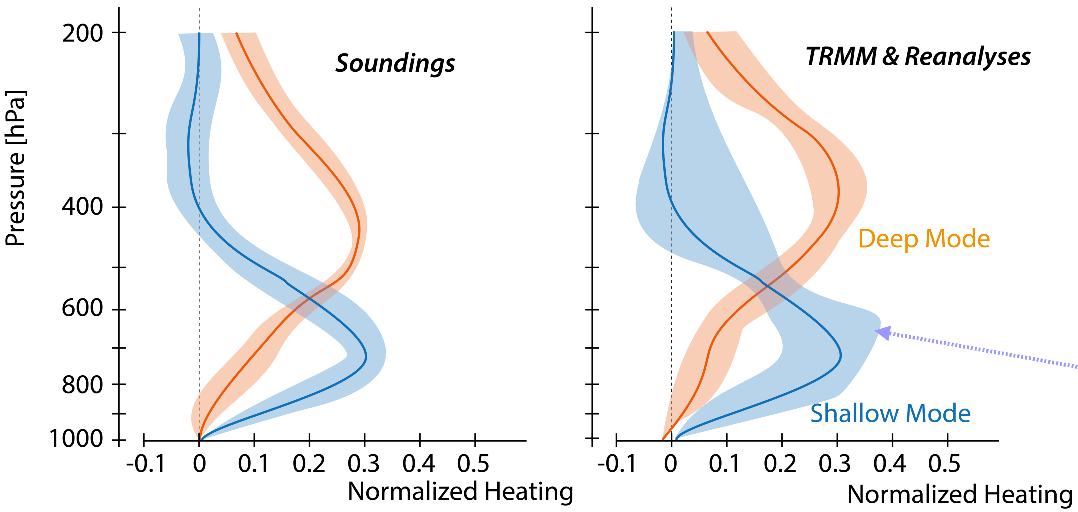
A Comparison of MERRA and NARR Reanalyses with the DOE ARM SGP Data

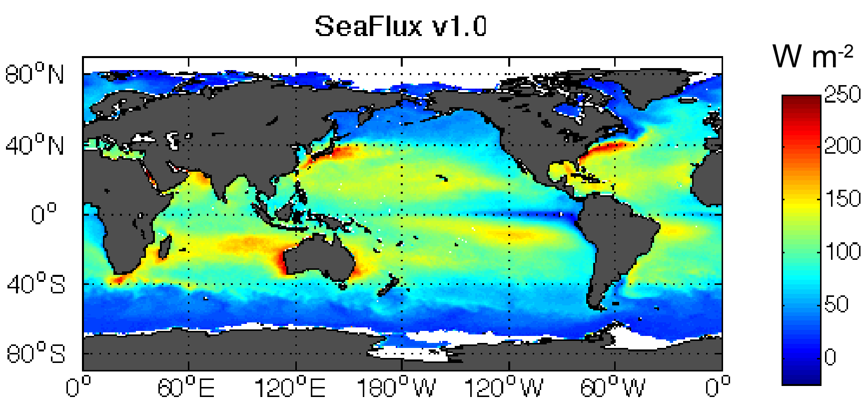
Kennedy et al., J. Climate (2011)

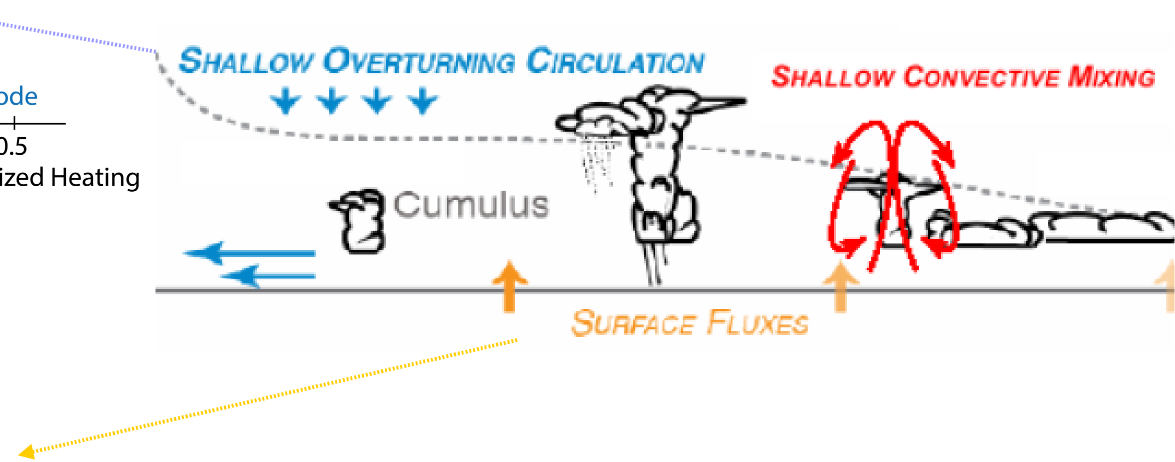
Surface evaporation and vertical structure of latent heating

Improved estimates of <u>surface evaporation</u> are needed (especially below clouds) to assess the global energy budget and advance understanding of boundary-layer and low-cloud feedback studies. May require multi-sensor approaches and/or new sensors.

Improved estimates of the vertical structure of large-scale overturning circulations, <u>especially in the lower troposphere</u>, would help constrain models and their climate sensitivity.





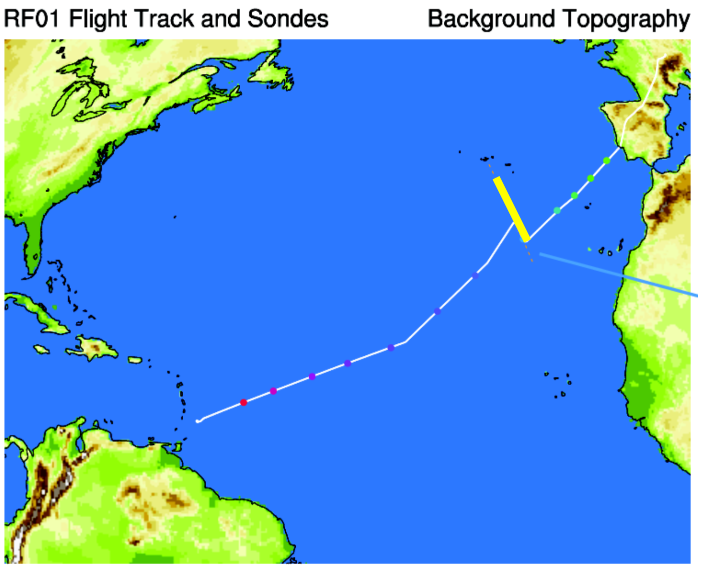


After Hagos et al., J. Climate, 2010 and Tao et al., AMS Monograph, 2014
SeaFlux surface latent heat flux: courtesy Carol Anne Clayson (WHOI)

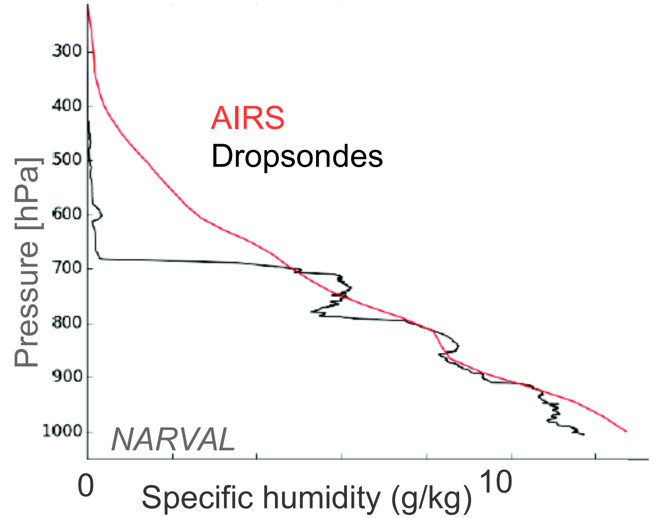
Highly vertically resolved water vapor

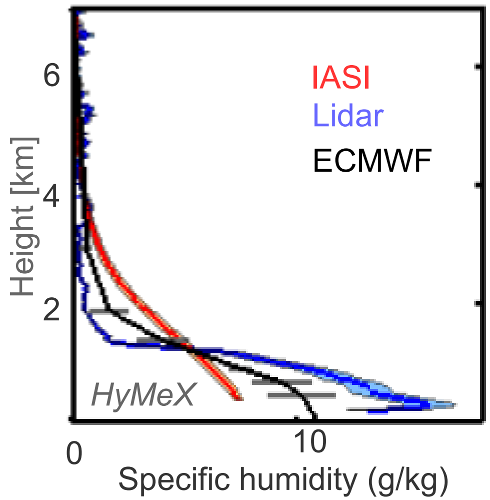
The vertical distribution of water vapor exhibits very sharp gradients between the PBL and the free troposphere that influence atmospheric processes in many important ways. To capture them, observations of water vapor are required at a higher vertical resolution than is available from the current atmospheric profiling instruments.

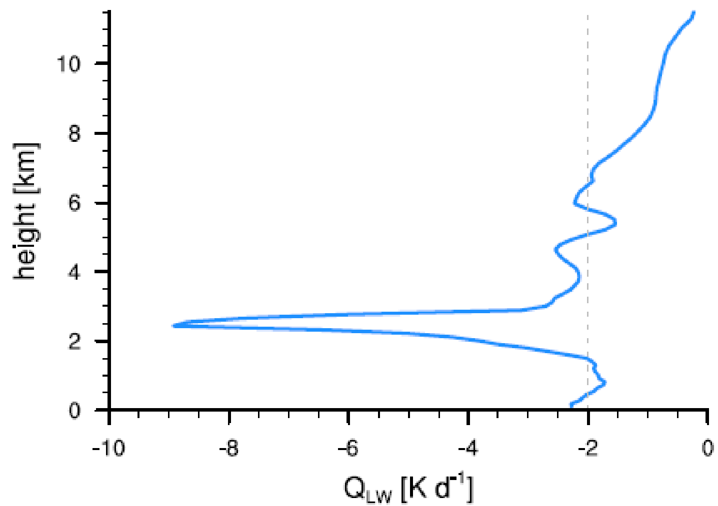
NARVAL flights over tropical Atlantic



Courtesy Bjorn Stevens (MPI) and Peter Kalmus (JPL)





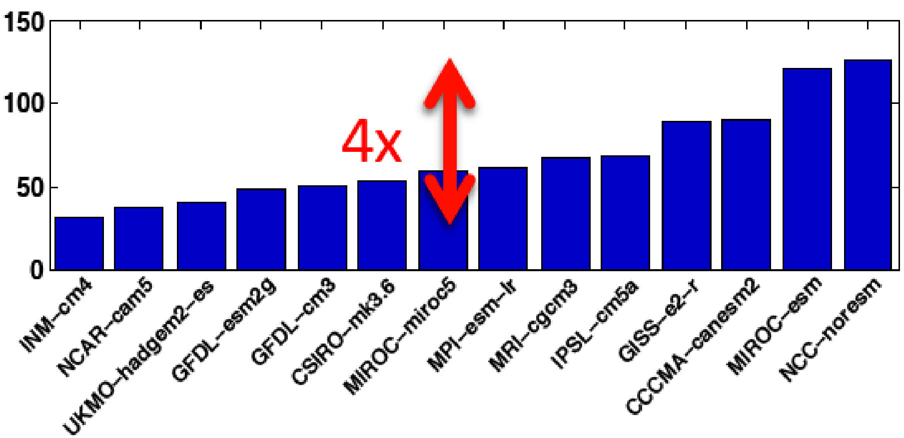


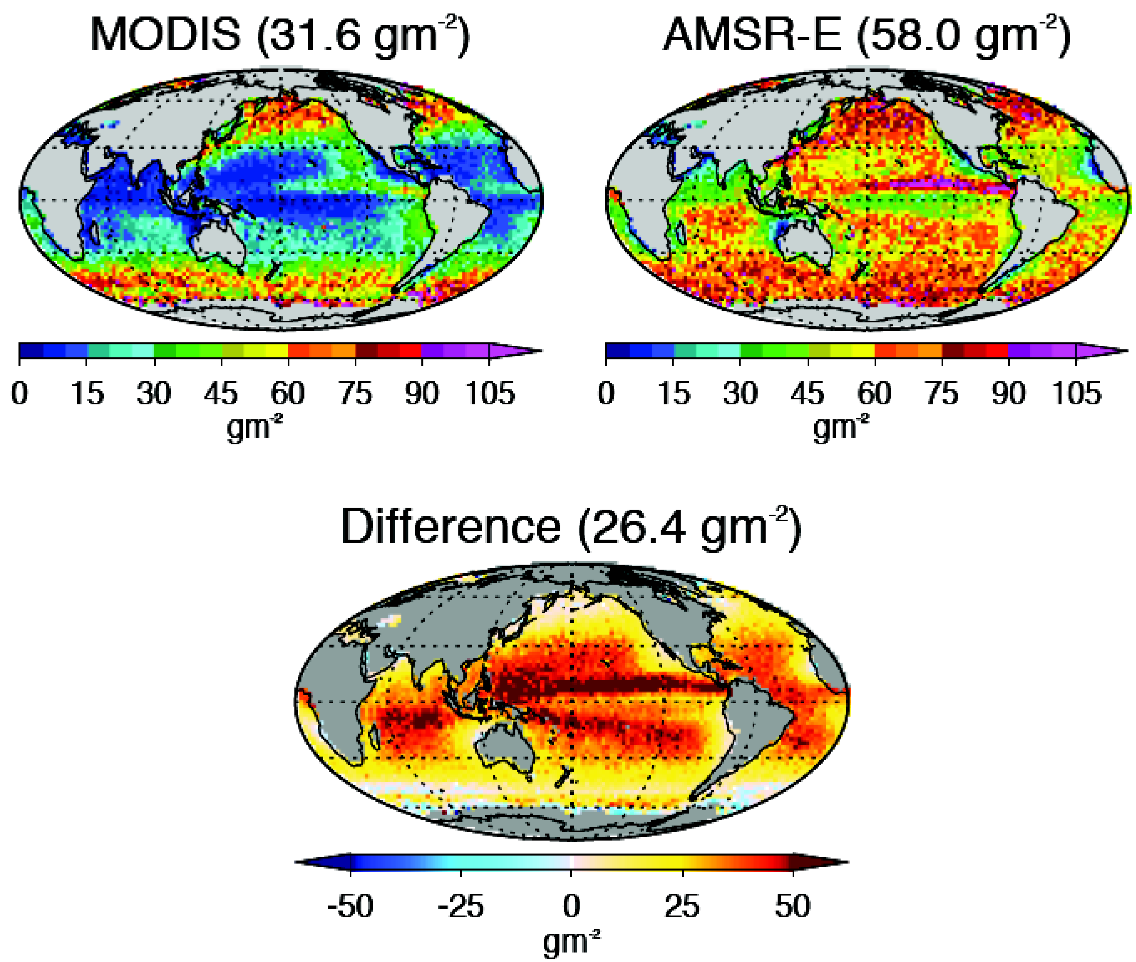
Chazette et al, ACP (2014)
Stevens et al, BAMS (2015)

Better estimates of condensate (cloud) water path, particularly in scenes with small broken clouds.

Estimates of cloud water path remain very uncertain, both in models and in observations. Better separating clouds from precipitation in observations requires the use of multiple sensors (e.g. radar, lidar, visible/ir imagery, passive microwave) and an improved sampling of the boundary layer.

Liquid Water Path (global mean)
in CMIP5 models [g/m^2]

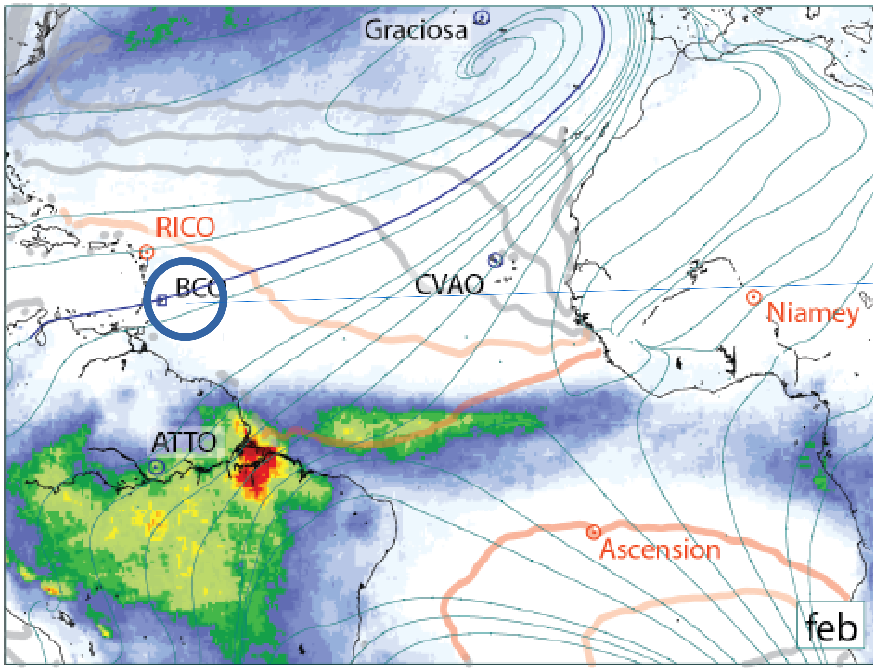


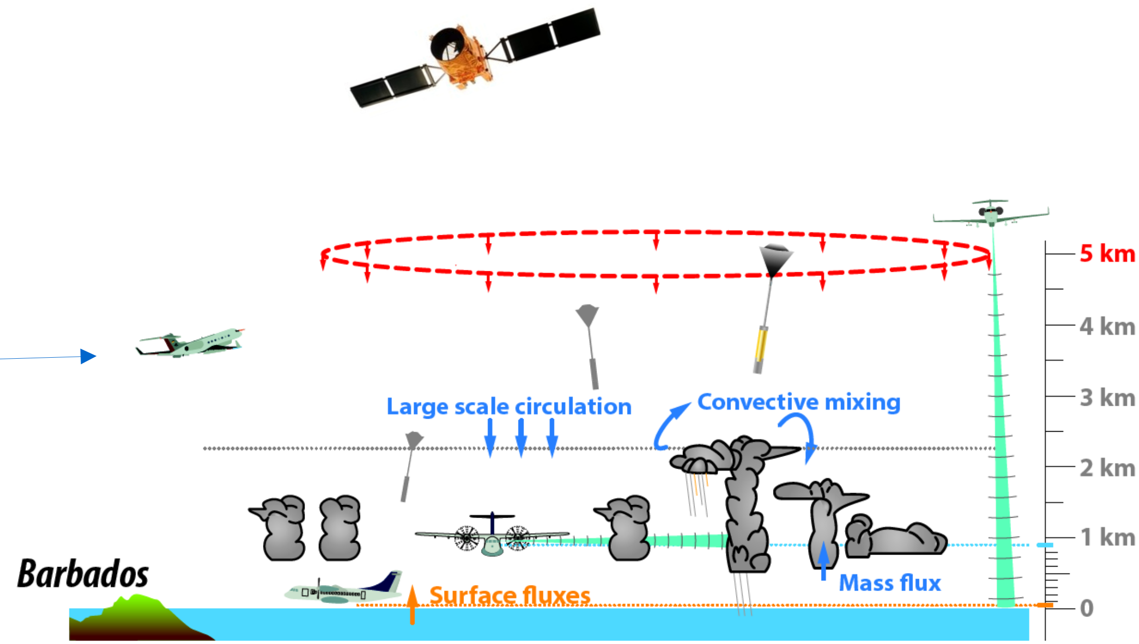


Courtesy Matt Lebsock (JPL)

Support for a more continuous culture of complementary field experiments

An opportunity to develop synergies among communities involved in satellite observations, in-situ measurements and numerical modelling around key science questions and in areas associated with critical observational challenges.





→ *e.g.* campaigns NARVAL-II (2016) and EUREC^{4}A (2019 or 2020) in the Tropical Atlantic off Barbados

→ focus on clouds-circulation coupling questions

→ exploit technological advances in in-situ measurements (e.g. BCO, aircrafts, stations)

→ evaluate satellite observations (e.g. ADM-Aeolus, EarthCare)

→ ISSI team proposal

Stevens et al, BAMS (2015); Bony et al (in prep)

Conclusion

Advancing the understanding and prediction of the role of clouds in climate requires improved observations of Water, Heating & Circulation:

1. Atmospheric cloud radiative effects (i.e. radiation budget + vertical cloud information)
2. Highly-vertically resolved water vapor, especially in the lower troposphere
3. Better estimates of cloud water path, particularly in scenes with small broken clouds.
4. Improved estimates of surface evaporation and vertical structure of latent heating
5. Wind vertical profiles and large-scale vertical velocity (omega)

Field experiments are opportunities to develop synergies between modelling, space observation and in-situ measurements around key science questions, to test new ideas and technological advances, thus helping to address the challenge.

Thank you

Interaction between cloud-radiative effects and the general circulation: a hot topic!

1 August 2014 JOURNAL OF CLIMATE

Southern Hemisphere Cloud–Dynamics Biases in CMIP5 Models and Their Implications for Climate Projections

Kevin M. Grise

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Lorenzo M. Polvani

LETTERS nature geoscience
PUBLISHED ONLINE: 4 JANUARY 2016 | DOI: 10.1038/NGEO2630

Amplification of El Niño by cloud longwave coupling to atmospheric circulation

Gaby Rädel[1], Thorsten Mauritsen[1*], Bjorn Stevens[1], Dietmar Dommenget[2], Daniela Matei[1], Katinka Bellomo[3] and Amy Clement[4]

LETTERS nature geoscience
PUBLISHED ONLINE: 19 JANUARY 2015 | DOI: 10.1038/NGEO2345

Circulation response to warming shaped by radiative changes of clouds and water vapour

Aiko Voigt[1*] and Tiffany A. Shaw[1,2,3]

15 January 2016 JOURNAL OF CLIMATE 783

Clouds and the Atmospheric Circulation Response to Warming

Paulo Ceppi and Dennis L. Hartmann

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

Link between the double-Intertropical Convergence Zone problem and cloud biases over the Southern Ocean

PNAS

Yen-Ting Hwang[1] and Dargan M. W. Frierson

15 September 2015 JOURNAL OF CLIMATE

The Influence of Atmospheric Cloud Radiative Effects on the Large-Scale Atmospheric Circulation

Ying Li and David W. J. Thompson

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

Sandrine Bony

And many more...