Clouds, Circulation and Climate Sensitivity

Sandrine Bony, Bjorn Stevens, Dargan Frierson, Christian Jakob, Masa Kageyama, Robert Pincus, Ted Shepherd, Steve Sherwood, Pier Siebesma, Adam Sobel, Masahiro Watanabe, Mark Webb.

Earth's Climate is Changing

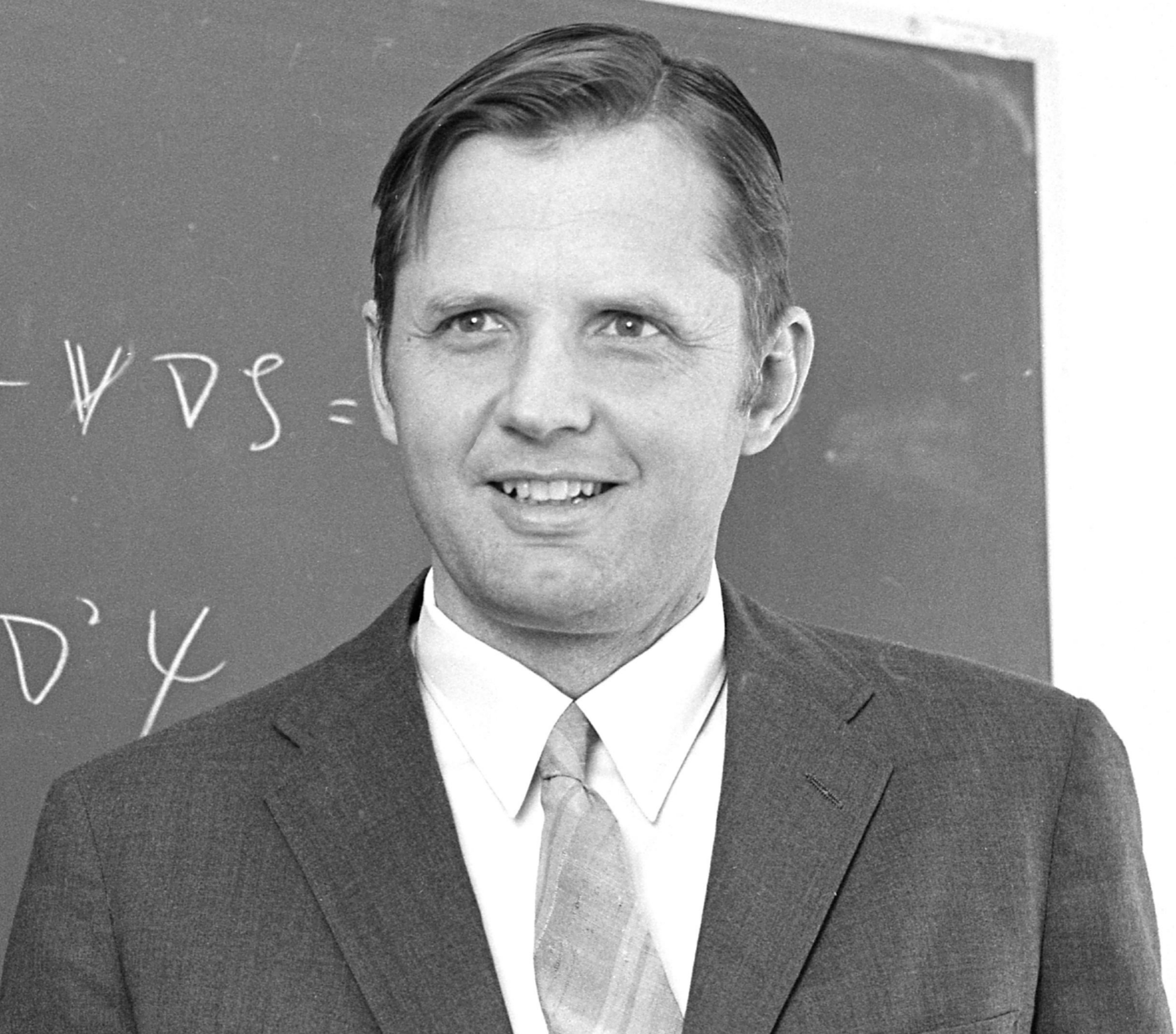
What does this mean and what can we anticipate about the future?

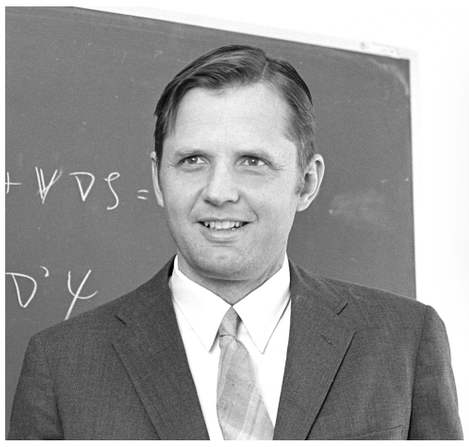
The climate system has abundant complexity, making it difficult to decide what is important.

It is neither feasible nor prudent to attempt to represent this complexity in its fullness.

Our burden is to decide what is important

and where coordinated efforts can accelerate progress, and focus on that.

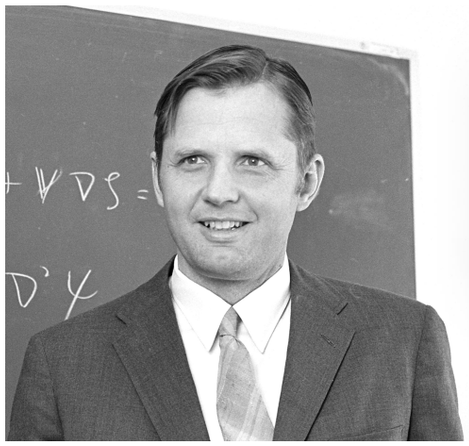




On the numerical simulation of buoyant convection

By D. K. LILLY, *General Circulation Research Laboratory, U.S. Weather Bureau, Washington*

(Manuscript received October 21, 1961, revised version March 6, 1962)



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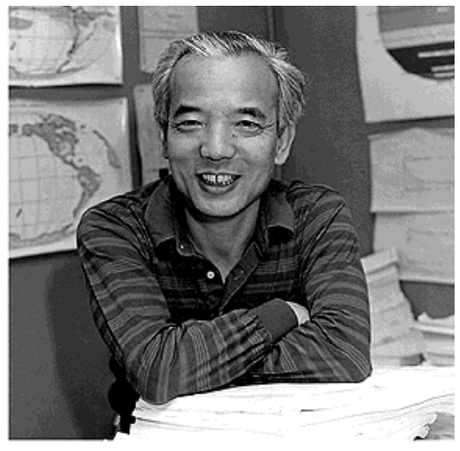
Thermal Equilibrium of the Atmosphere with a Convective Adjustment

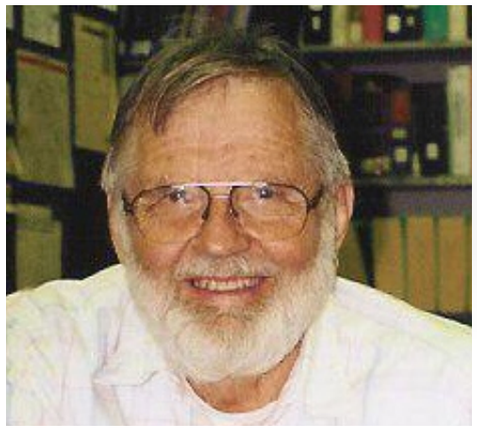
SYUKURO MANABE AND ROBERT F. STRICKLER

General Circulation Research Laboratory, U. S. Weather Bureau, Washington, D. C.

(Manuscript received 19 December 1963, in revised form 13 April 1964)



Lilly and Manabe were two of the first people Joseph Smagorinsky hired when setting out to build a team to use computational methods to help understand Earth's general circulation.



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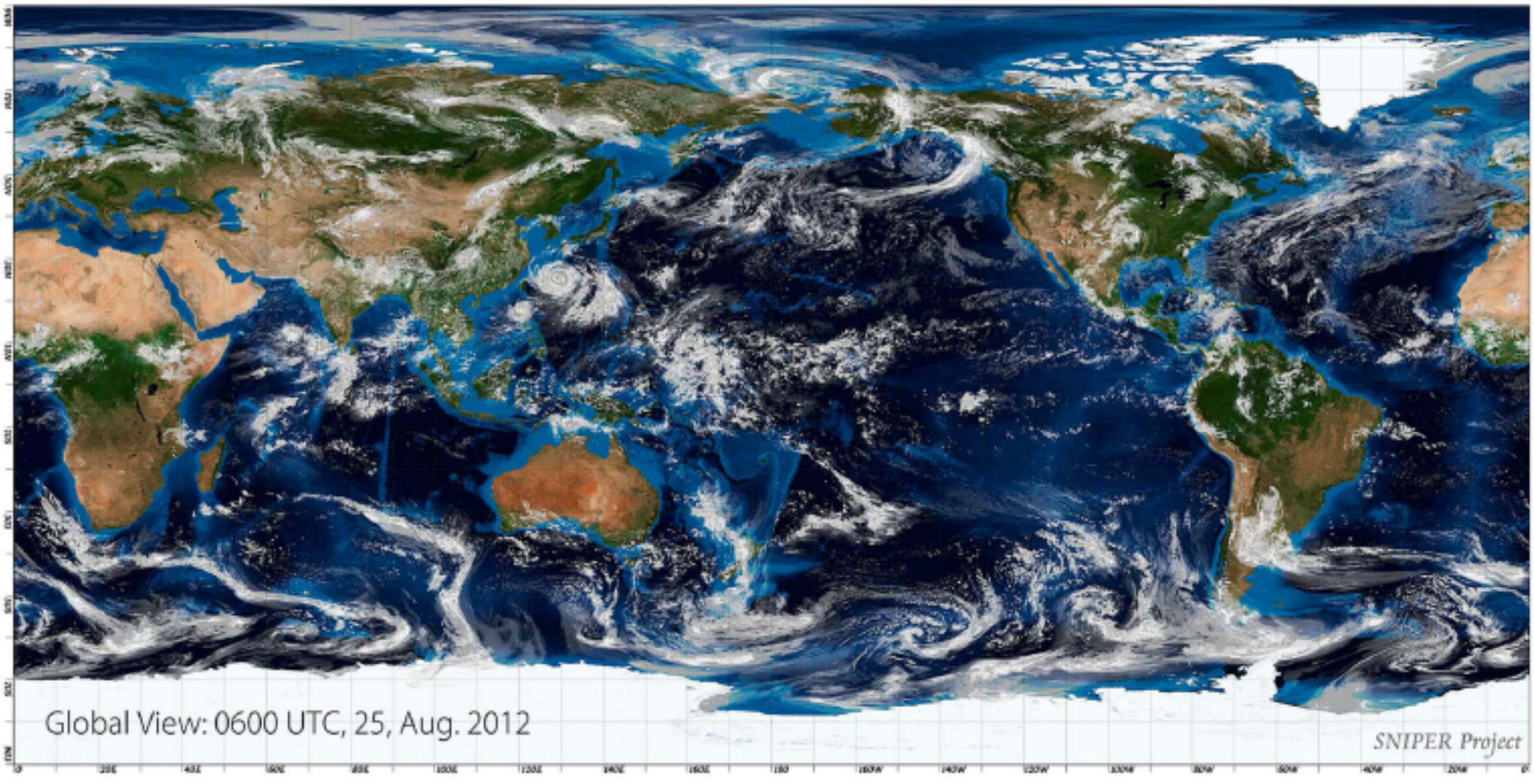
Smagorinsky was fifty years ahead of his time … but time passes.

Revolutionary advances in numerical modelling

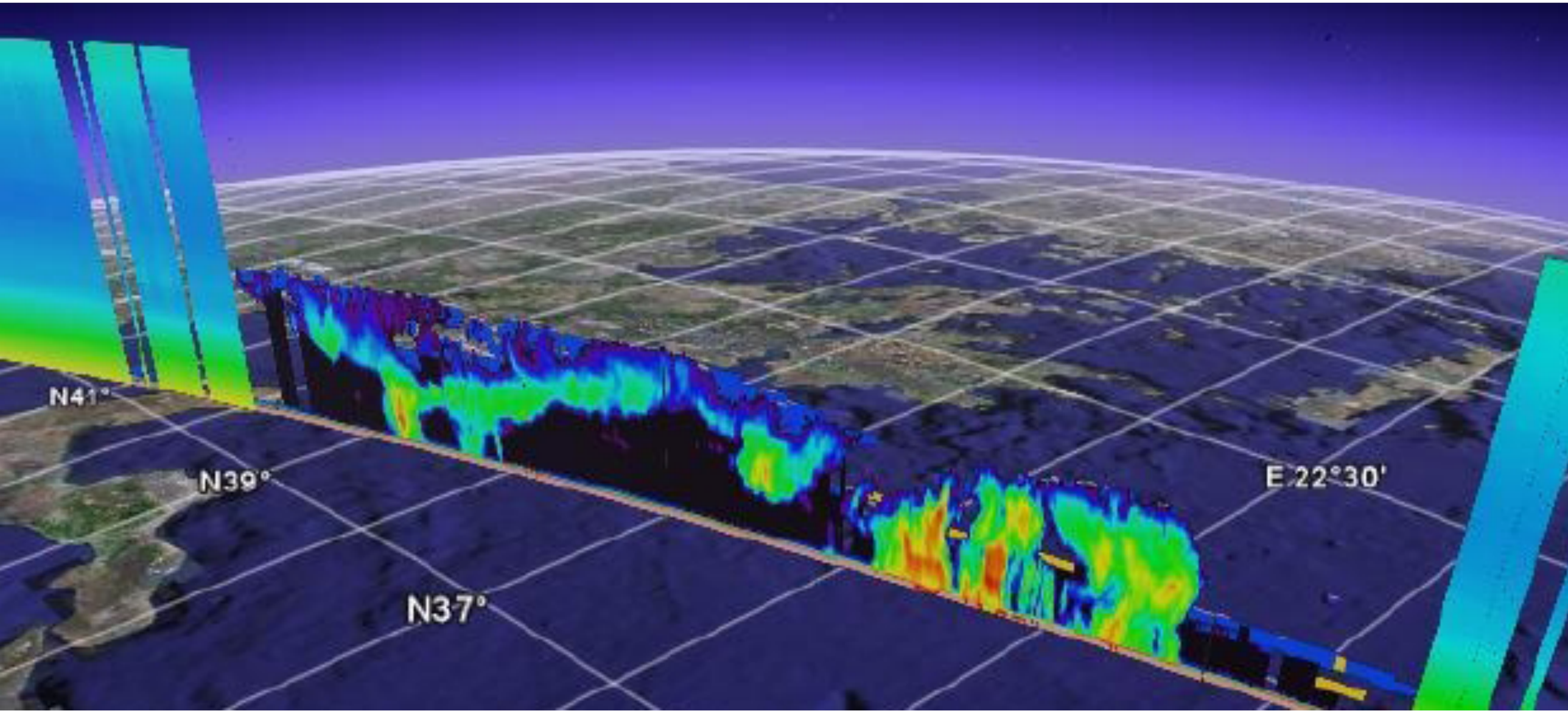
Global Cloud Resolving Model (NICAM) simulation at **sub-kilometer** resolution (870 m)



Miyamoto et al. *GRL*, 2013

Revolutionary advances in Earth Observation

Now possible to observe clouds and aerosols through multiple instruments, and in three dimensions to carry out process studies using space observations to bridge the cloud and planetary scales



NASA GSFC

Clouds, Circulation and Climate Sensitivity

4 QUESTIONS

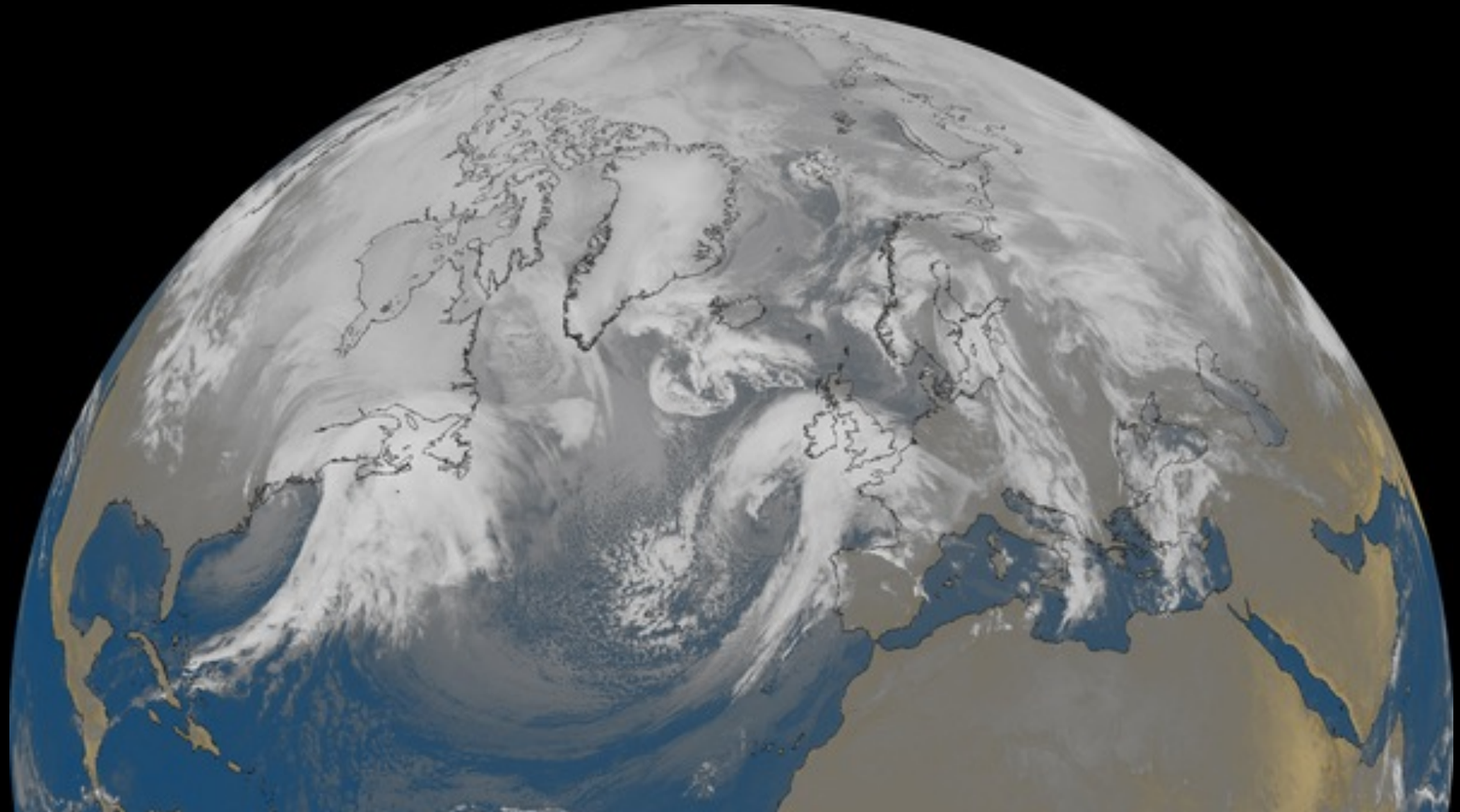
emerged after 18 months of community consultation, culminating in a workshop in March 2014

How will storm tracks change in the future?

How will storm tracks change in the future?

No doubt that the Storm Tracks are important:

- Major component of the general circulation:
  - key control of weather-related climate impacts, severe weather envelope,
  - organizes precipitation and the formation of clouds in the extra tropics.
- A major source of model biases (e.g. position of the jets, blockings, radiation budget, ocean coupling).
- Appear sensitive to external forcings (e.g. GHGs, ozone hole, sea ice) in ways that drive uncertainty in regional climate changes and impacts.

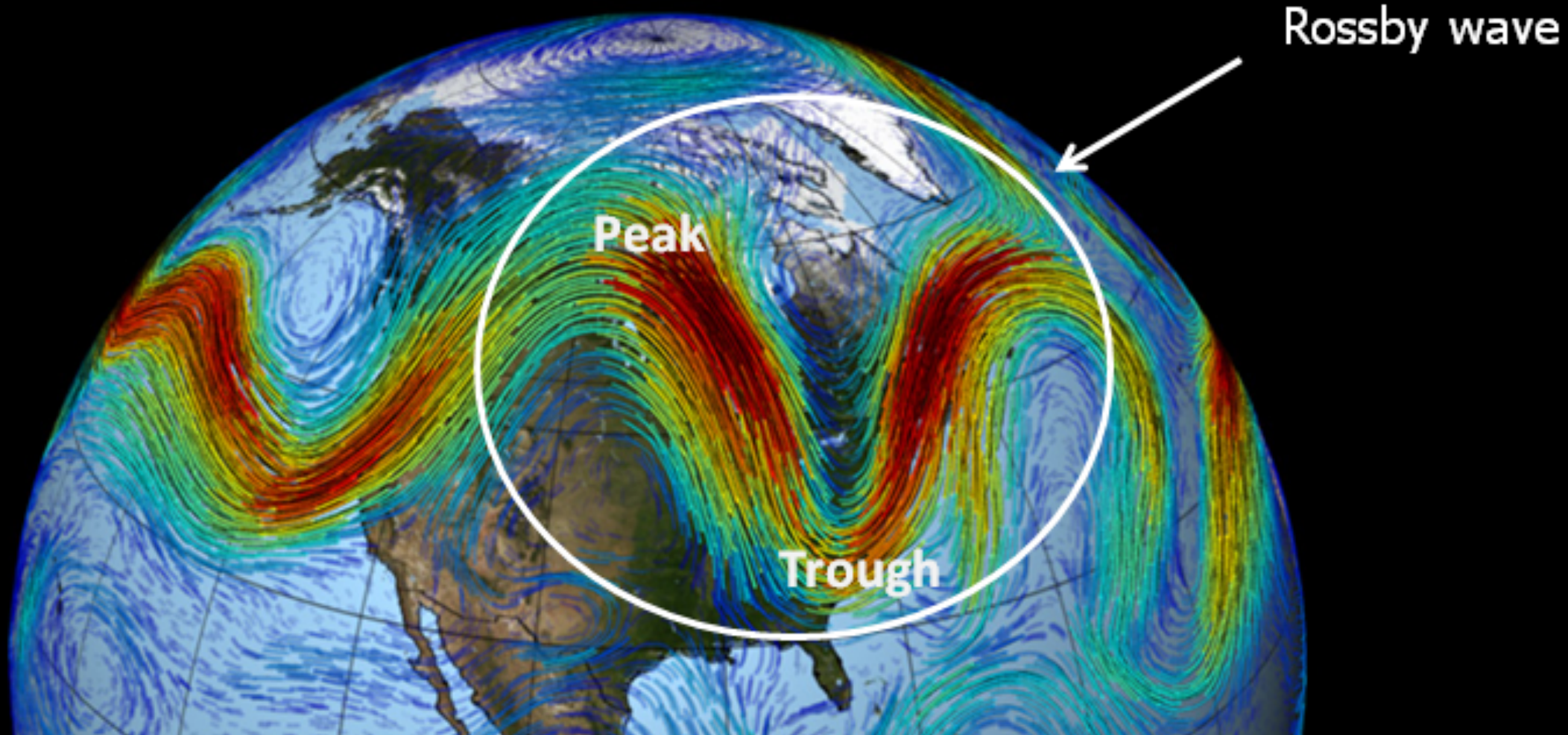


How will storm tracks change in the future?

A case in point: Last winter's US cold snaps, UK floods

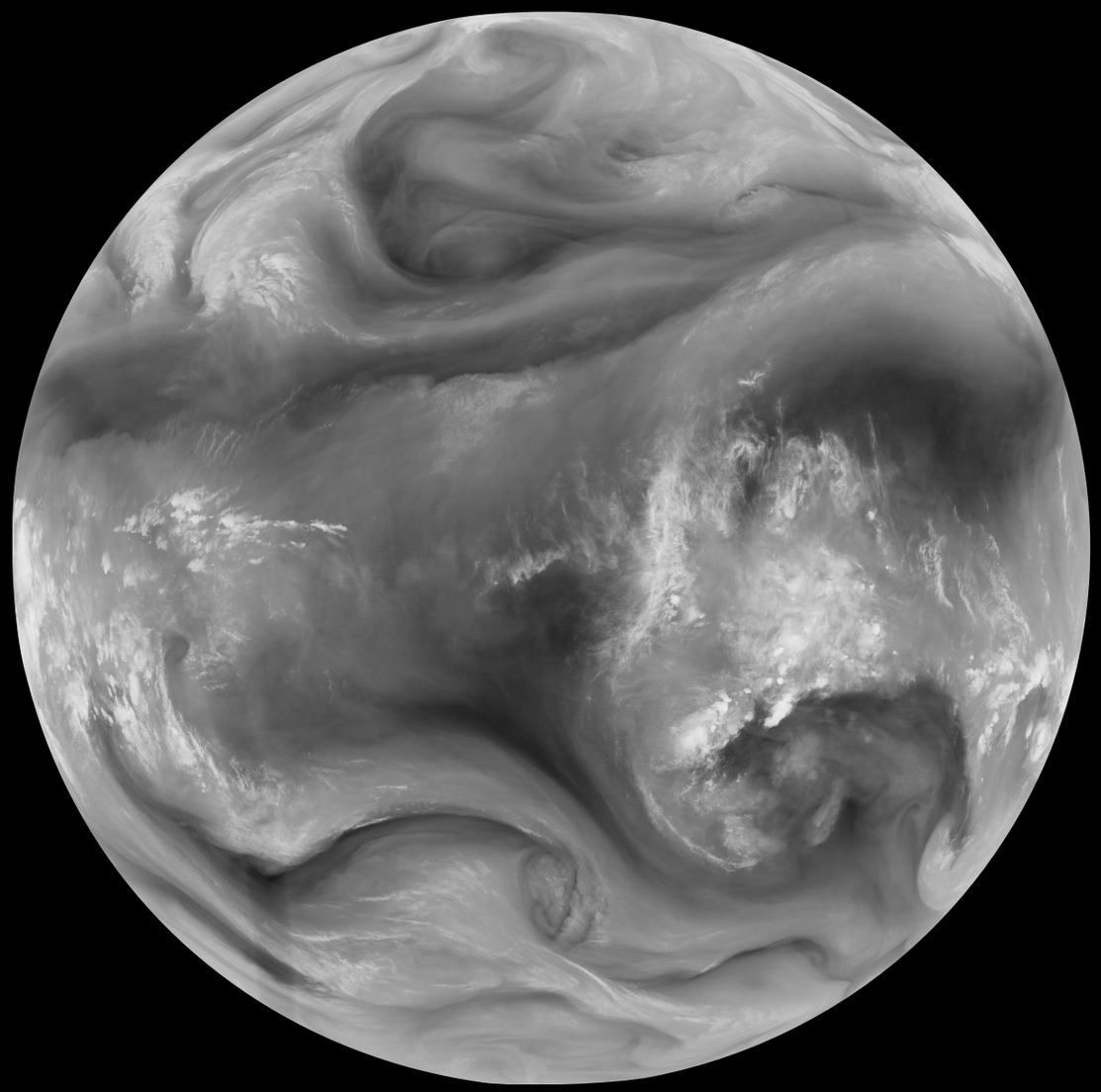
- Proximate explanation is meteorological
- Is this unusual behaviour a harbinger of things to come ?

How will the storm tracks change as the troposphere becomes warmer and wetter, the stratosphere becomes cooler, and the cryosphere shrinks ?



How will storm tracks change in the future?

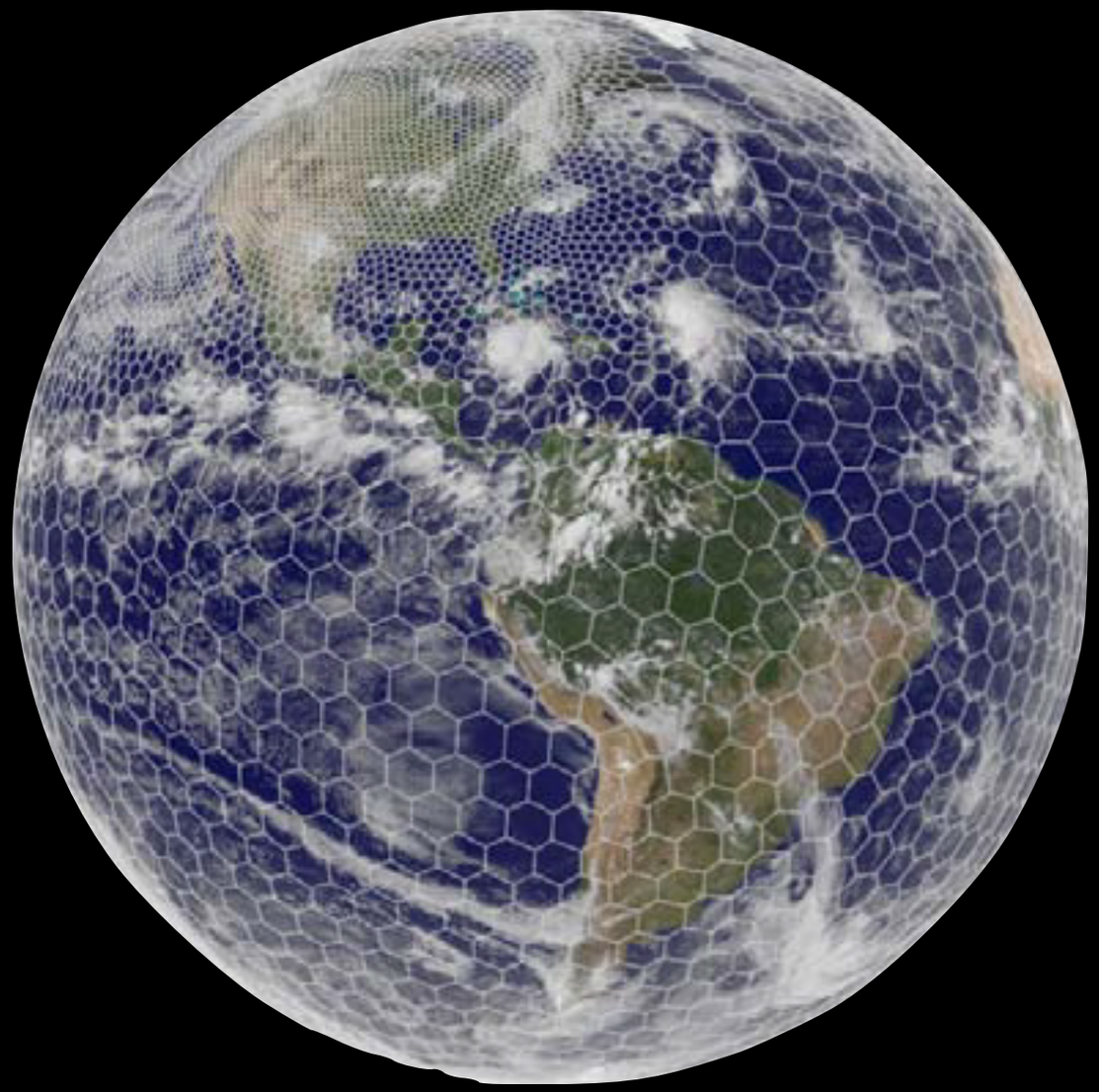
Most of our understanding of the storm tracks is based on dry dynamics, but water is Earth's atmosphere's distinguishing constituent, and water changes profoundly with climate change.



- What is the role water, phase changes and radiative processes (clouds) in the storm tracks? (T-NAWDEX, DOWNSTREAM)
- How might the balance between moist and dry dynamics change as climate warms? (latitudinal temperature gradients weakening, greater role for liquid processes)
- How do the storm tracks interact with the changing tropics and polar regions? (rapidly warming Arctic, role of stratosphere)

How will storm tracks change in the future?

Implications for climate modelling and climate change studies?

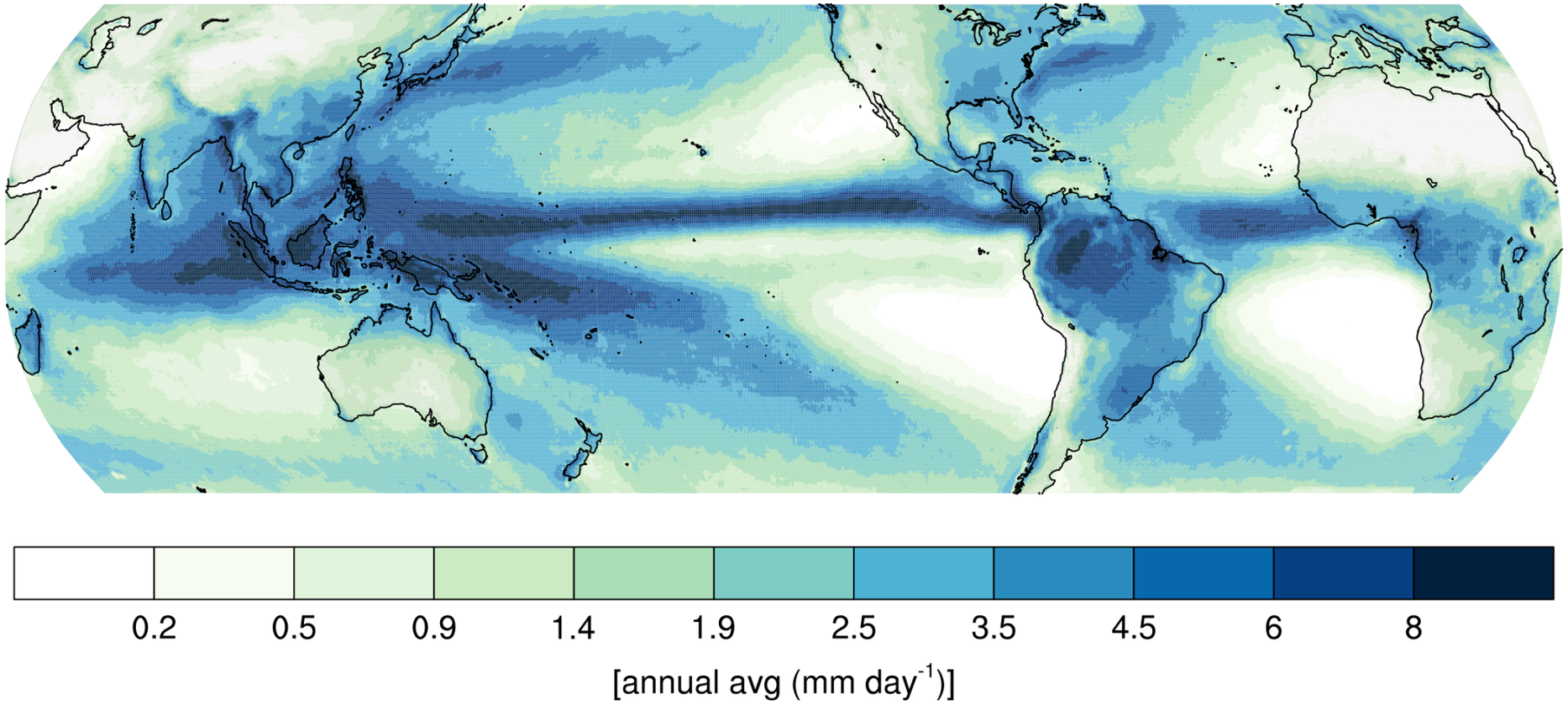


- Persistent biases in the simulation of storm tracks (position of the jets, blockings..) … how much of the skill in the Northern Hemisphere storm tracks is through compensating errors?
- Does regionally localized forcing (sea ice, ozone) affect the storm tracks? Can the paleo-record inform investigations of these questions?
- Can high-resolution (100m) studies of baroclinic life-cycles, or NWP techniques, better inform our understanding of diabatic effects on storm tracks?
- Can we develop dynamical story lines of plausible changes in regional climate and extremes?

2

What controls the position and strength of tropical rain belts?

What controls the position and strength of tropical rain belts?

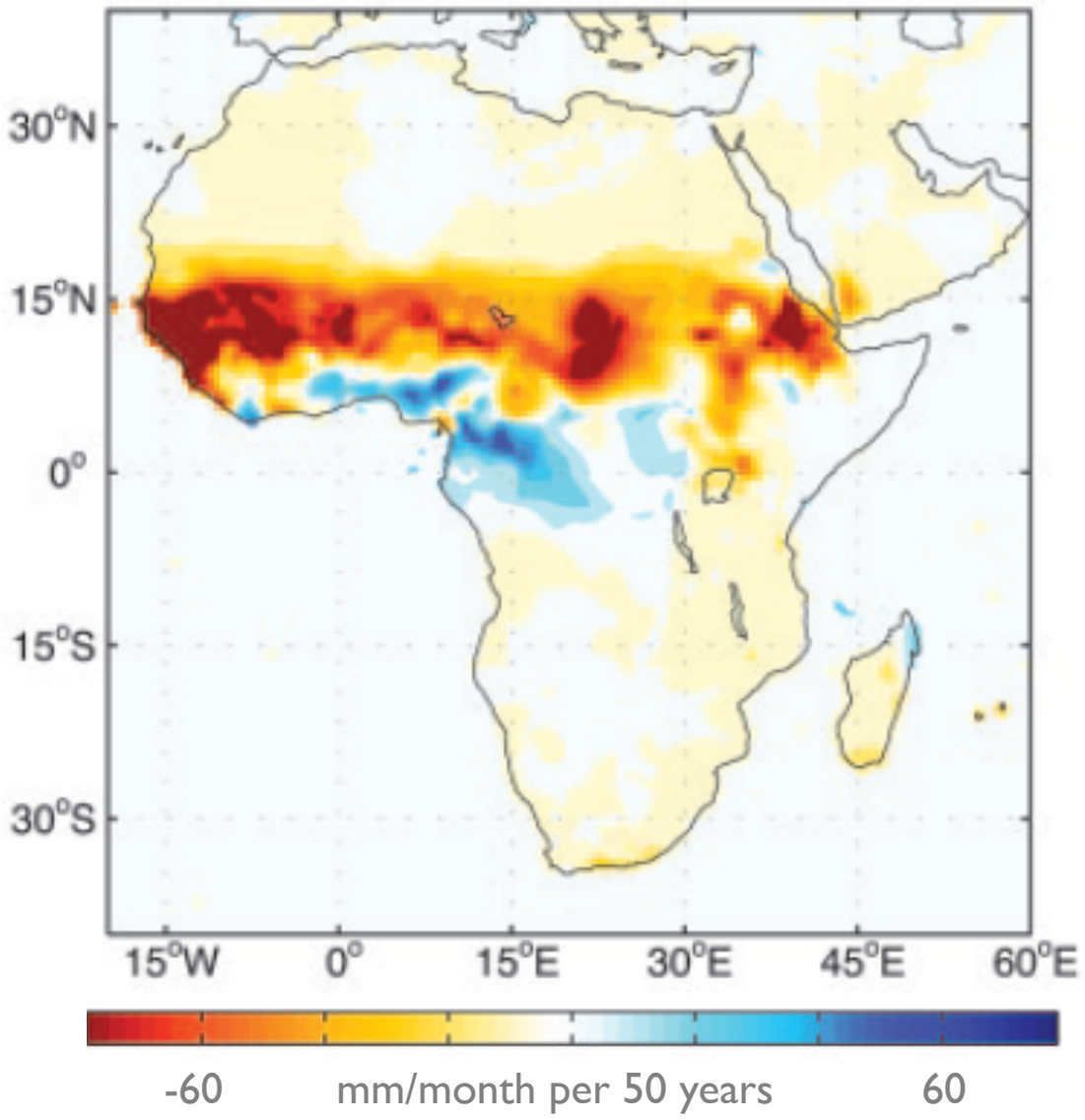


- Tropical rain bands organize the circulation over half of the globe, patterns of evaporation and ocean wind stress, as well as patterns of cloudiness and cloud radiative effects.
- Through teleconnections shifts in tropical rainfall have profound remote influences.
- Rainfall over land also has a profound influence on vegetation and carbon cycle dynamics, and air-quality.

Precipitation from TRMM

What controls the position and strength of tropical rain belts?

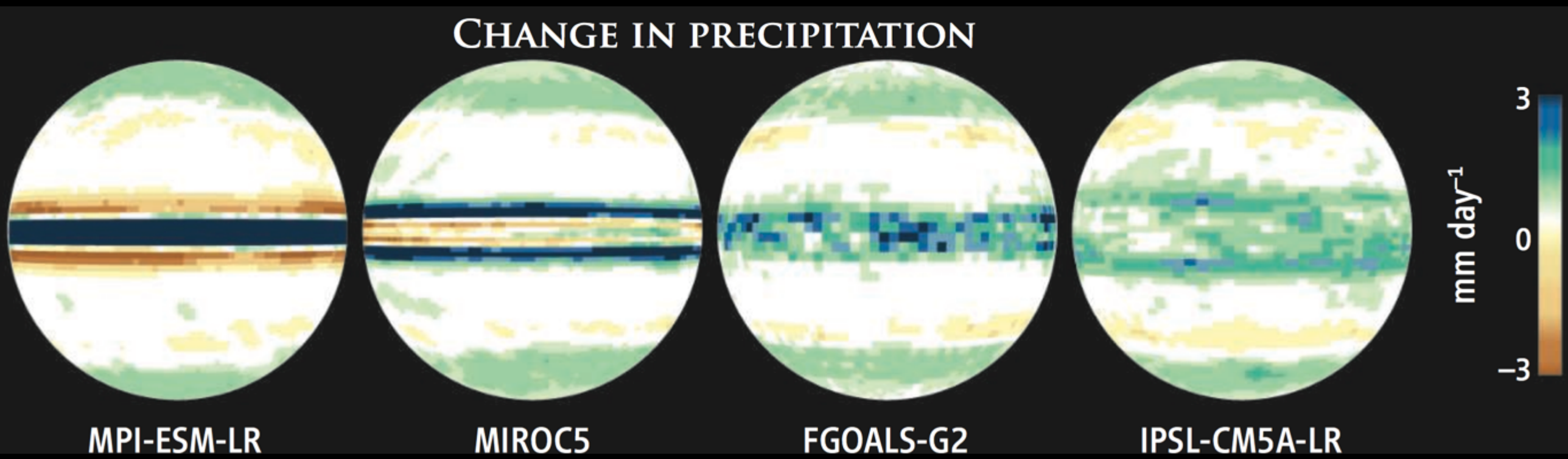
CRU (JJA) rainfall trends from 1950 to 2000



- Rain belt shifts responsible for severe droughts e.g. Sahelian drought
- How will rain belts respond to anthropogenic forcings (e.g. GHG, aerosols, land use)?
- Mid-Holocene Green Sahara enigma: How was there rain all the way to 30N?

Held et al., *PNAS,* 2005

What controls the position and strength of tropical rain belts?



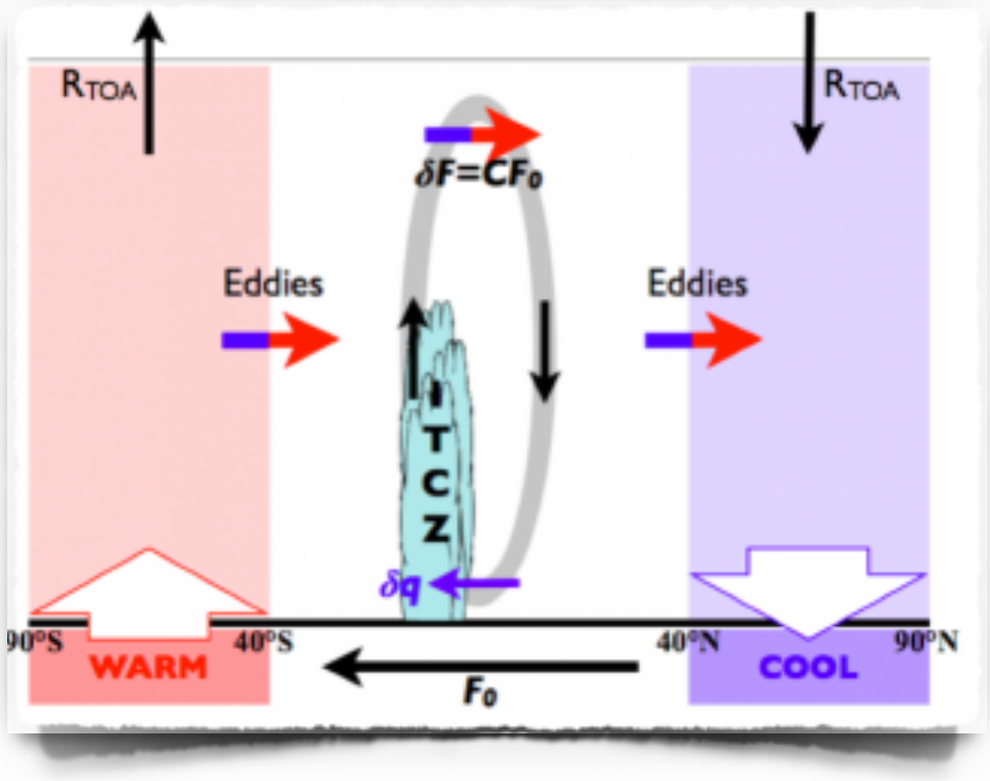
In simple aqua-planet configuration (CMIP5) : large inter-model differences in the position of tropical convergence zones (present-day climate & response to +4K)

We have to understand this, as it is relevant to regional climate changes

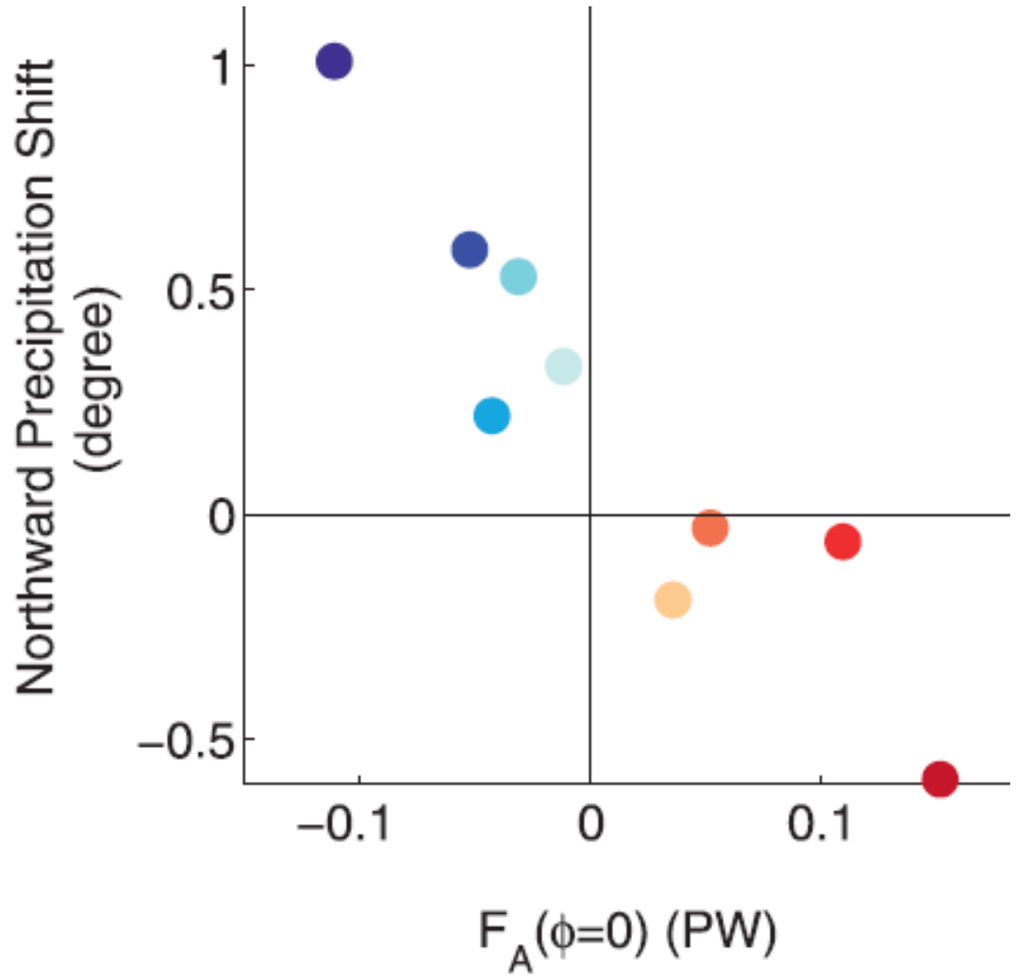
Stevens and Bony, *Science* (2013)

What controls the position and strength of tropical rain belts?

Energetic frameworks are being developed to interpret rain belt shifts

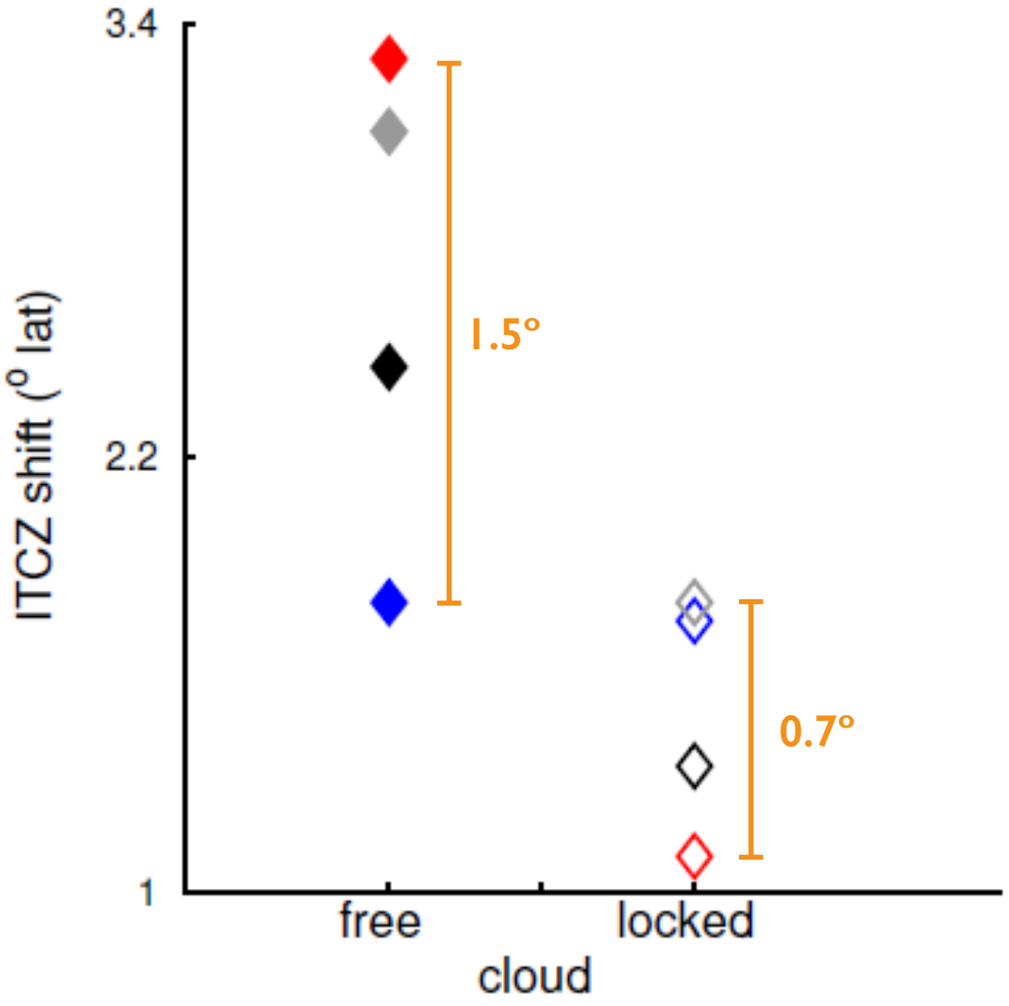


inter-hemispheric energy transport



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

What controls the position and strength of tropical rain belts?



- The strength of the rain belt shift to inter hemispheric heating differences depends on the model.
- Much of the spread can be attributed to how clouds couple to radiation.
- Paleo record provides an interesting test for rain band shifts
- Modern observations are increasingly able to resolve the vertical distribution of heating and its covariability with synoptic disturbances in the tropics.

Not just a convection problem, clouds matter … and over land perhaps also the representation of the land surface.

Voigt et al., *GRL*, 2014

3

Is convective aggregation important for climate?

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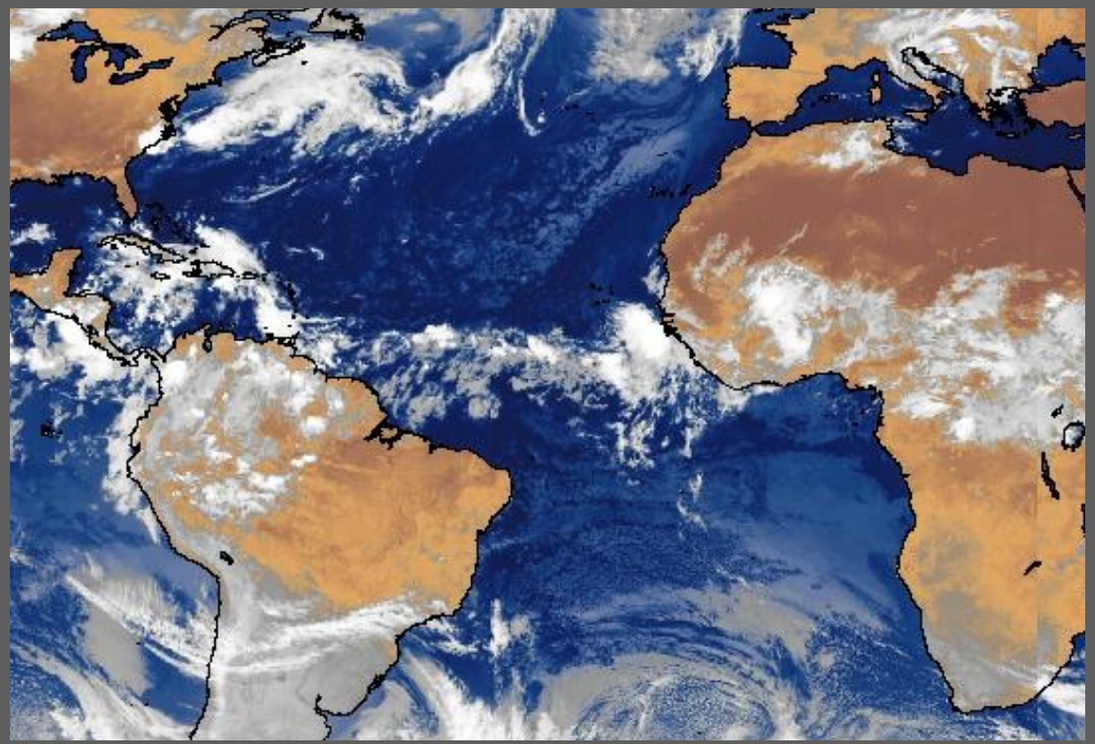
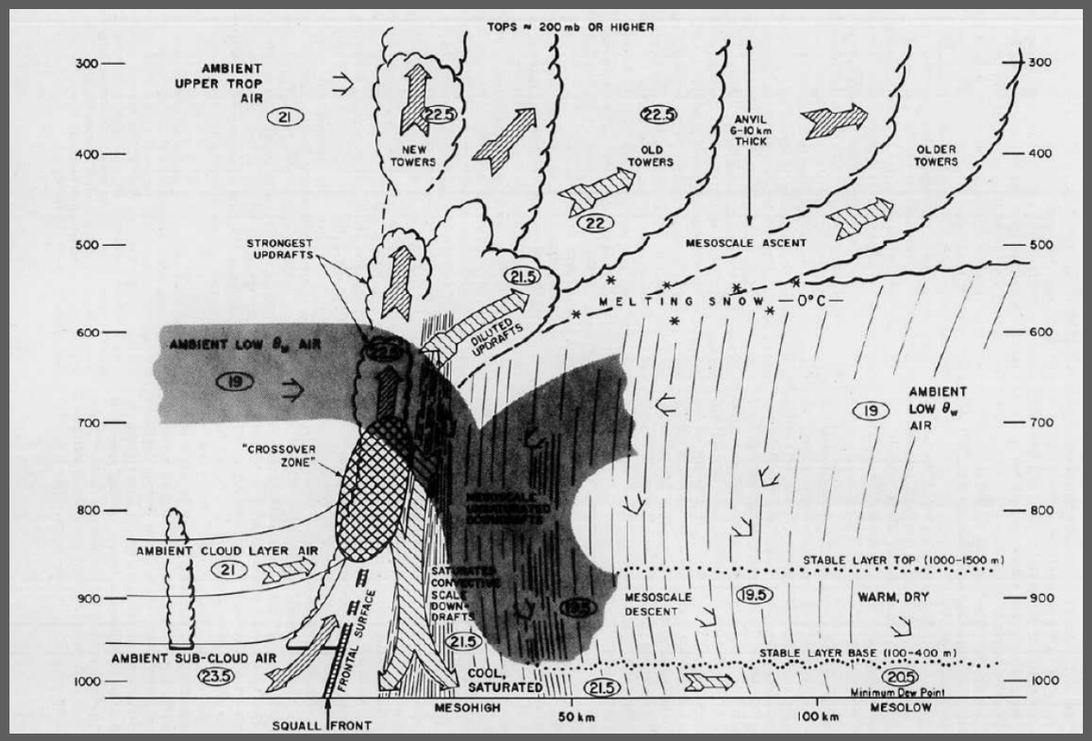
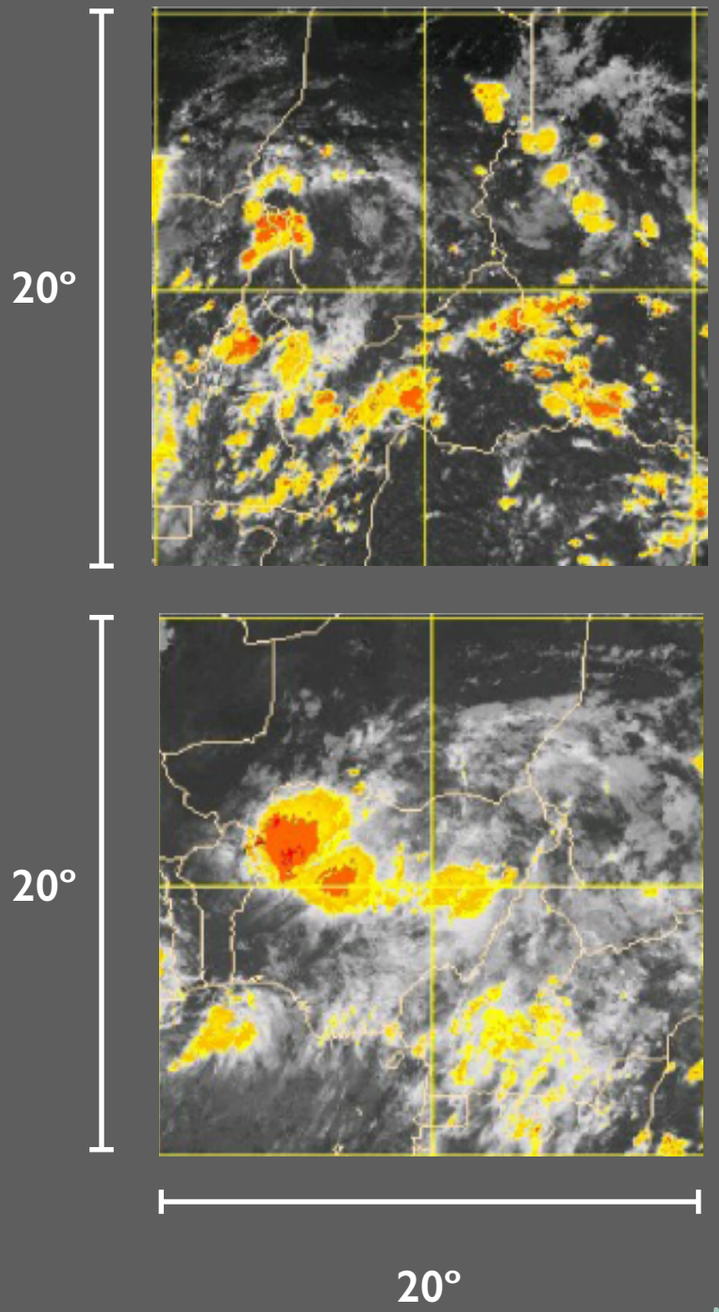




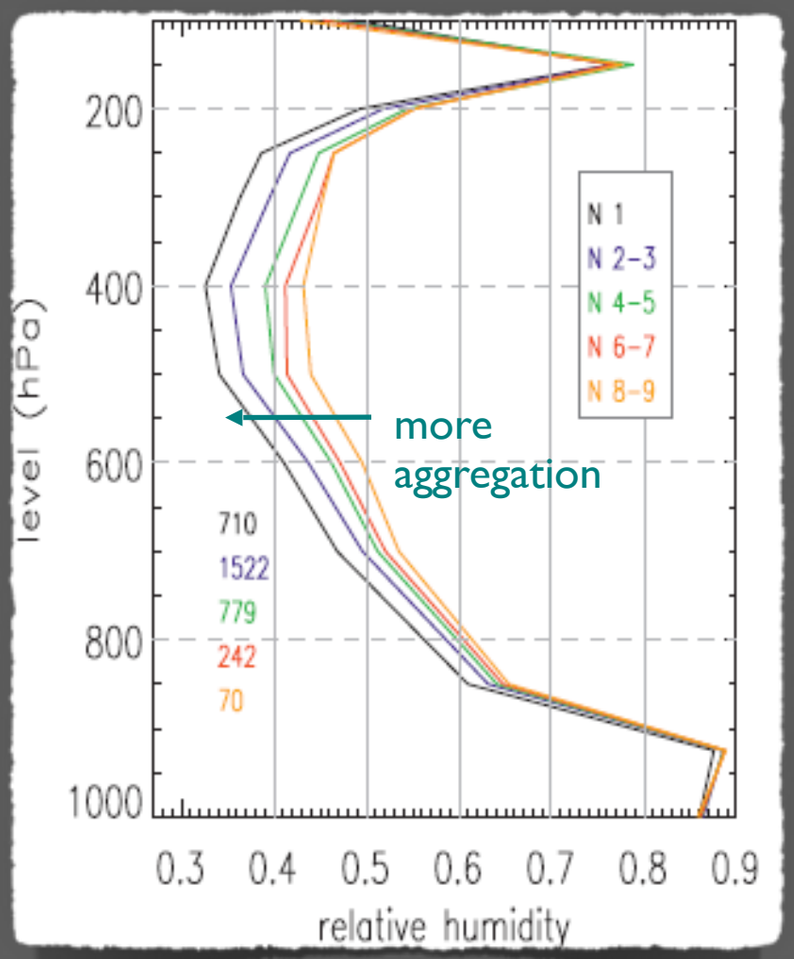
- On planetary scales the answer is clear.
- On the storm scale organization/aggregation is important for weather.
- Features organized on the synoptic and mesoscale play a very important role in delivering rainfall in many tropical regions.
- The temporal distribution of rain matters also for other components of the Earth system.

SATMOS; Zipser *1977*

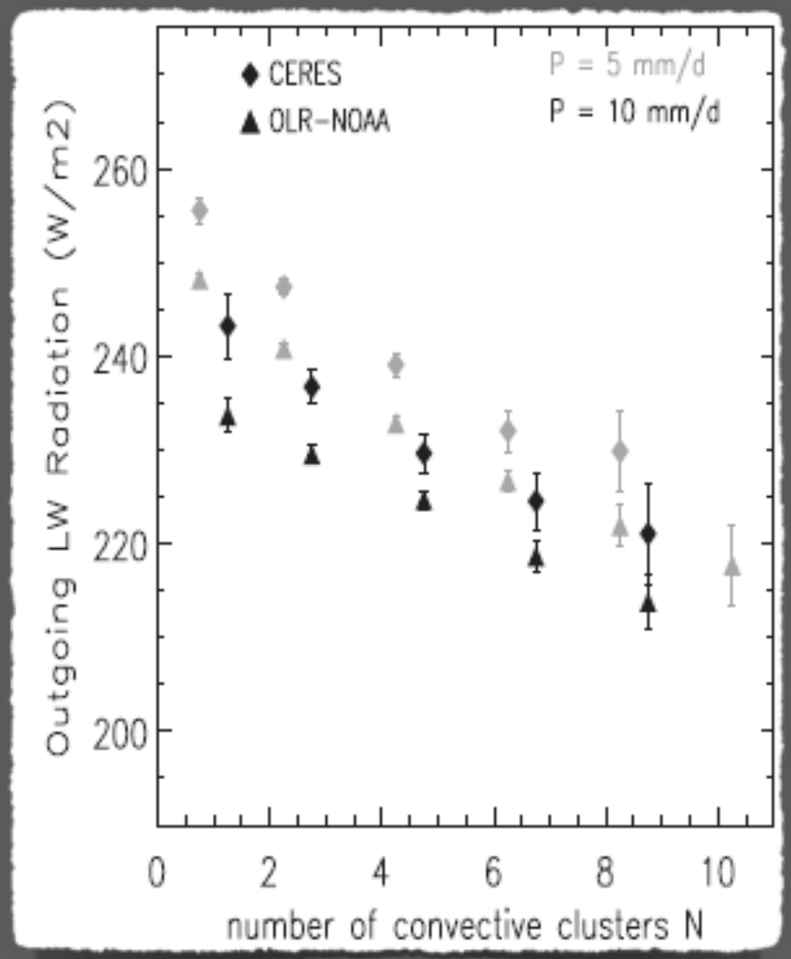
Is convective aggregation important for climate?



troposphere is drier, clearer
(RH, AIRS data)



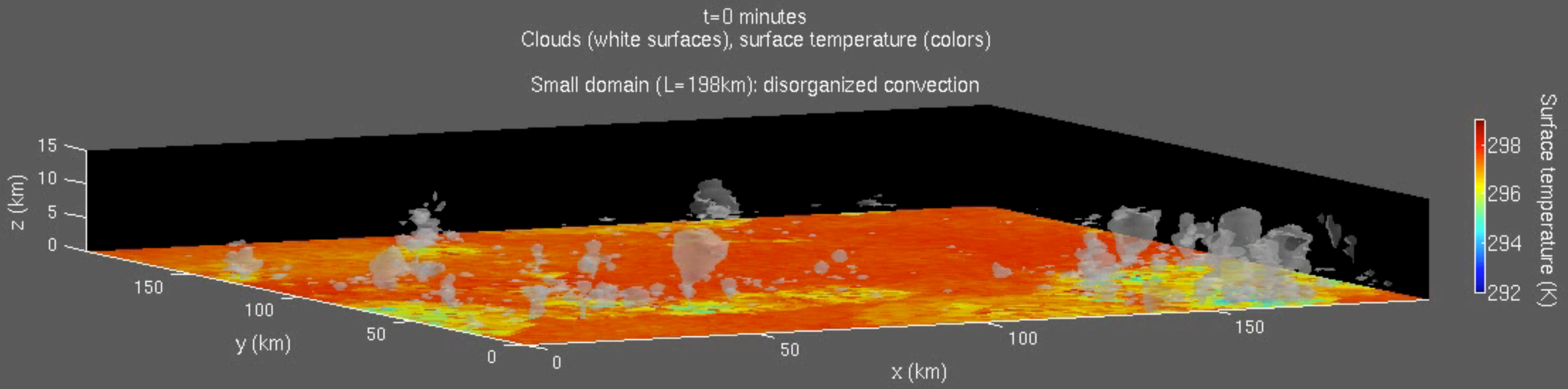
radiatively cools more efficiently
(OLR, CERES data)

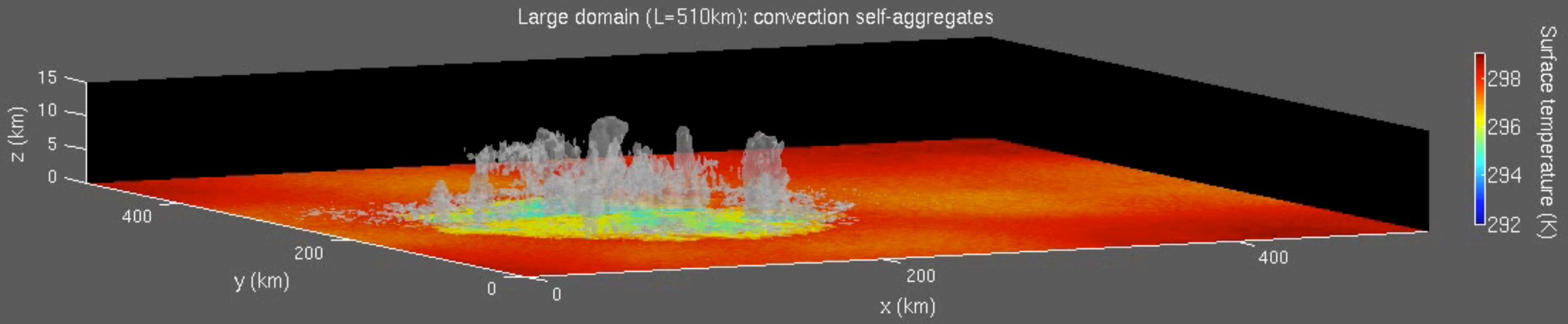


Numerical and observational studies suggest that it might be

Tobin, Bony & Roca, *J. Climate* 2012; Tobin et al., *JAMES,* 2013, see also Bretherton et al., *J. Atmos Sci., 2003,*

Is convective aggregation important for climate?

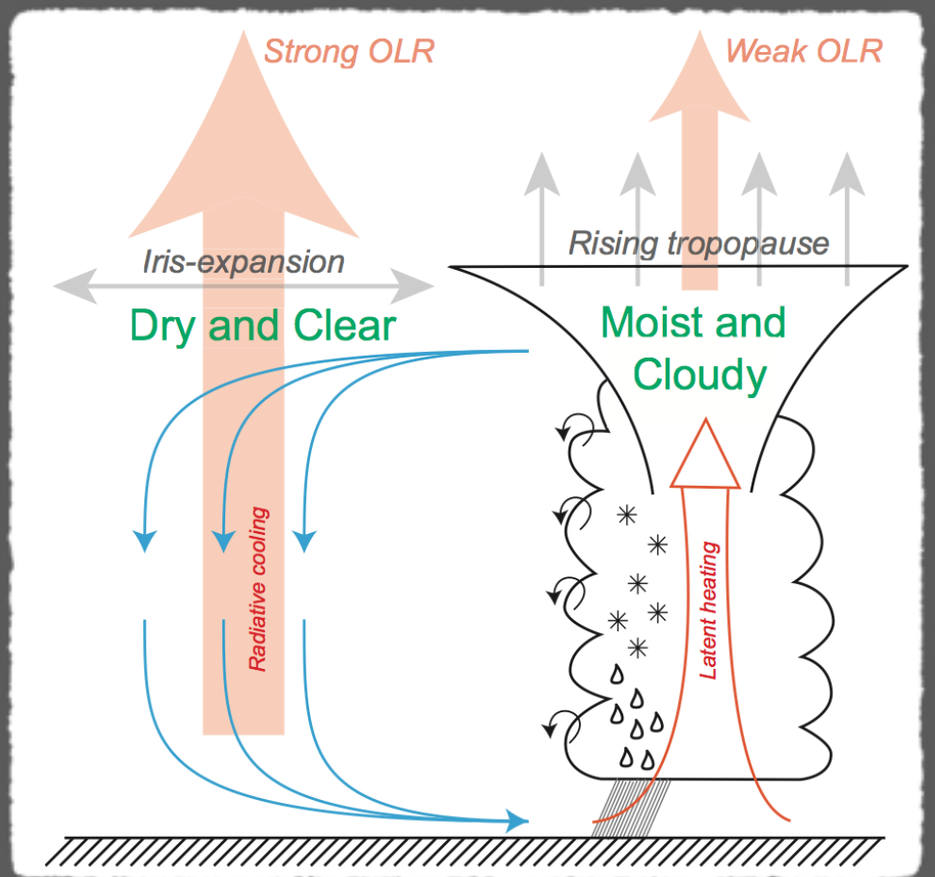


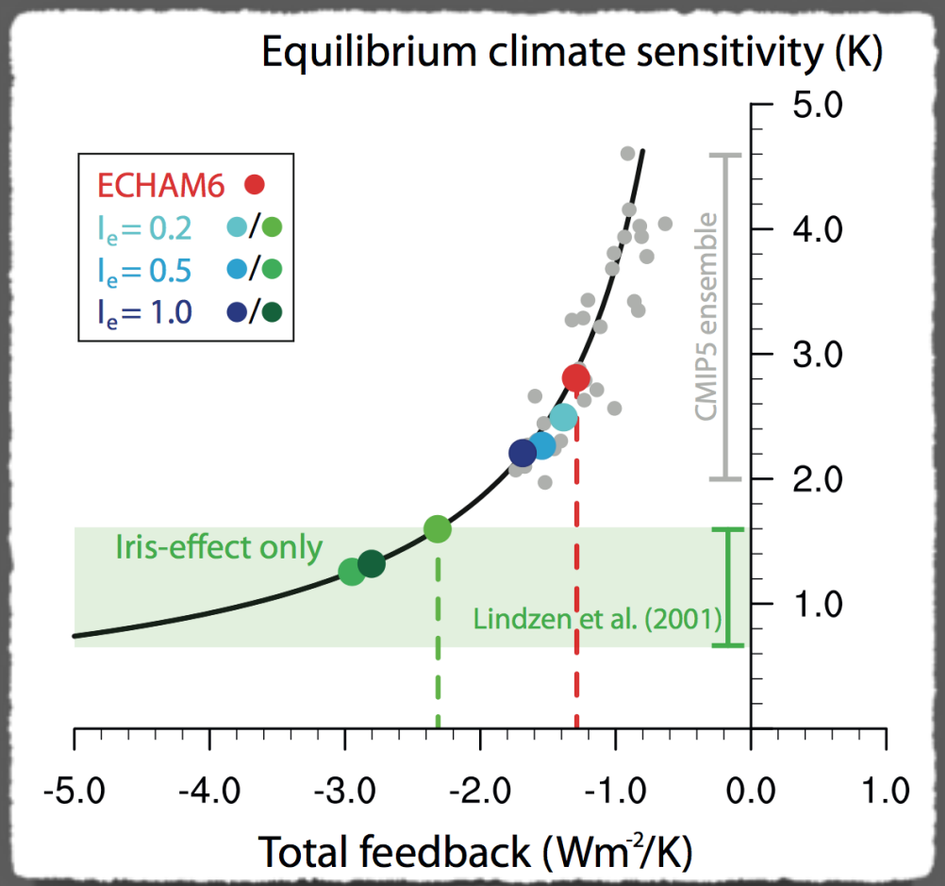


Even in the absence of external drivers (e.g. rotation, shear), convection can aggregate spontaneously and some theoretical work suggests that aggregation increases with temperature.

Simulation courtesy of Caroline Muller (LadHyX), cf Wing & Emanuel, *JAMES,* 2014 Khairoutdinov & Emanuel, *AMS,* 2010, Held et al. 1993, Muller and Held 2012

Is convective aggregation important for climate?





- Can observations or proxies provide evidence for such a dependence?
- May changes in convective aggregation feed back on global warming?
- If so, are climate models missing an essential ingredient?
- And if they are might this also explain persistent biases (rainbands, MJO)?

Mauritsen and Stevens 2014.

4

How does convection contribute to cloud feedbacks?

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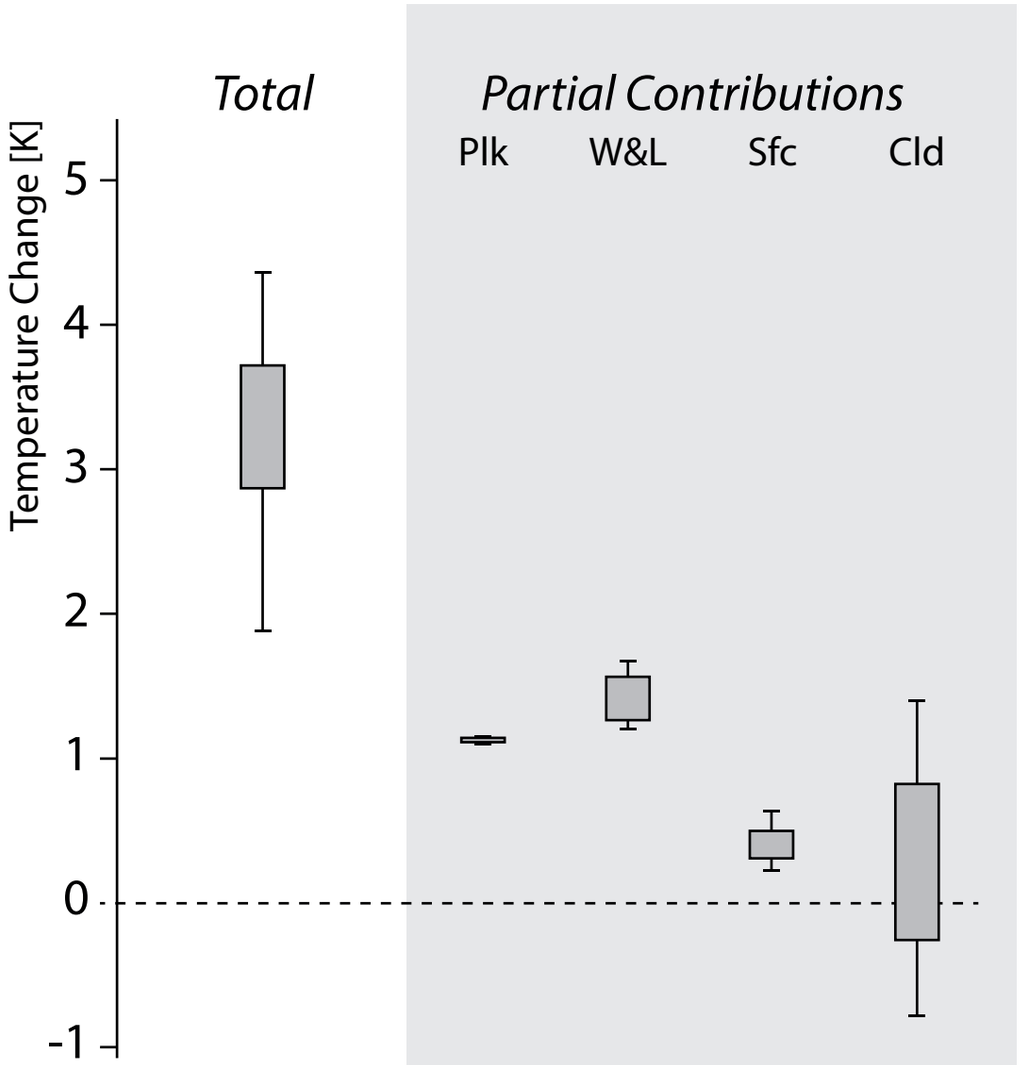


Climate sensitivity conditions the climate response:

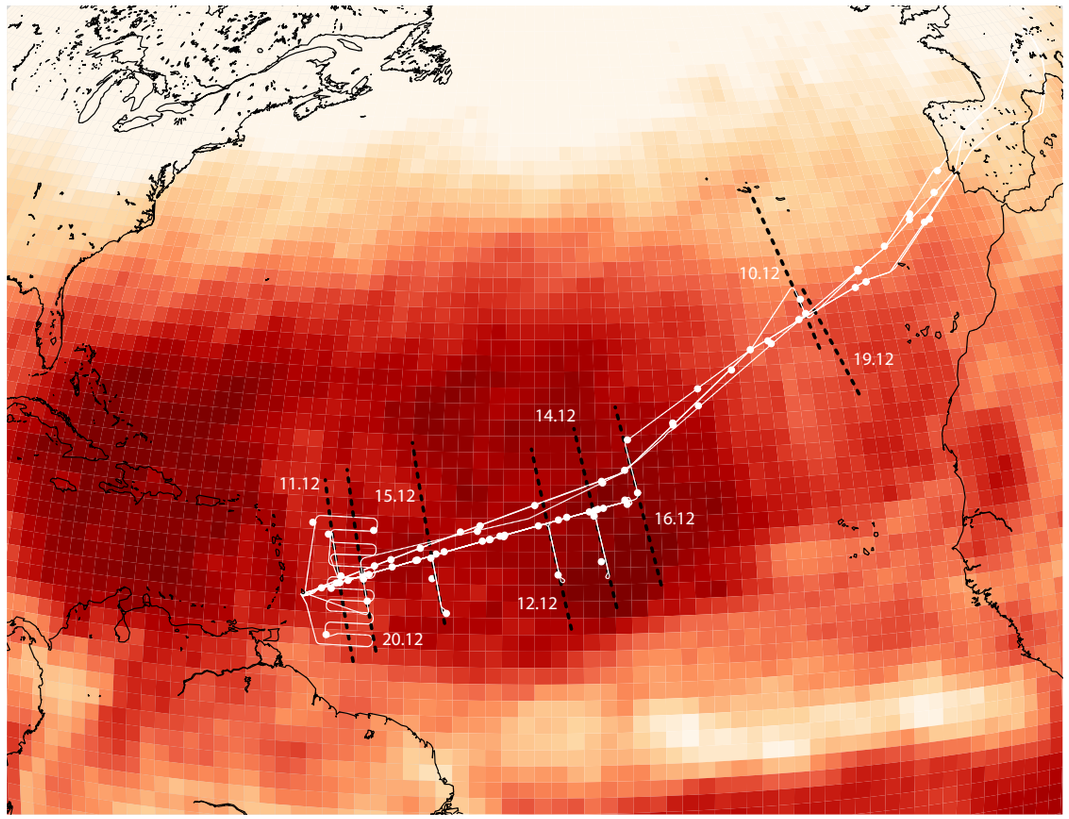
- European summer temperatures.
  (Cattiaux et al., 2013)
- Pattern amplitudes.
  (Hourdin et al., 2013, Stevens et al., 2013)
- Transient climate response.
  (Dufresne and Bony, 2008)
- Precipitation response.
  (Popke et al., 2014)

Climate sensitivity conditions many aspects of the climate system's response to forcing and uncertain cloud feedbacks contribute the most to uncertainty in climate sensitivity.

Bony & Stevens. *Chpt 13, Clouds and Climate* 2013

How does convection contribute to cloud feedbacks?

NARVAL HALO Flights (10-20.12.2013)

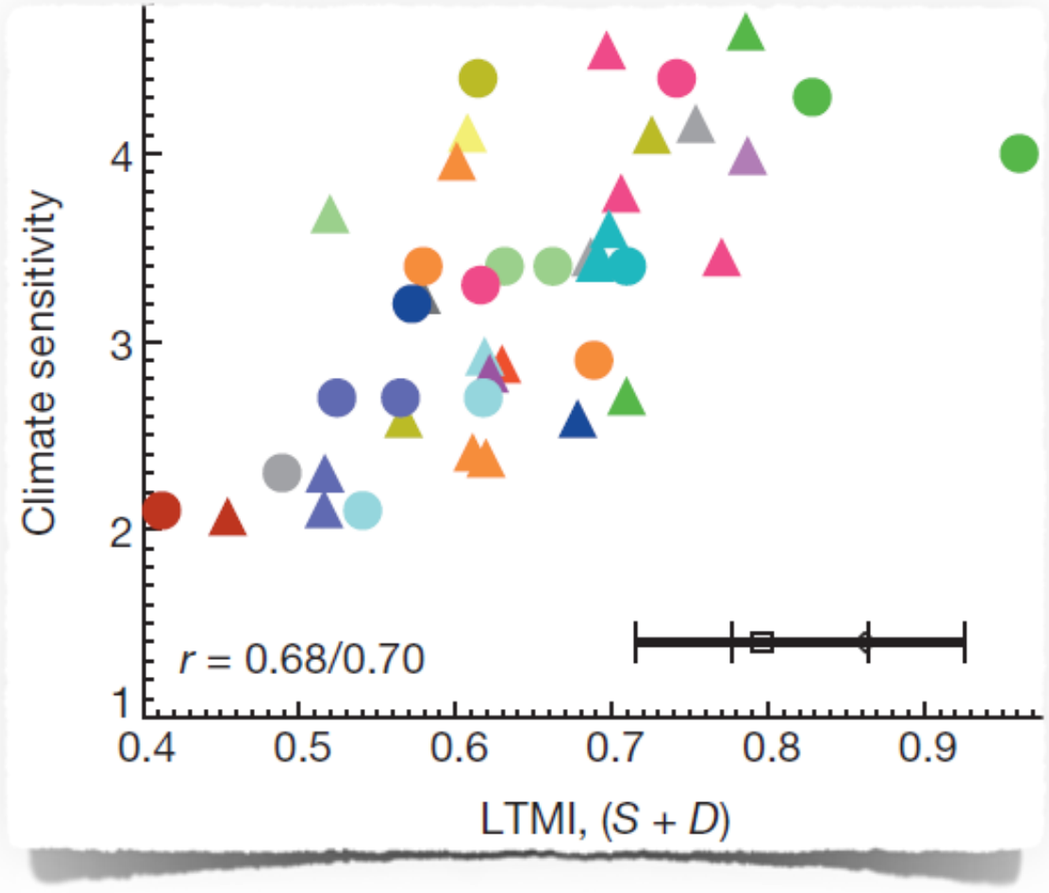


Central subtroipcal atlantic, 10.12.2013

- Several cloud-feedback mechanisms have been identified and are now independently corroborated by multiple lines of evidence, and most of them involve changes in large-scale dynamics and convection.
- Most of the inter-model spread in climate sensitivity results from differing low-cloud feedbacks in ways that are intimately tied to convection.
- High resolution modeling, and new types of observations (profling instruments), are increasingly being used to test and develop ideas … but there are important gaps.

Not just a cloud problem, convection matters

How does convection contribute to cloud feedbacks?



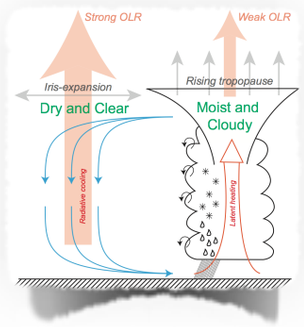
Climate Sensitivity vs mixing strength in present-day climate

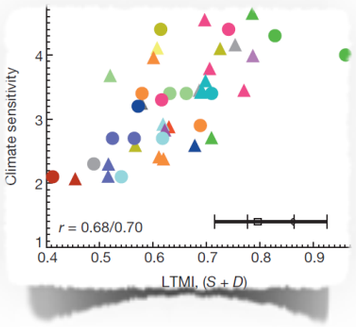
- Mechanism potentially explaining widespread positive low-cloud feedback in GCMs.
- Transport of water vapour out of the low-cloud layer by shallow circulations intensifies in warmer atmosphere.
- Suggests that models with more shallow circulation have higher sensitivity, and more shallow circulations are more consistent with the reanalysis.
- But how good is the reanalysis at representing the strength of lower tropospheric mixing?

Climate sensitivity of the CMIP5 models appears to be related to strength of lower tropospheric mixing in the tropics

Rieck, Stevens and Nuijens, *J. Atmos. Sci.* 2012: Brient and Bony, *Climate Dynamics*, 2013; Bretherton et al., *JAMES*, 2013; Sherwood, Bony & Dufresne, *Nature*, 2014; Zhoa et al., *J. Atmos. Sci.*, 2014, Gettleman et al., *J. Atmos. Sci.*, 2014.

How does convection contribute to cloud feedbacks?





Convective processes are key actors in the story-line for a high, and for a low, sensitivity world.

Clouds, Circulation and Climate Sensitivity

The Four Questions:

1. How will storm tracks change in the future?
2. What controls the position and strength of tropical rain belts?
3. Is convective aggregation important for climate?
4. How does convection contribute to cloud feedbacks?

One Assertion:

Focusing on the four questions will accelerate progress by spurring model development, by inspiring new observations, by stimulating new analysis and by expanding and exploiting the paleoclimate proxy record – but to be successful we need to work together.

Paper on 'The Four Questions' in preparation (to be submitted in Sept 2014)

Discussion in Antarctica after this Session