With contributions from
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F Landerer
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OCO team
Cloudsat team

Multiscale character of the water cycle* of Earth

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* An atmospheric centric perspective & largely a focus on precipitation

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*"Water is the next oil."**

The GEWEX 'Grand Science questions

1. ***How can we better understand and predict precipitation variability and changes?*** *PREDICTION*
2. ***How do changes in land surface and hydrology influence past and future changes in water availability and security?*** *TERRESTRIAL WATER CYCLE*
3. ***How does a warming world affect climate extremes, especially droughts, floods, and heat waves, and how do land area processes, in particular, contribute?*** *EXTREMES IN A WARMING WORLD*
4. ***How can understanding of the effects and uncertainties of water and energy exchanges in the current and changing climate be improved and conveyed?*** *UNDERSTANDING*

To what extent are these changes predictable – and how does the predictability change with space/time scale?

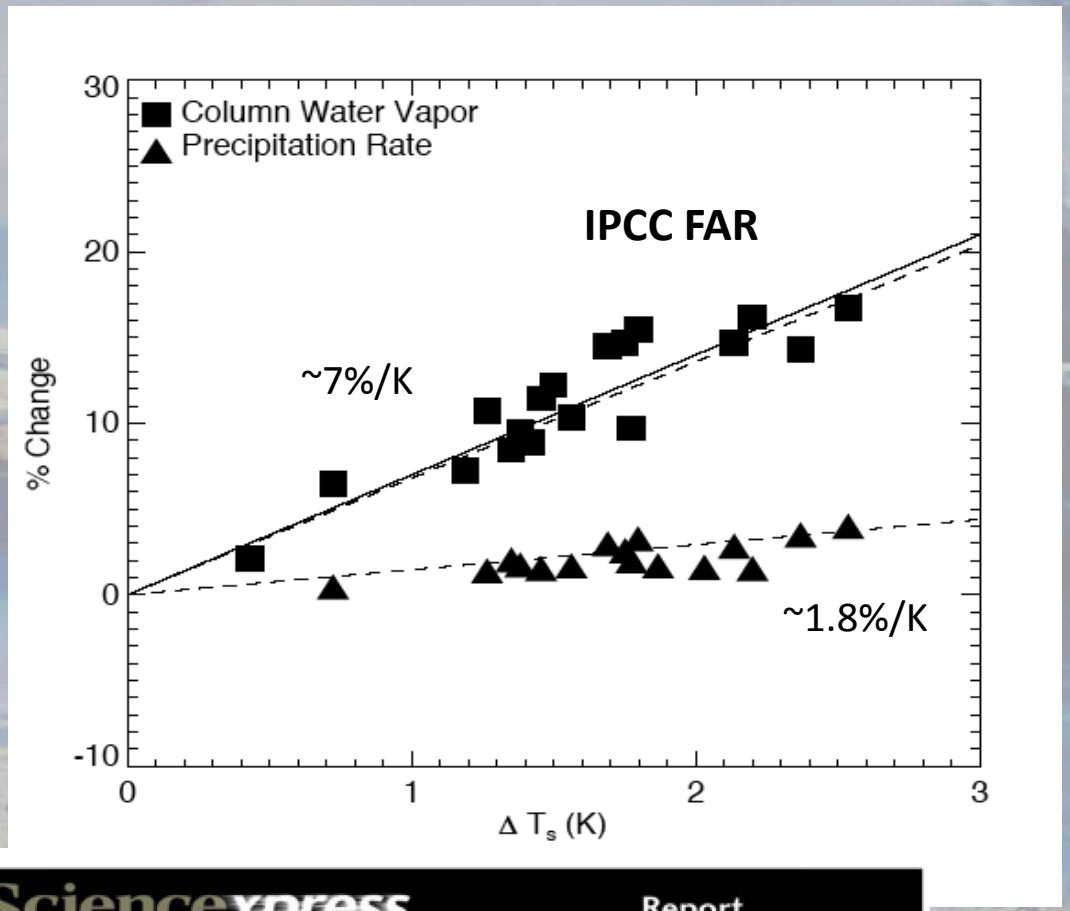
Do aerosol regulate the water cycle in any significant way?

***Conclusion of a National Security report on risks associated with changing climate.**

Outline: I will touch on aspects of predictability

- The Global-mean
- Regional scale
- Process level
- Challenges in modeling the water cycle

1) The global-average accumulation



E.g. Allen and Ingram, 2002
Stephens et al., 2009

Sciencexpress Report

How Much More Rain Will Global Warming Bring?

Frank J. Wentz,* Lucrezia Ricciardulli, Kyle Hilburn, Carl Mears

Simple expectations of water availability imply that the efficiency ~1
Why 2%/K ?????

The energy balance control

$$\Delta R_{net,atm} \approx L\Delta P$$

Suppose

$$\Delta R_{net,atm,clearsky} \approx L\Delta P$$

(ie neglect effects of clouds, change to sensible heating)

$$R_{net,atm,clearsky} \sim W^{b} \quad ;$$

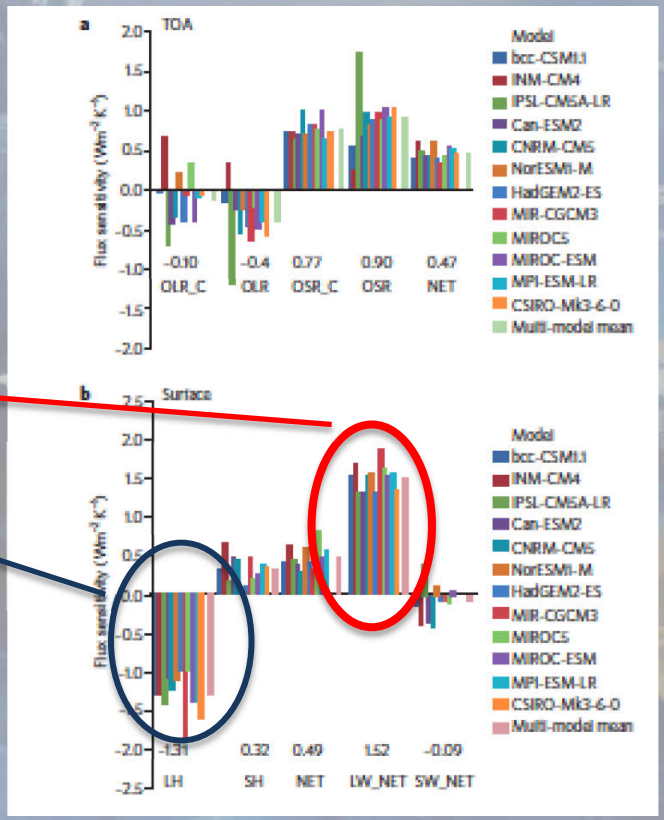
W = total column vapor

$b < 0.5$ ('curve of growth' effects)

$$\frac{\Delta R_{net,atm}}{R_{net,atm}} = b\frac{\Delta W}{W}$$

$$\boxed{\frac{\Delta P}{P} \sim b\frac{\Delta W}{W}}$$

Energy Flux Sensitivities CMIP5

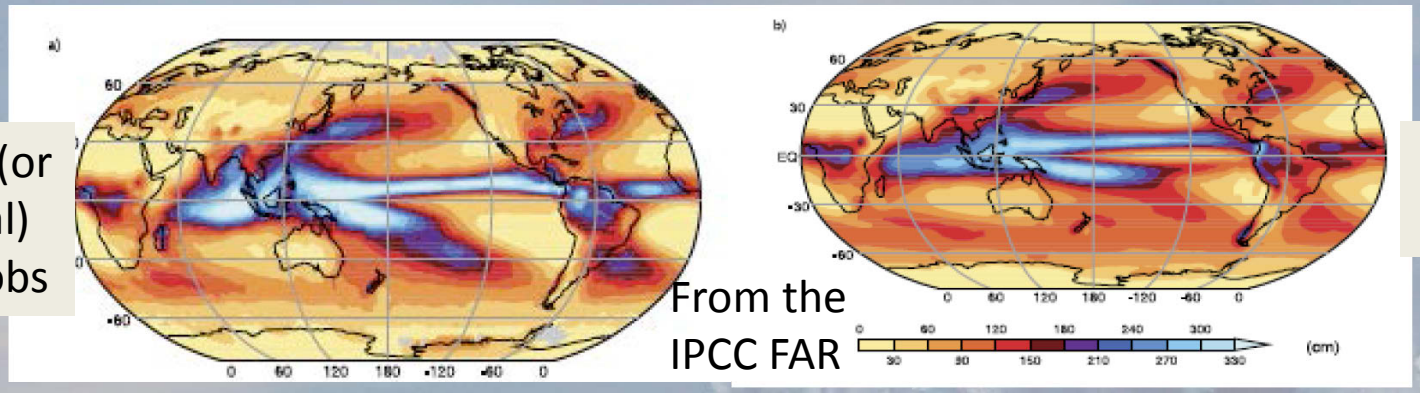


Are climate-related changes to the character of global-mean precipitation predictable?

Graeme L Stephens[1] and Yongxiang Hu[2]

Stephens & Hu, 2010 ERL

Annual (or seasonal) Precip obs



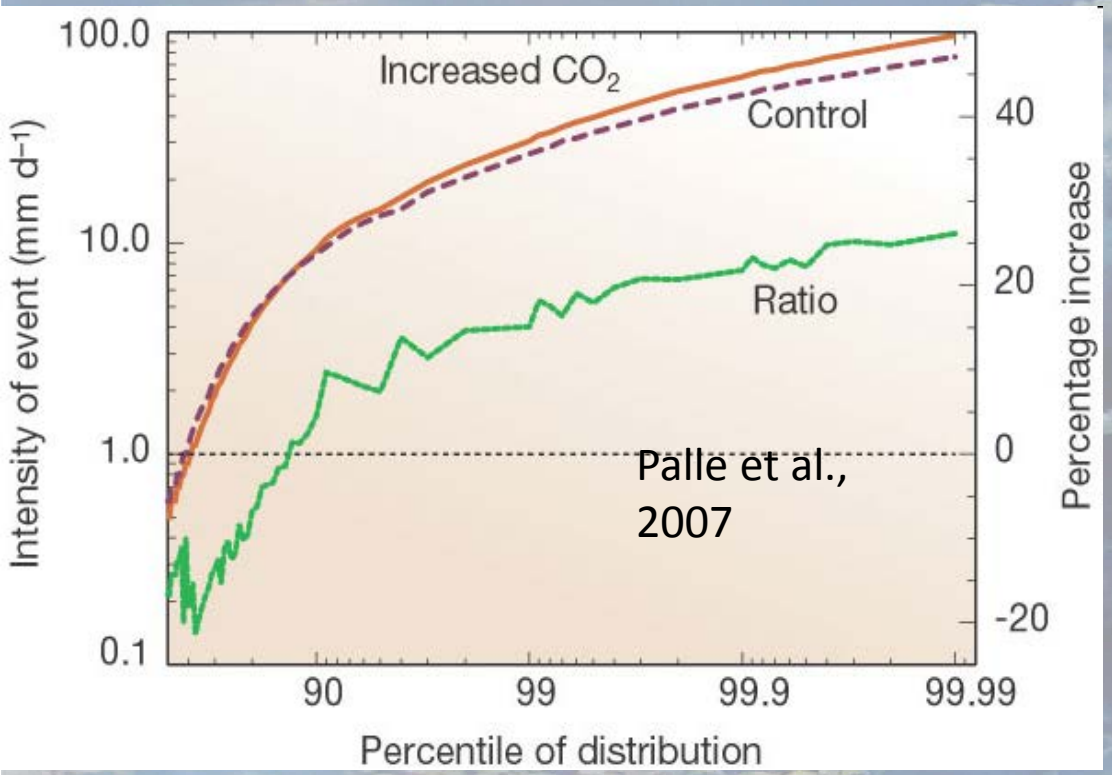
From the IPCC FAR

Model ensemble

In a climate modeling context, usually only **accumulation** is considered. But for many reasons

- The **frequency and duration** (how often) matters
- The **intensity** (the rate when it does rain) matters
- The **phase**: snow or rain also matters

accumulation over Δt = Σ freq of occurrence X intensity when raining



A model example - difference 2XCO2-1XCO2

GCM CO_2 vs Control

ΔT = 3.6K (2090s)

$\Delta P_{99.99}$ = 25%

$\Delta P_{99.99}$ / ΔT ~ 7%/K

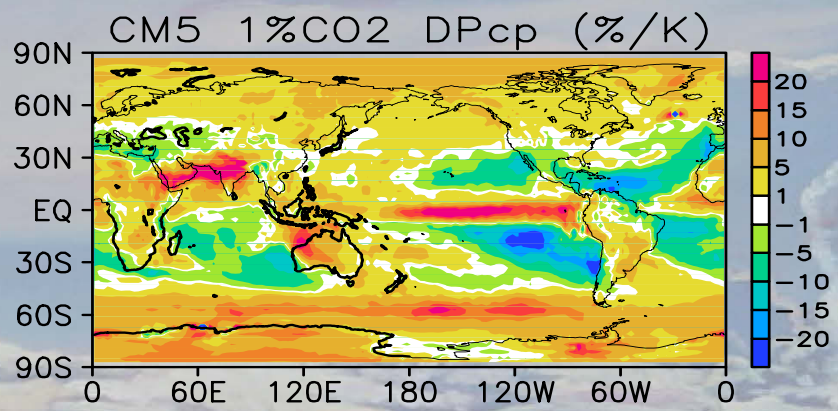
C-C

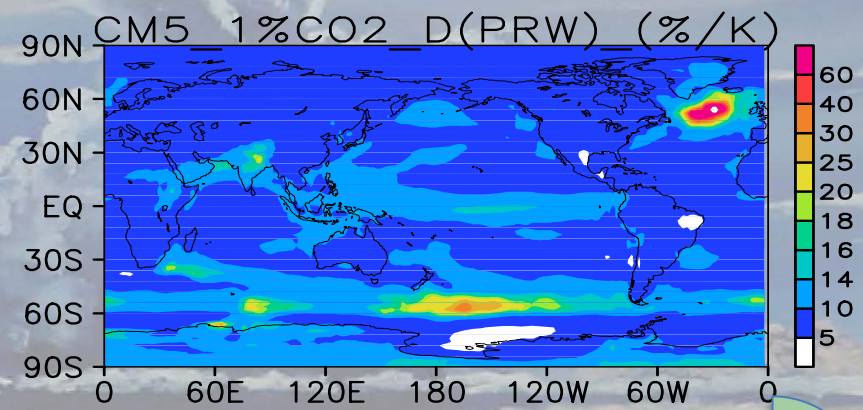
The pdf shifts from light to heavier rains that appear to follow the rate of change of water supply (7%/K) (in models).

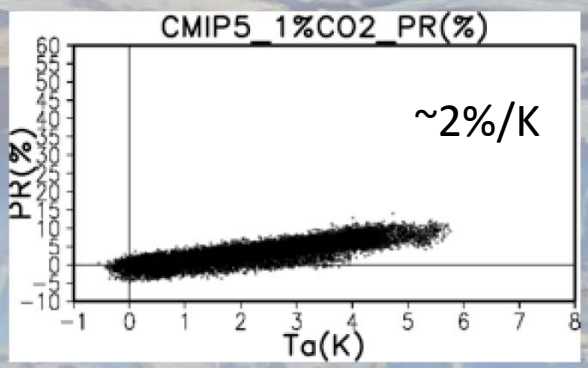
Summary: The predictability of Global means

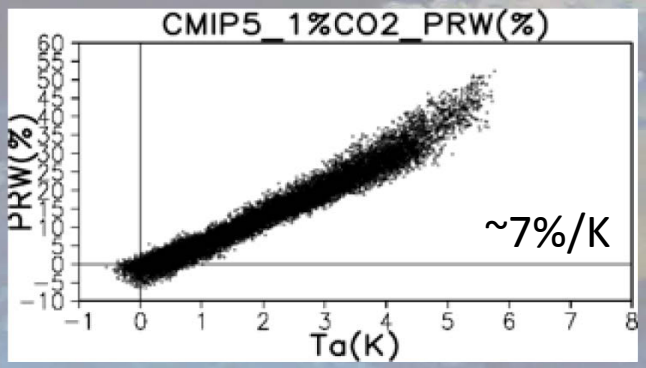
- Precipitation change is set by the change in total water vapor (W) and its effect on the energy balance. Projected changes are a direct a consequence of the water vapor feedback.
- To the extent that increased W is predictable (from C_C arguments), then the global increase of precipitation too is predictable.
- The pace of precipitation increase does not keep pace with the increased vapor (~2%/K versus 7%/K)
- The implication is the water re-cycle (Δtimescale ~ΔW/ΔP) slows. One way this slowing can occur is though reduced frequency of storms.
- Empirical evidence suggests that storms increase in intensity though increased water supply and a shift in the pdf occurs

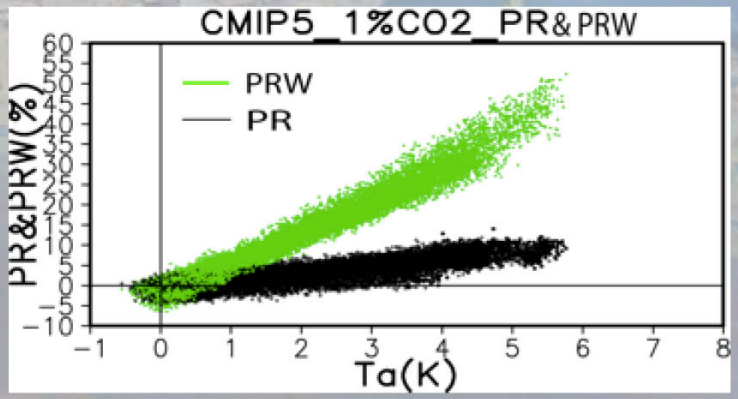
2) The global resolved scale - dynamics controlled, water supply dependent

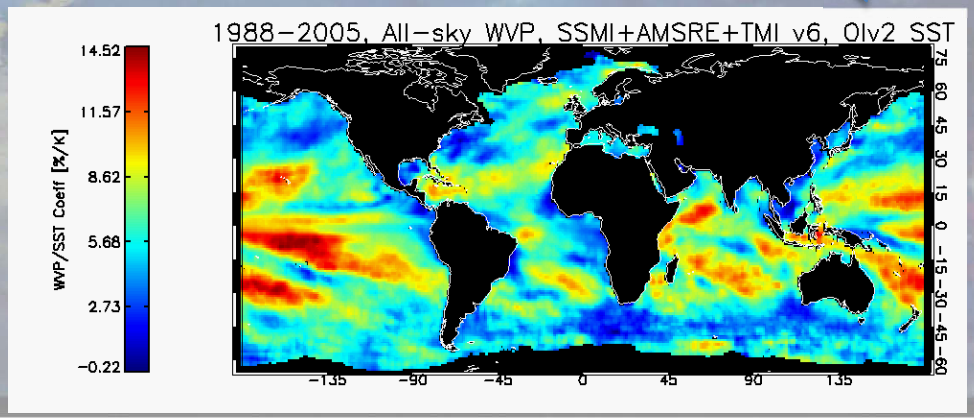




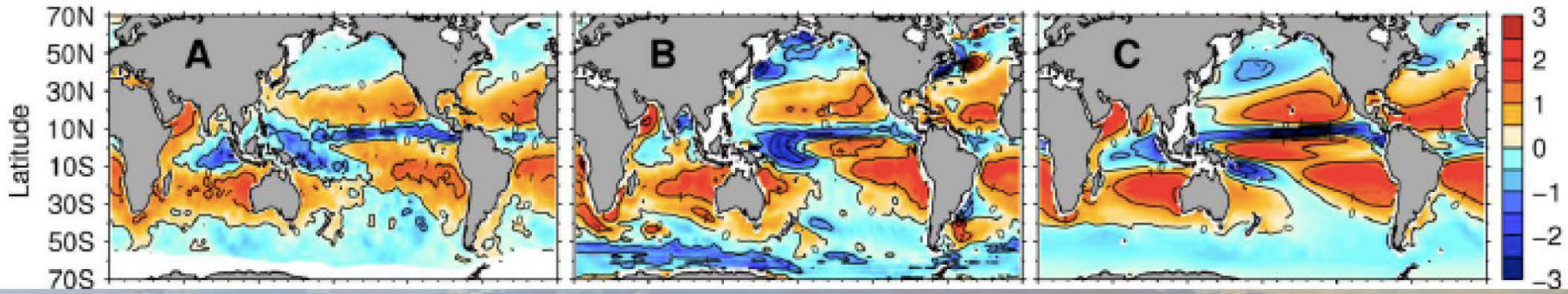








Changes in the saltiness of the oceans tells about how the water cycle is changing – the wet areas get wetter and the dry areas drier - we think this is also occurring over land



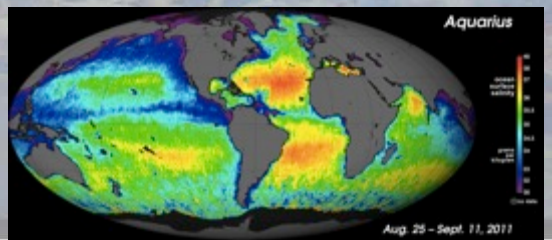
Durack et al. 2011
Change in Salinity over 50 years

Evaporation –minus precipitation

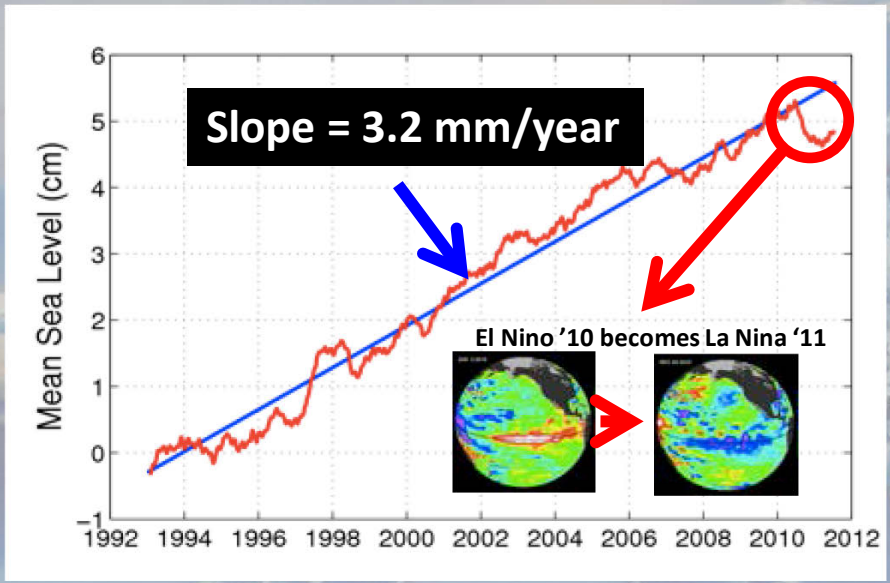
Salinity

These look a like

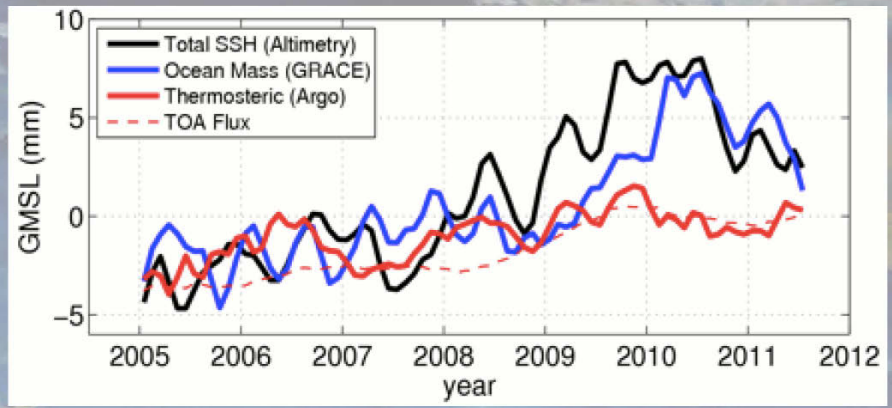
First global map of salinity from Aquarius, Launched in 2011

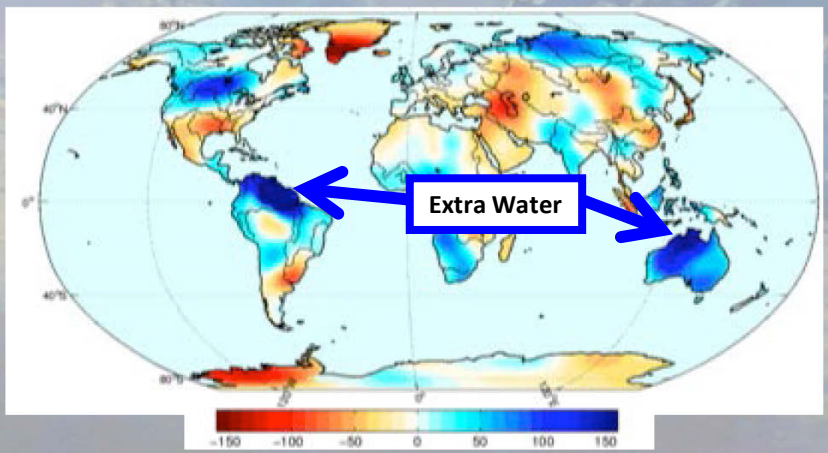


The imprint of system dynamics and moisture transport on regional changes to the terrestrial water balance



- Altimetry shows drop in global mean sea level.
- Significant part can be attributed to mass transport from ocean to land caused by La Nina.



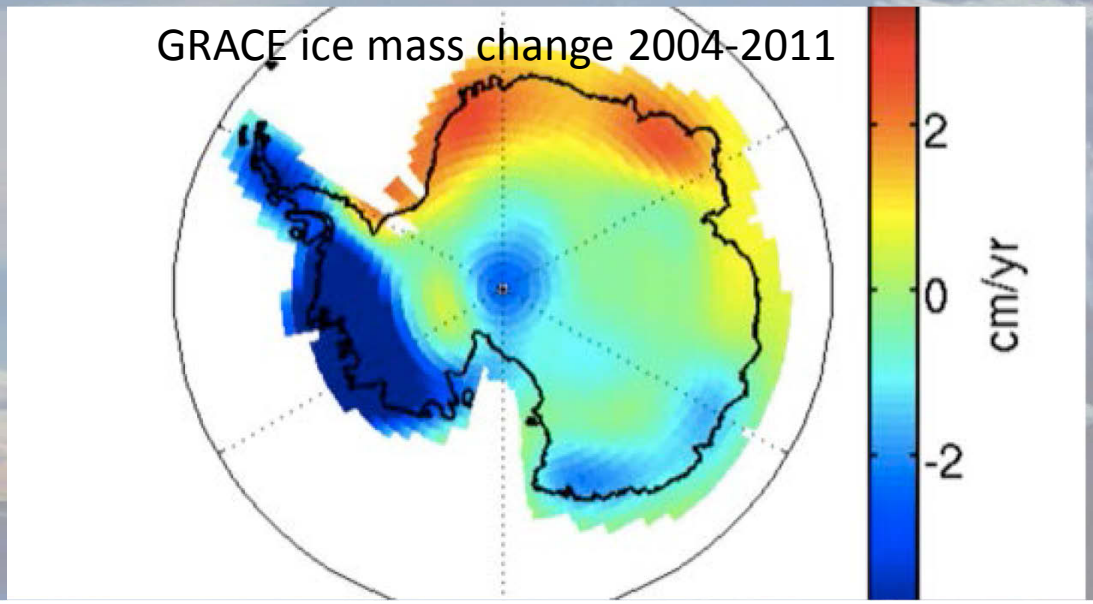


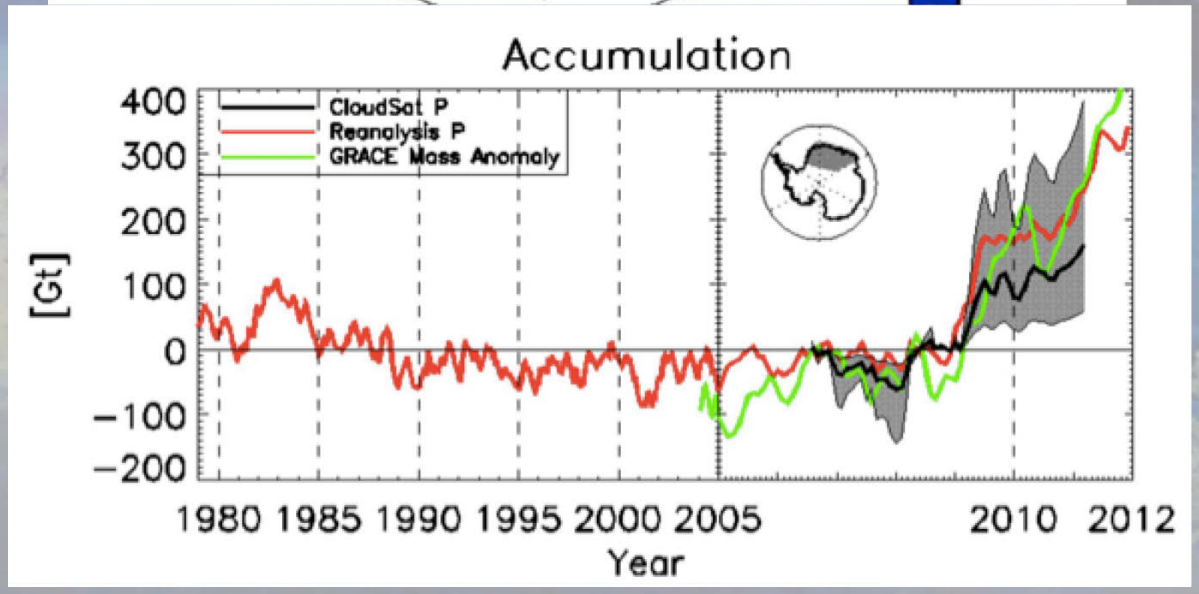
Mass in millimeter of water thickness

Evaporation Global Sea Level Drops 5 mm in 2010/11

Reference: Boening et al. (2012)

SNOWFALL – a real challenge to observe





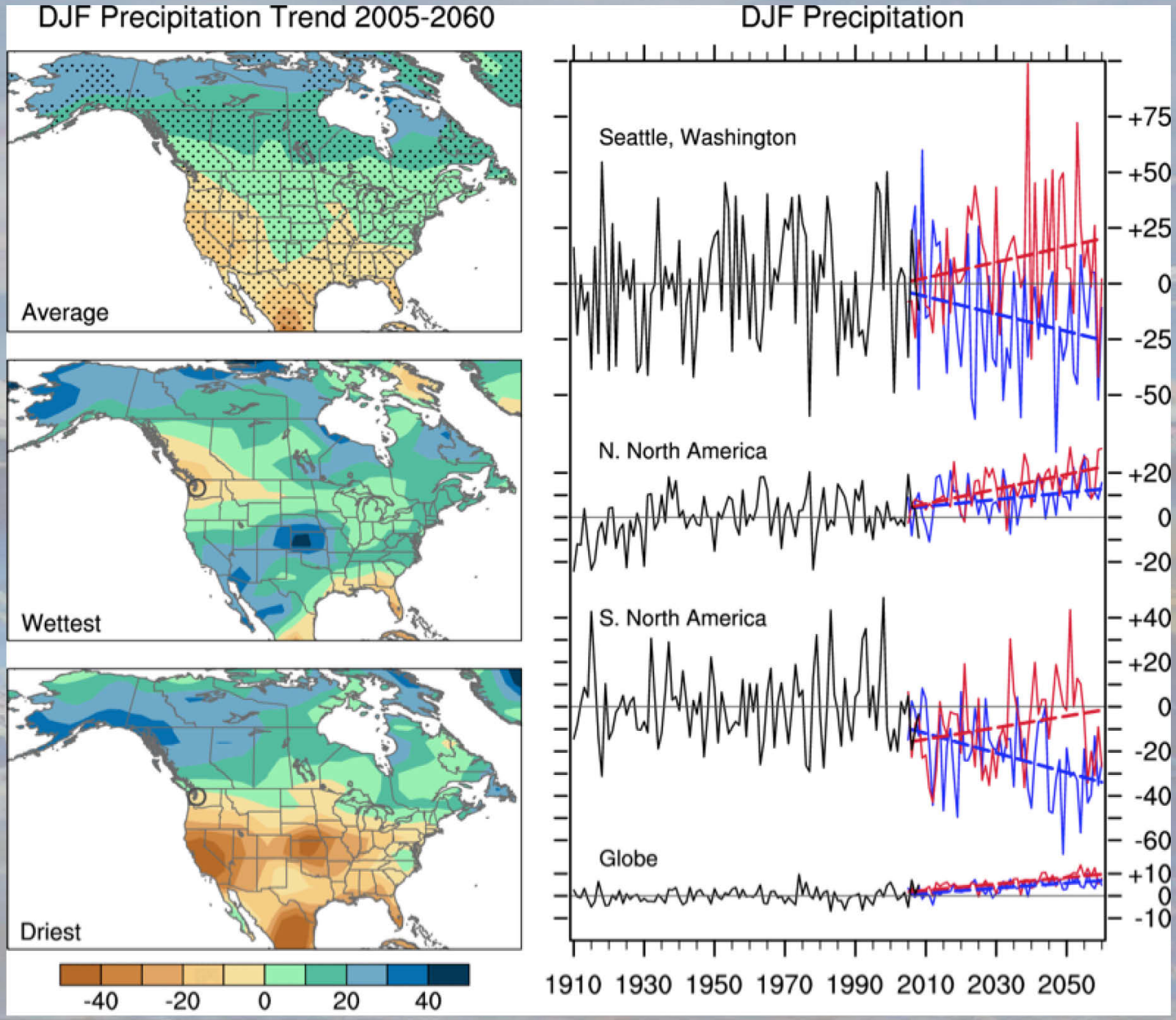
This mass increase is equivalent to about 10% of the annual sea level rise

The ice mass gain through snowfall is a consequence of the change in circulation and storm trajectory in 2009/2010

Boening et al., 2012; GRL

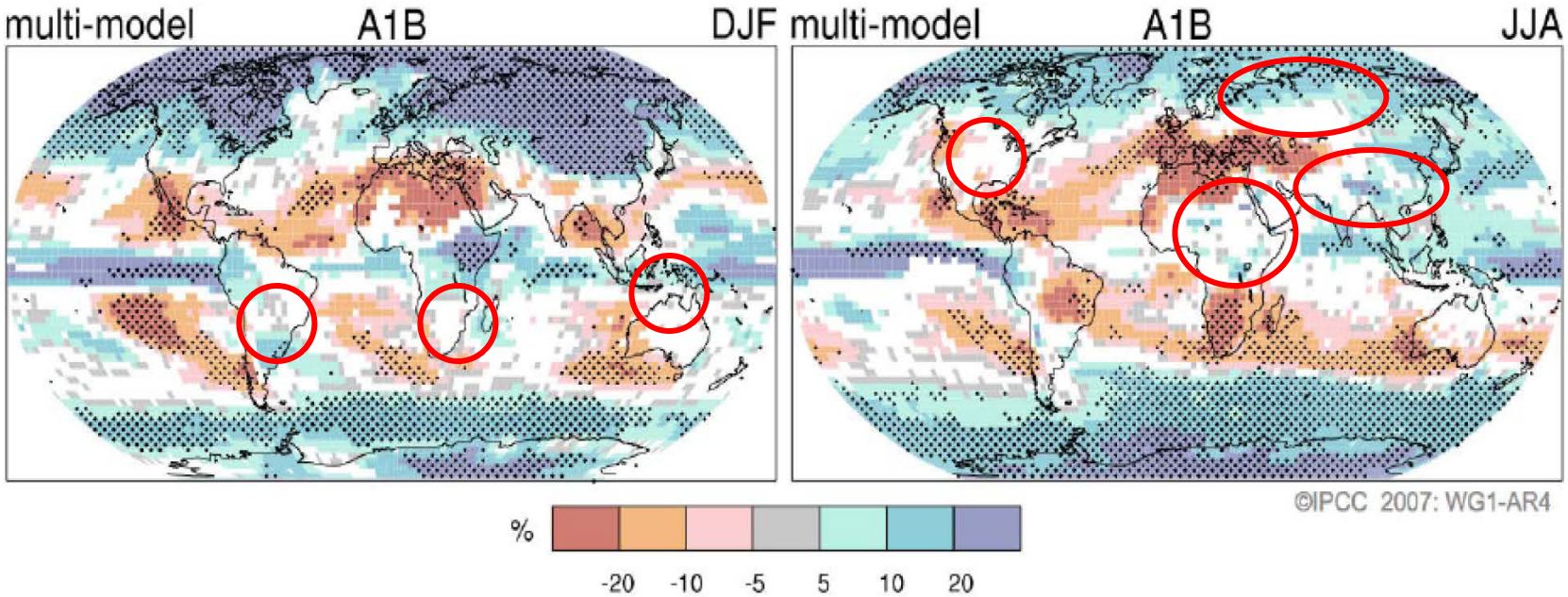
The Challenges of Precipitation over land Land

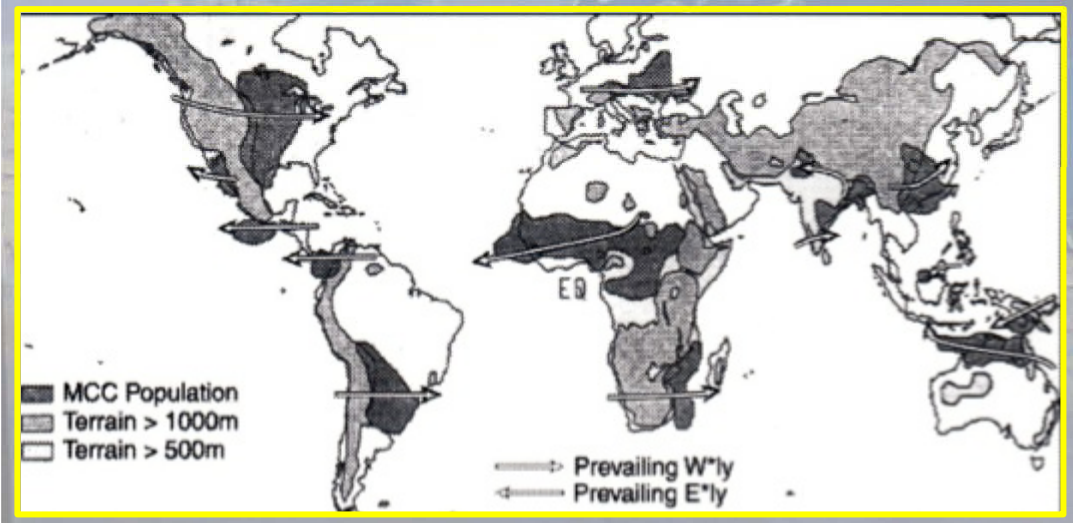
- Over **land in summer** and over **tropical continents**, the strong negative correlations between temperature and precipitation suggest factors other than C-C are critical: advection **of moisture is critical**.
- There is a strong diurnal cycle (that is not well simulated by most models).
- In these regimes, convection is a dominant role
- Recycling is more important in summer and advection of moisture from afar is less likely to occur????
- Monsoons play a key role where active.



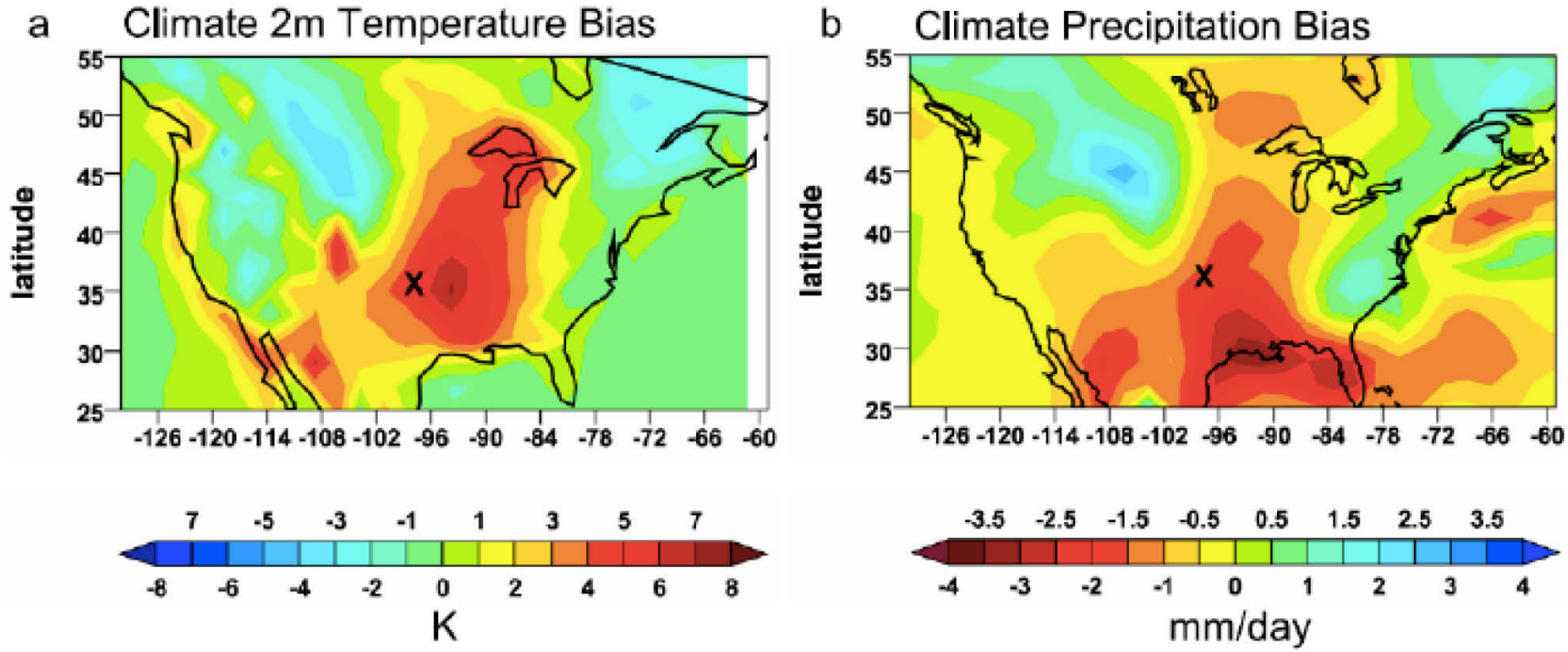
Deser et al., 2012

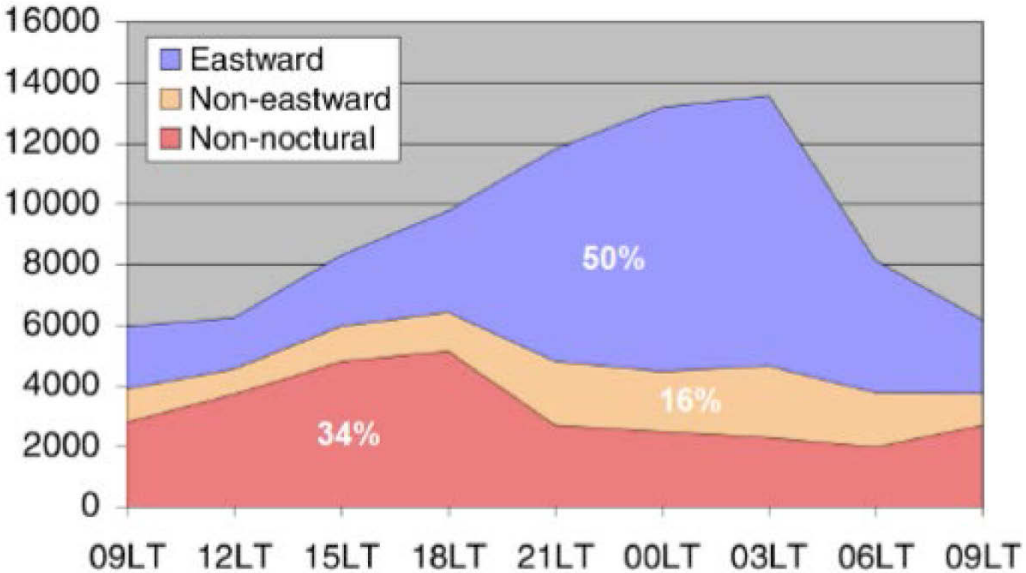
Projected Patterns of Precipitation Changes





MCCs occur downstream of mountains worldwide …





The conjecture is the biases are a consequence of lack of organized convective storms that originate over the Rockies and propagate eastward.

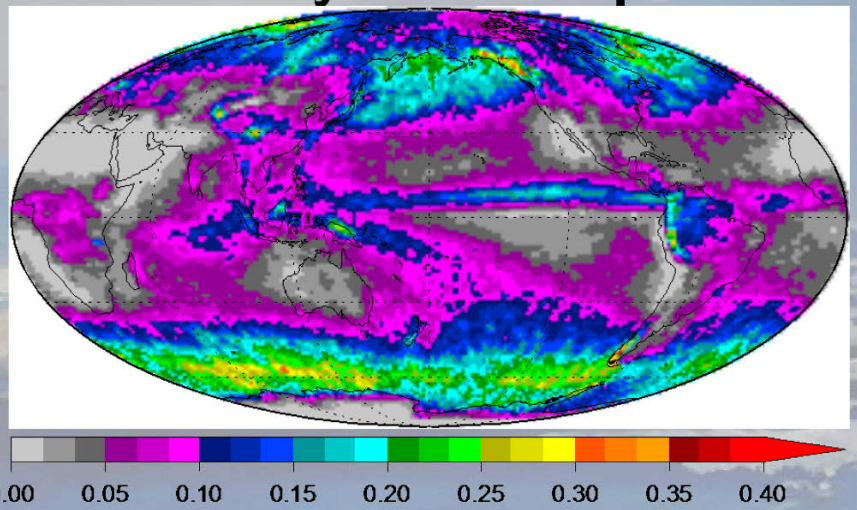
Summary –

We do not know how much of the water cycle is predictable on the regional scale:

- The predictability of regional scale changes of precipitation in part(but not entirely) is determined by the predictability of circulation changes.
- Precipitation over land, and especially in summer season remains a challenge with major storm types (eg MCCs) missing from current ES models
- Details of both the global and especially regional changes are strongly influenced by model resolution

3) Process level

Probability of Precipitation

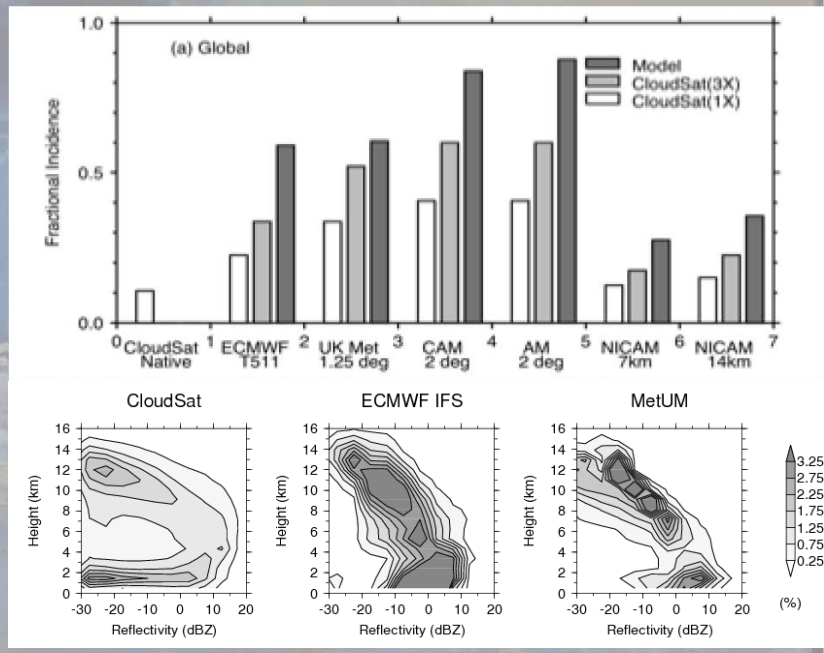


We now have definitve information about the global occurrence of precipitation (CloudSat)

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D24211, doi:10.1029/2010JD014532, 2010

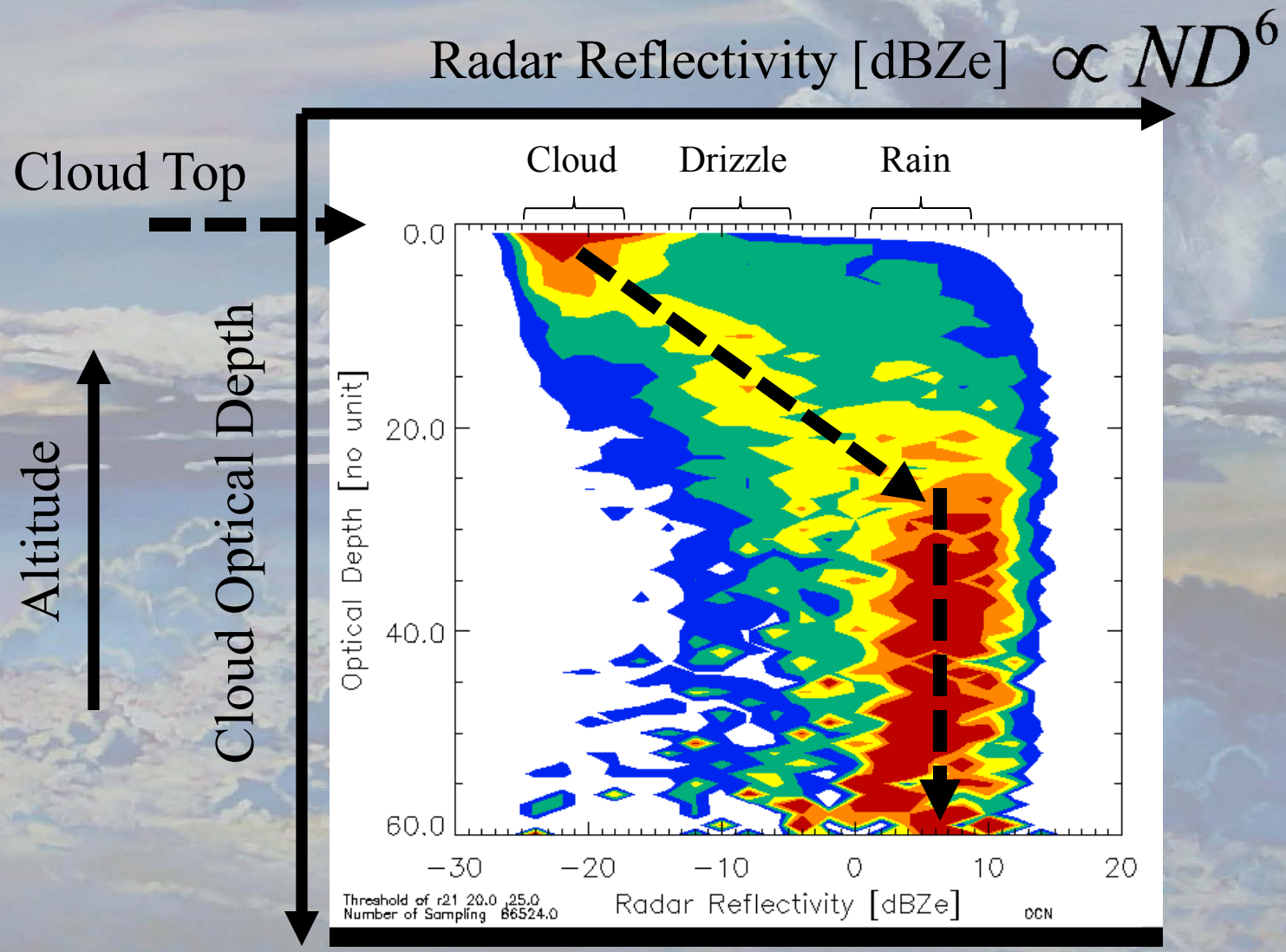
Dreary state of precipitation in global models

Graeme L. Stephens,[1] Tristan L'Ecuyer,[1] Richard Forbes,[2] Andrew Gettlemen,[3] Jean-Christophe Golaz,[4] Alejandro Bodas-Salcedo,[5] Kentaroh Suzuki,[1] Philip Gabriel,[1] and John Haynes[6]



Constrained accumulation over Δt raining = Σ freq of occurrence X Too frequent intensity when Too light

Global observations of the transition from cloud to precipitation



Nakajima et al. (2010)

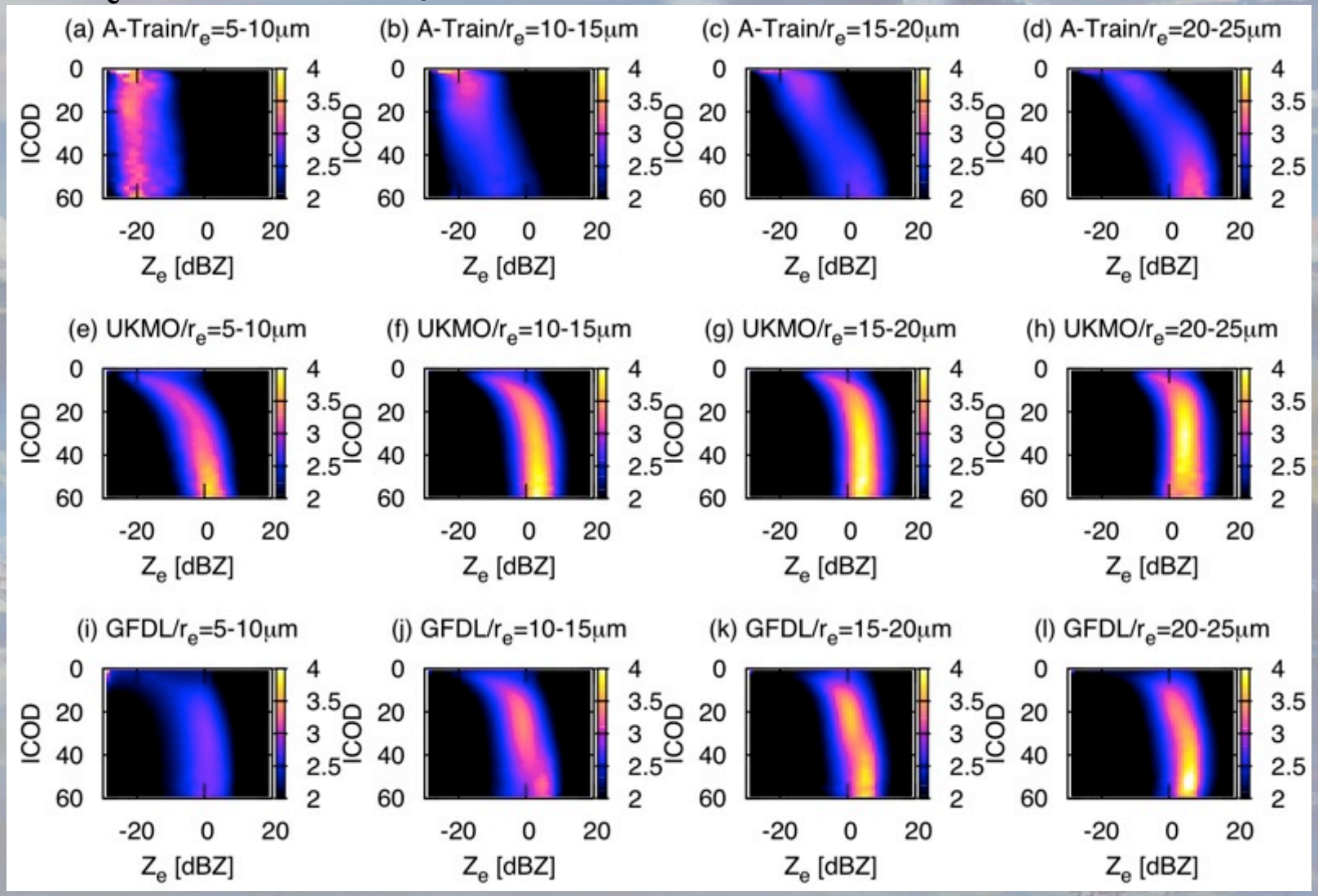
An assessment of the warm rain process in global ES models

R_e=5-10mm R_e=10-15mm R_e=15- R_e=20-25mm

A-Train

UKMO

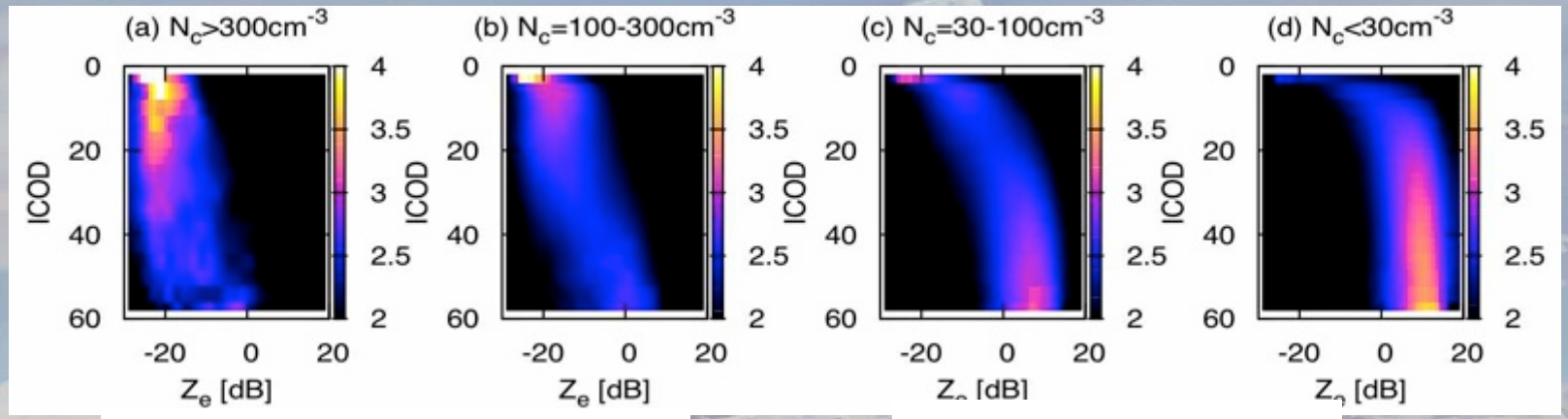
GFDL



Suzuki et al, 2012

And observations can now conrain the parameterizations

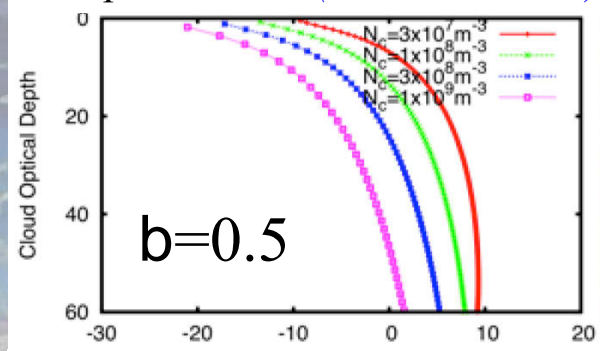
A-Train



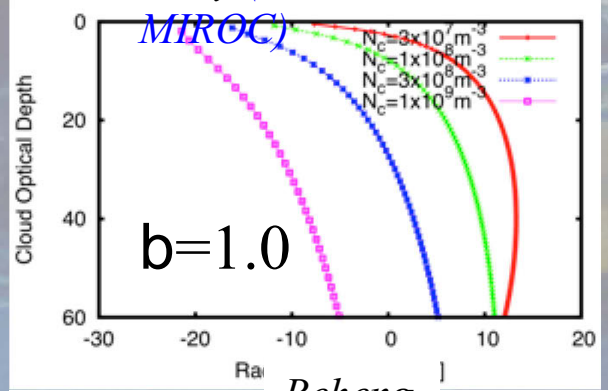
SCM

$$\tau_{aut} \propto N_c^b$$

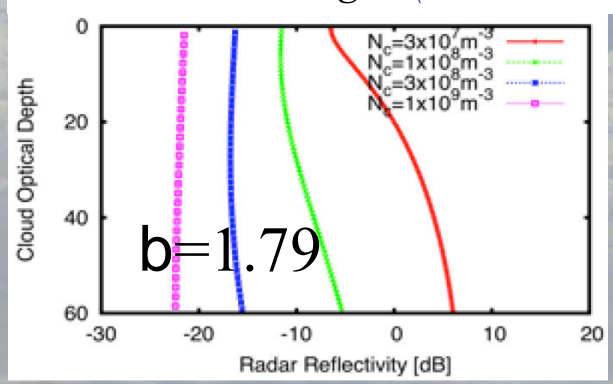
Tripoli-Cotton (UKMO, GFDL)



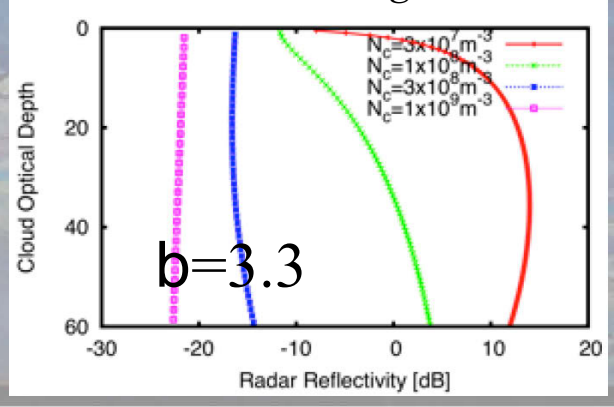
Berry (NICAM, MIROC)



Khairoutdinov-Kogan (PNNL/MMF)

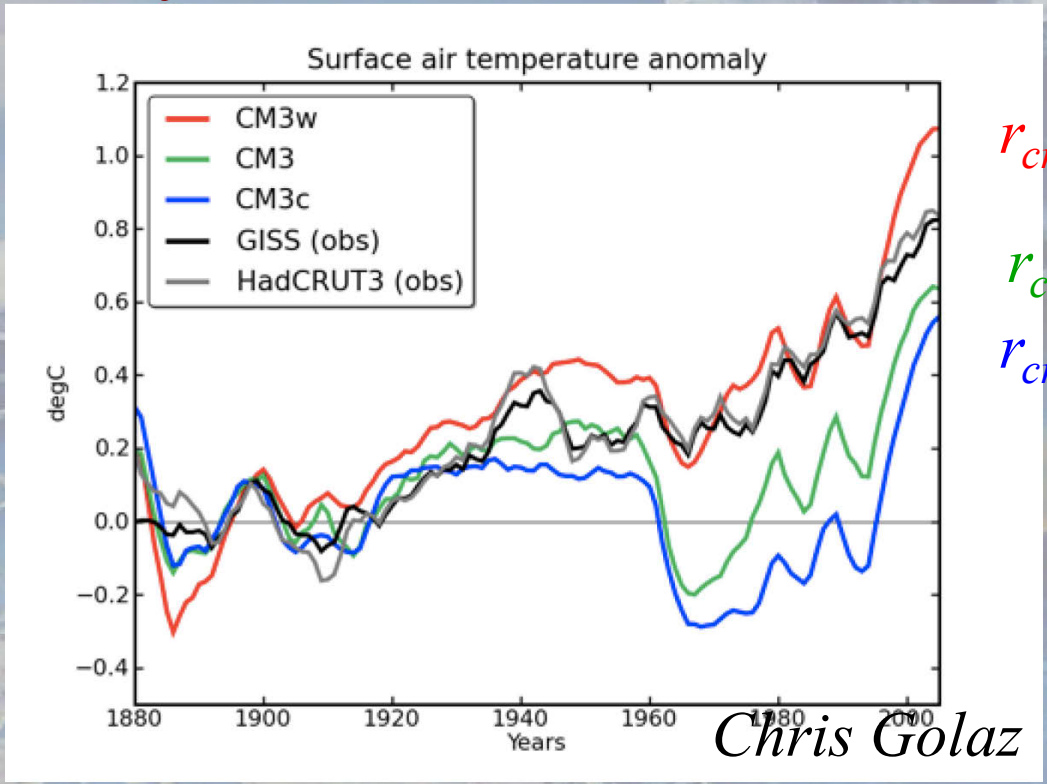


Beheng



Light rain matters –it affects the water balance of clouds, their albedo and how aerosol modulate these properties. This has a BIG effect on projected warmings with all the knock-on effects to the global water cycle

GFDL
CM3

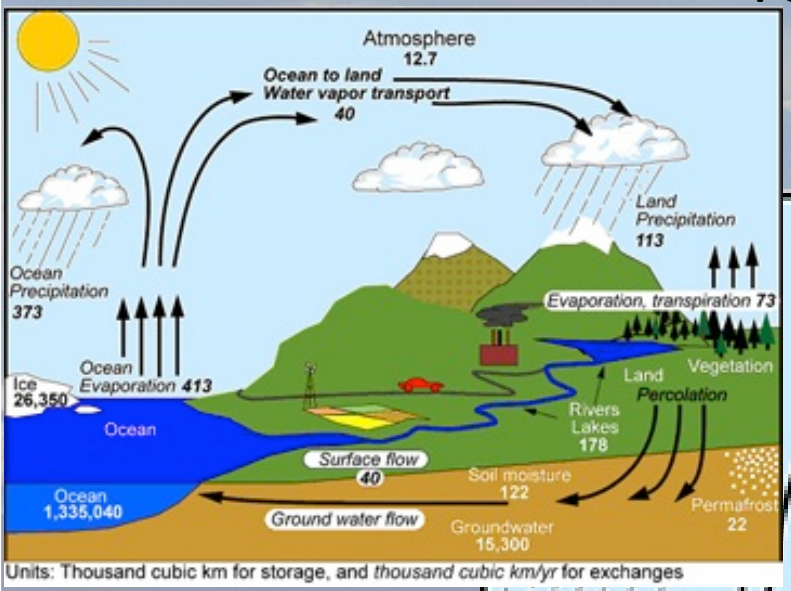


r_{crit}=6mm

r_{crit}=8.2mm

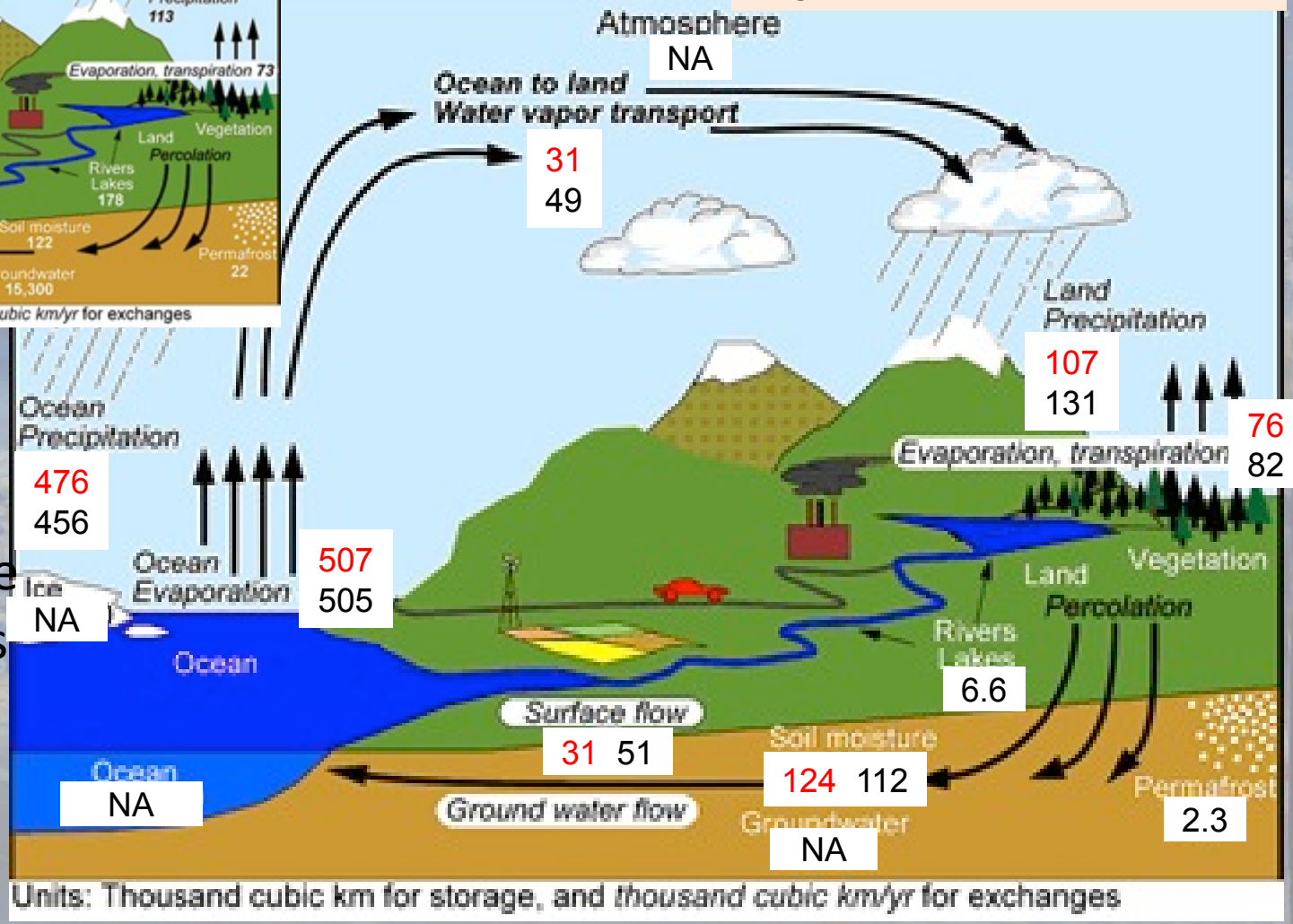
r_{crit}=10.6um

Key Challenges –pushing model resolution toward resolving what matters



Trenberth et al, 2007

State-of-the-art AGCM at:
Low-resolution N48
High-resolution N216

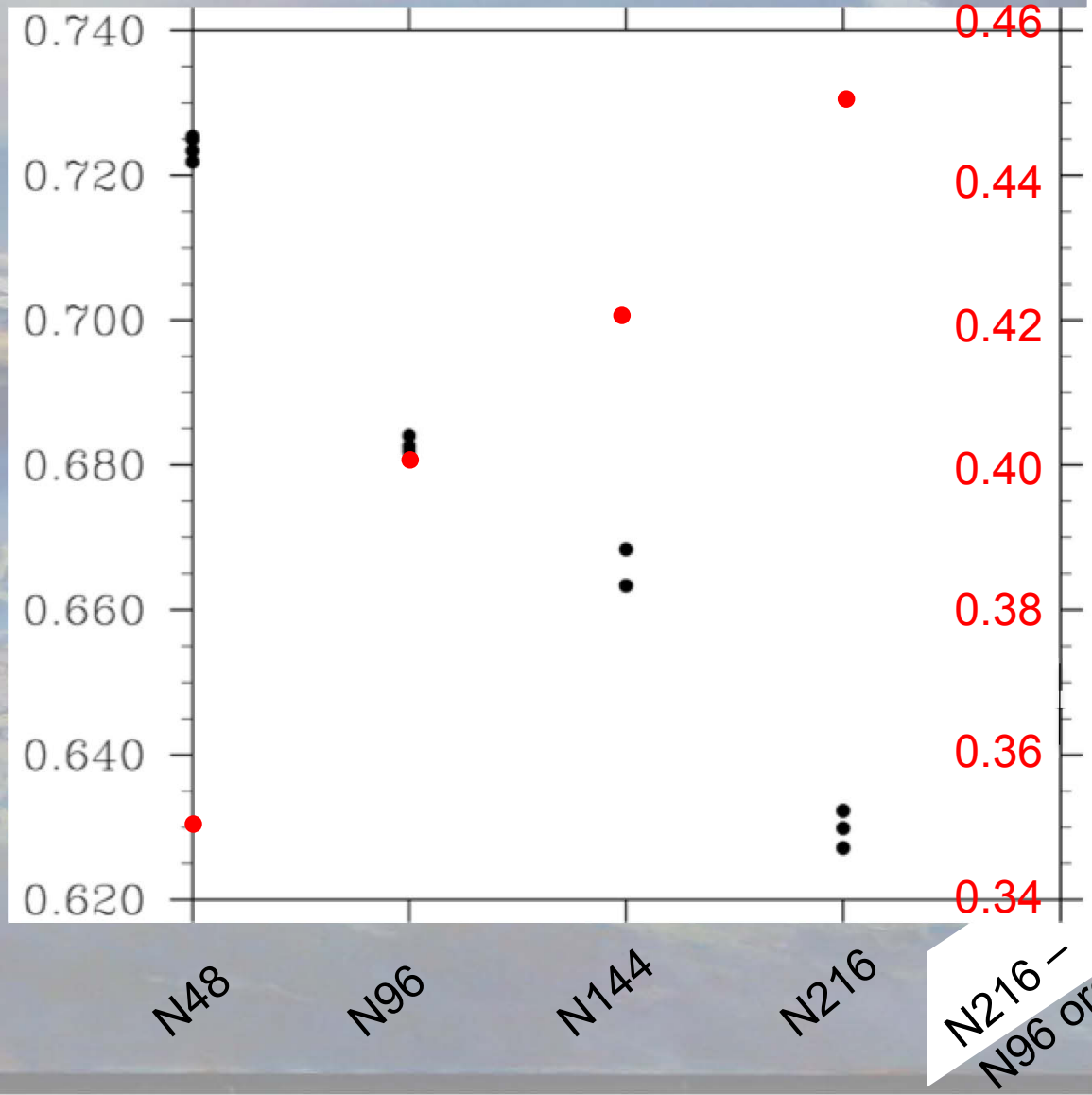


On the global scale resolution matters

Demory et al. 2012

M.-E. Demory

Evaporation to precipitation ratio over land



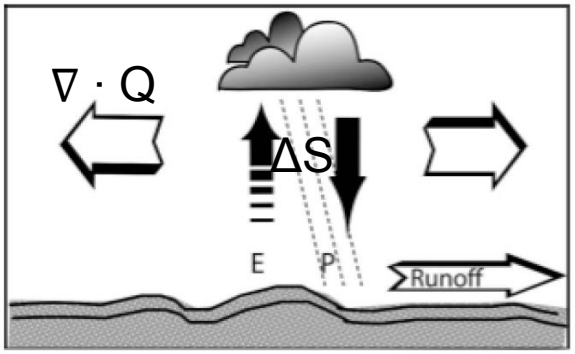


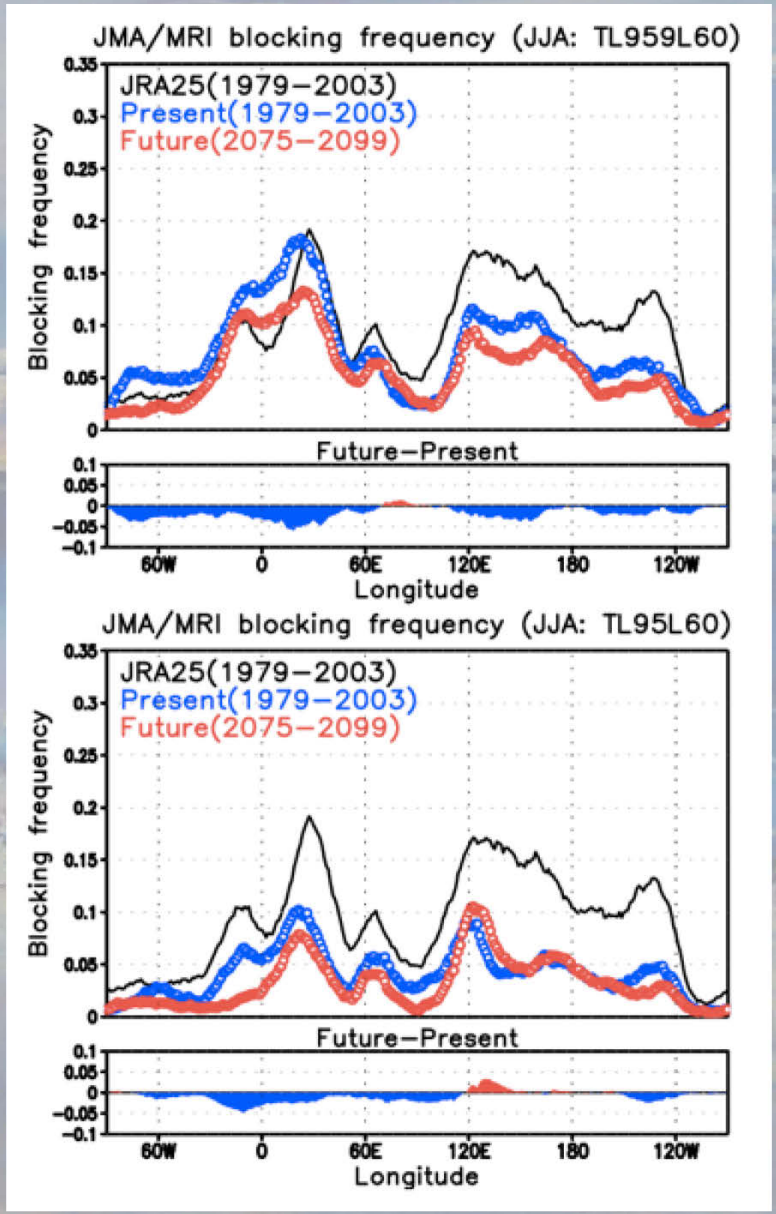
FIG. 2. Schematic of the local atmospheric water balance. The large arrows indicate atmospheric moisture divergence, which is mostly compensated for by evapotranspiration E and precipitation P, as changes in atmospheric moisture storage are small. At the surface $E - P$ is balanced by surface and subsurface runoff, and changes in soil moisture and groundwater.

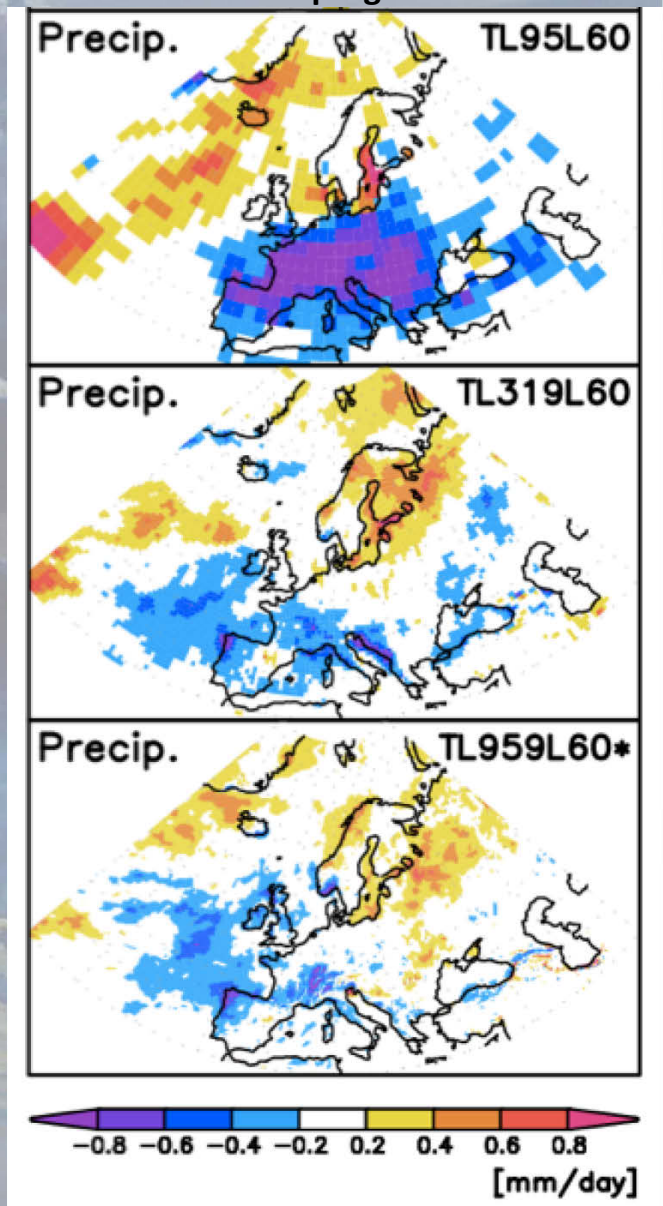
Trenberth et al., 2007

$\frac{-\nabla \cdot Q}{P}$ ERA-interim

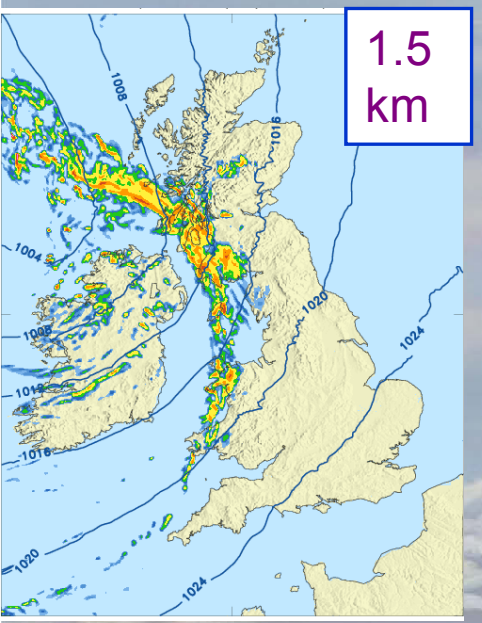
...and on the regional scale

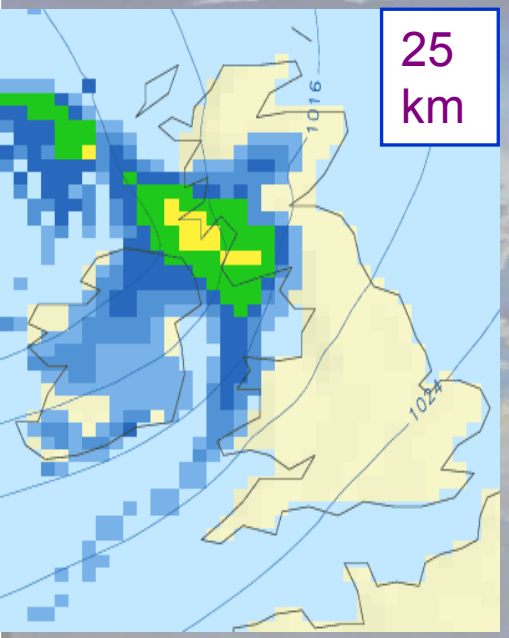
Timeslice estimates of climate change at T95 (180km), T319 (60km) and T959 (20km) – Matsueda and Palmer work in progress

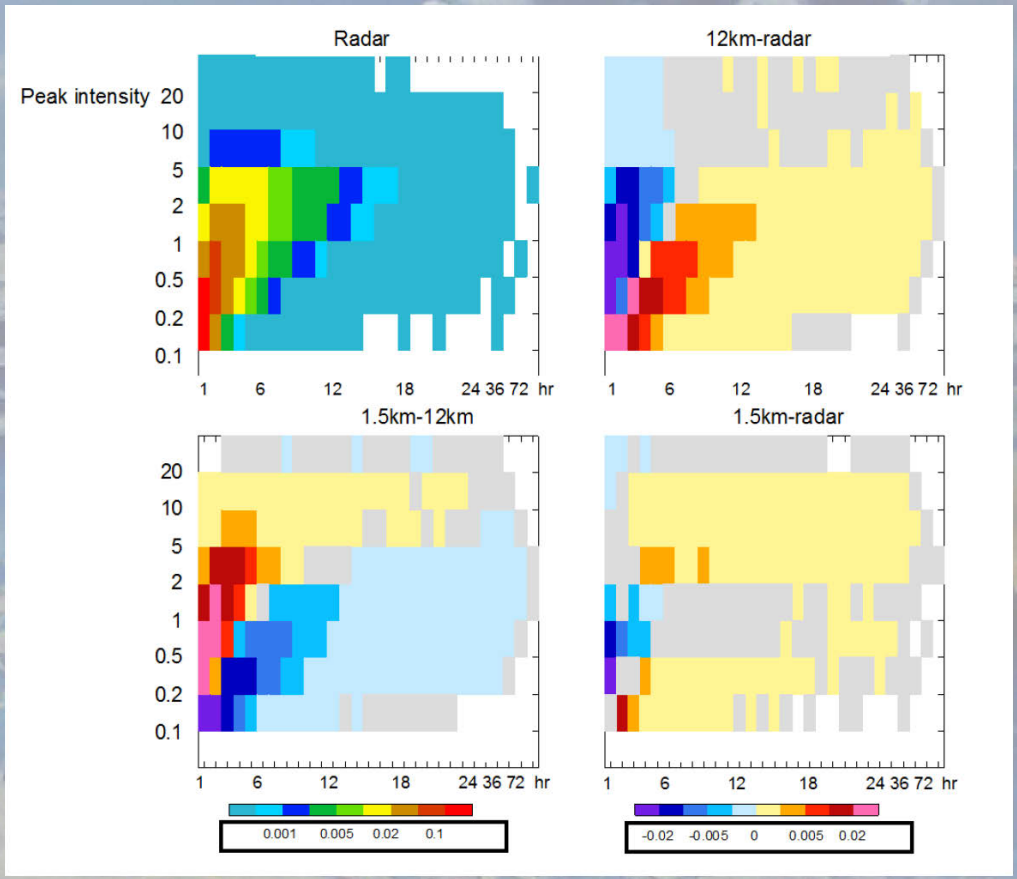




..and to the processes themselves







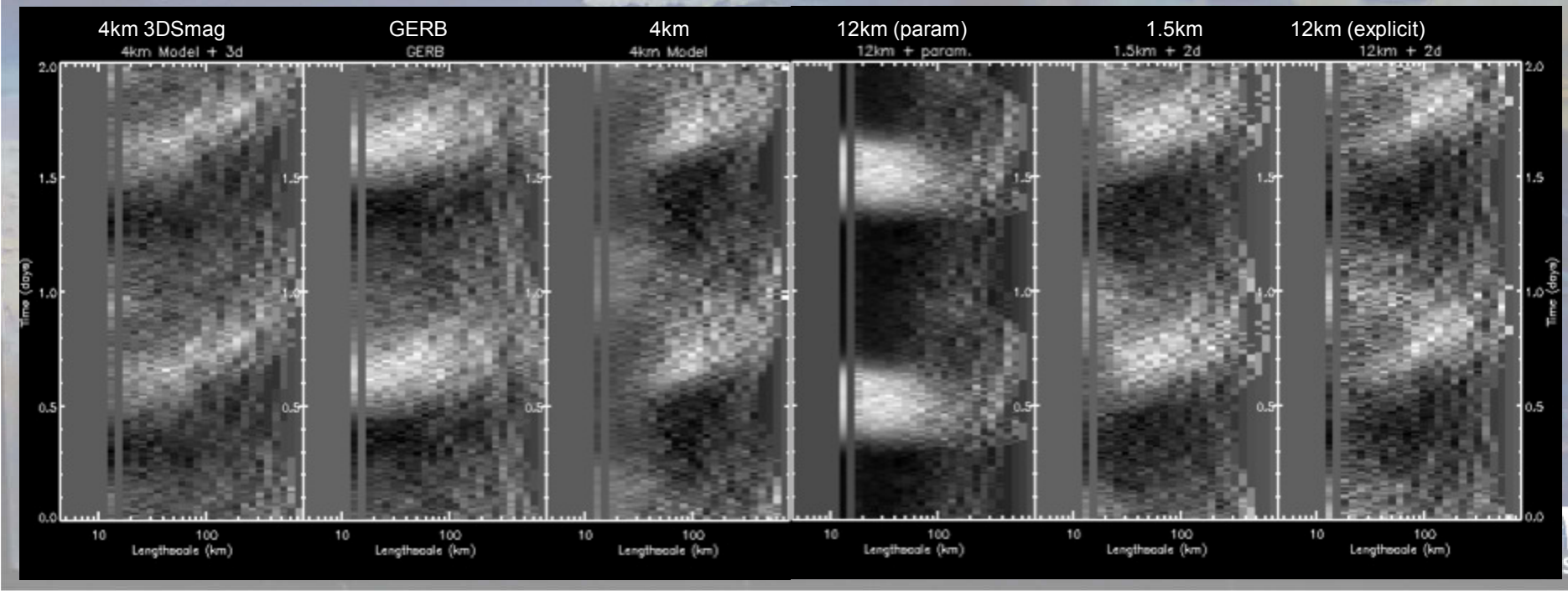
The character (spatial structure, frequency and intensity of precipitation) is dramatically improved when convection is explicitly 'resolved'

Cascade

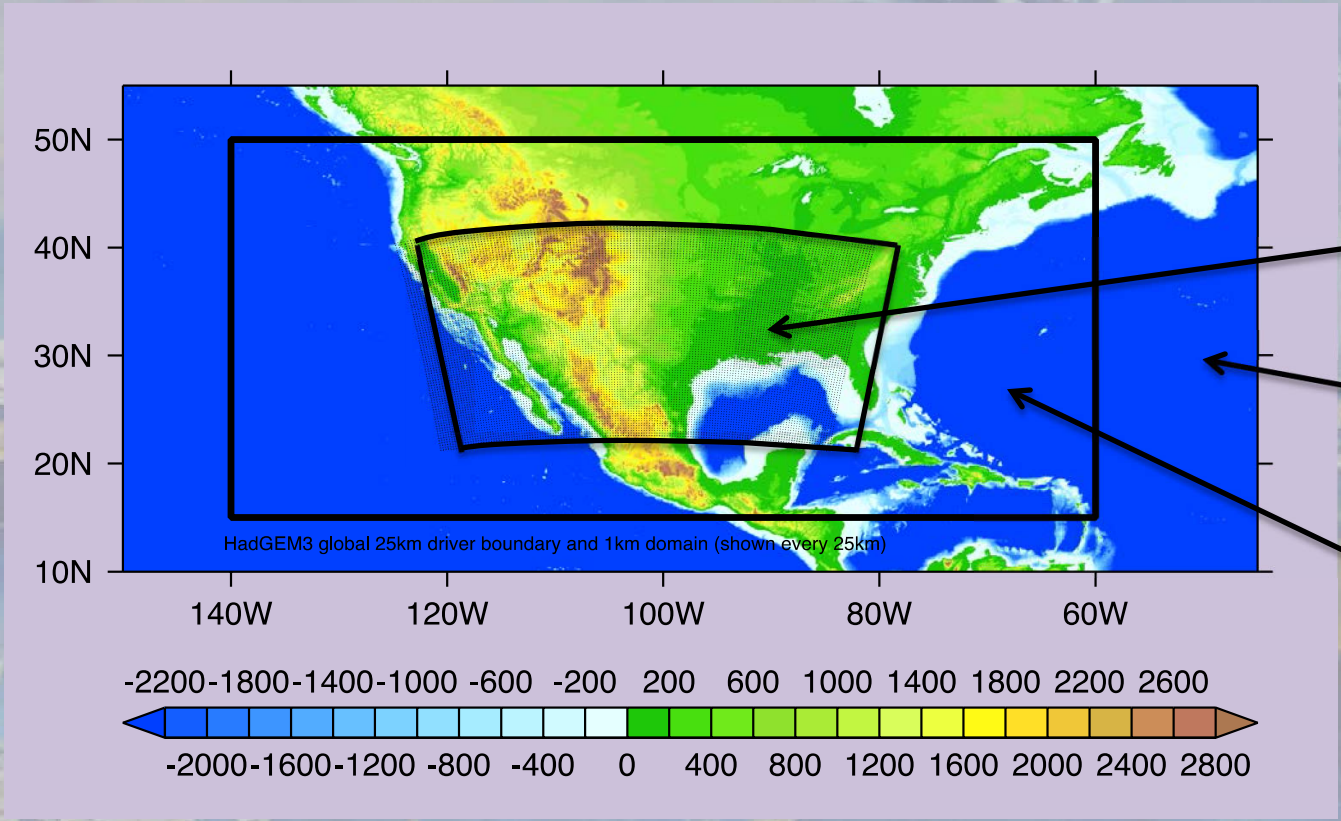
The diurnal cycle over West Africa (Pearson, Dixon and Parker)

Diurnal Cycle in Frequency of High Cloud (<150Wm^{-2}) as a function of size (Area^{½})

- Observations show clouds growing in length scale during day with small clouds peaking in early afternoon and big clouds peaking in the late evening through to early morning for very largest clouds
- 12km model with paramterized convection shows all lengthscales peaking at roughly the same time except vey largest clouds which peak in early evening
- Models with explicit convection capture the growth of the clouds during the day and have timing of diurnal cycle OK
- Maximum in small clouds in explicit runs occurs erroneously around midnight due to unrealistic fragmentation of cirrus clouds, which can partly be ameliorated by changing in the vertical mixing scheme



New initiatives – 3 way partnership (JPL,UT& UKMO): High resolution Climate modeling RESOLVE)



1.5 km, annual Within the 2000 – 2010 decade

25 km global, coupled 50 year integration 1960-2010

4km, decadal (2000-2010)

The focus is a systematic exploration of the dependence of the terrestrial water processes on model resolution:

- Convection and storms (ARs, MCCs, TCs,…)
- Model biases in seasonal temperature/precipitation
- Hydrological applications/droughts/floods

Summary

Global-mean precipitation - controlled by energy balance and quantifiable consequence of the water vapor feedback within the system. Predictability on this scale rests on the degree to which the water vapor feedback is predictable

Regional scale - to a significant extent these changes are shaped by atmospheric circulation changes but we do not know the extent to which regional scale changes are predictable. The impacts of changes to atmospheric circulation on regional scale watercycle changes can be dramatic.

Process-scale - significant biases to the CHARACTER of precipitation (the intrinsic dreariness of models) is related to how the precipitation process is parameterized in models. This model dreariness also affects the way aerosol influence clouds and thus affects the forcing of the climate system.

We still do not know the extent to which the water cycle is influenced by aerosol but anecdotal evidence is building

Observations- we still have a way to go and need to approach the problem in a more integrated way (tie clouds, aerosol and preciptation and then link to soil moisture, etc) - globally our capabilities lag behind the science and model development