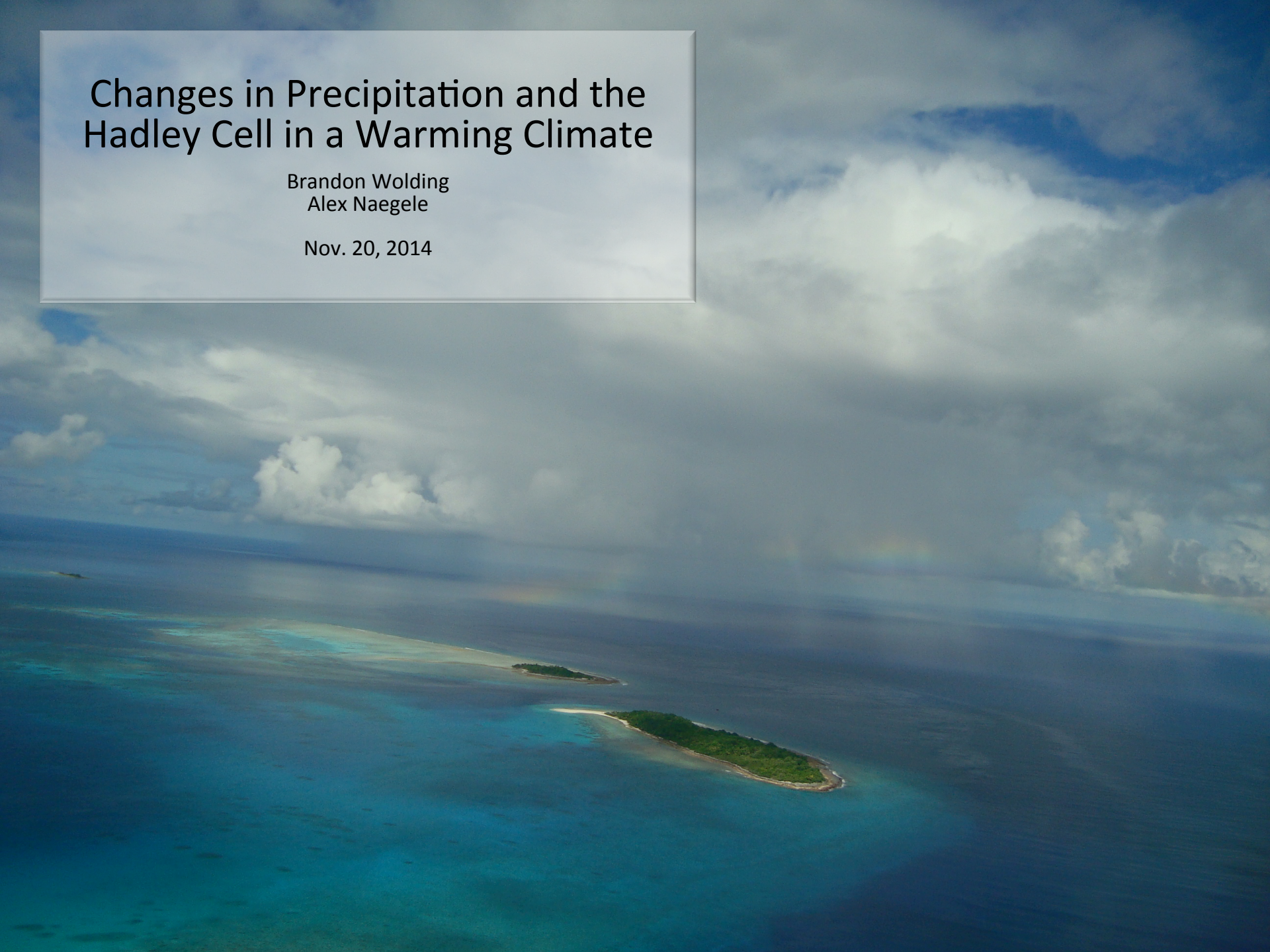
Changes in Precipitation and the Hadley Cell in a Warming Climate

Brandon Wolding
Alex Naegele

Nov. 20, 2014



GEOPHYSICAL RESEARCH LETTERS, VOL. 39, L18704, doi:10.1029/2012GL052910, 2012

Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones

Jack Scheff[1] and Dargan M. W. Frierson[1]

Received 28 June 2012; revised 8 August 2012; accepted 10 August 2012; published 21 September 2012.

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[4] Meanwhile, a number of studies [e.g., *Yin*, 2005; *Lorenz and DeWeaver*, 2007; *Lu et al.*, 2007; *Previdi and Liepert*, 2007; *Frederiksen et al.*, 2011] noted that in almost every CMIP3 model, the midlatitude storm tracks, baroclinic zones, and jets shift poleward with 21st-century greenhouse warming, and the subtropical dry zones and descending Hadley-Ferrel branches expand poleward in their wake. In contrast to the above mechanism, this less well understood dynamical response should mainly act to reduce P poleward of the subtropical P minima (potentially including wet regions as well as dry), and not on the dry margins of the tropical wet belt.

[5] In *Scheff and Frierson* [2012] (hereinafter SF12), the present authors showed that the robust future P reductions in the CMIP3 model subtropics are almost entirely located in midlatitude-driven P poleward of the model P minima, suggesting that their main cause is this poleward expansion of the dry zones, and not the thermodynamic "dry-get-drier" mechanism described above. In the present study, we extend the SF12 methods and results to 36 new models in the CMIP phase 5 multimodel archive [*Taylor et al.*, 2012] (listed in Table 1), further clarify the seasonal, hemispheric and regional variation in the results, and note some of the few differences between CMIP5 and CMIP3.

2. Results

2.1. All Models on the Same Grid

[6] Figure 1 depicts, for each point on a common ¼ × ¼ degree grid, the multimodel statistics of the 21st-century (1980–2099) trends of seasonal P in the native model gridboxes containing that point. All trends and significances are defined as in SF12, but using the CMIP5 scenarios "historical" and "rcp8.5". As shown in the legend, bold blue colors mean that almost all 36 CMIP5 models in Table 1 significantly increase P, bold red colors mean that almost all models significantly decrease P, and very light or white colors mean that few or no models have a significant trend in P. In contrast, pastel (and/or purple) hues represent disagreement within CMIP5 on the presence (and/or sign) of a significant model-gridbox-scale P response. The multimodel-mean late 20th-century (1980–1999) P climatology (computed as in SF12) is plotted as a reference, with thicker black contours corresponding to higher values of seasonal climatological P.

[1]Department of Atmospheric Sciences, University of Washington, Seattle, Washington, USA.

Corresponding author: J. Scheff, Department of Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA 98195-1640, USA. (jscheff@uw.edu)

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"…implicating dynamic poleward expansion of dry zones rather than thermodynamic amplification of dry-wet contrasts."

↓

"…wet regions get wetter, dry regions get drier."

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Robust responses of the hydrological cycle to global warming

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Abstract Using the climate change experiments generated for the Fourth Assessment of the Intergovernmental Panel on Climate Change, this study examines some aspects of the changes in the hydrological cycle that are robust across the models. These responses ...

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Overview

5686 JOURNAL OF CLIMATE VOLUME 19

Robust Responses of the Hydrological Cycle to Global Warming

ISAAC M. HELD

National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

BRIAN J. SODEN

Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, Florida

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1. Introduction

There remains considerable uncertainty concerning the magnitude of the temperature response to a given increase in greenhouse gases. But there are a number of climatic responses that are tightly coupled to the temperature response. Most of these are related, directly or indirectly, to lower-tropospheric water vapor. We are confident that lower-tropospheric water vapor will increase as the climate warms. We can predict, with nearly as much confidence, that certain other changes will occur that are coupled to this increase in water vapor. In this article we describe some of these robust hydrological responses to warming.

We use the archive of coupled climate models results organized by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change as our primary tool in assessing robustness. Some aspects of the hydrological responses to warming are consistent among these models and some are not. To study the latter requires one to understand the consequences of different model formulations, often at a detailed level. When studying a consistent part of the response, in contrast, one is not concerned with the specifics of individual models, but with providing simple physical arguments that add additional support for the plausibility of the response. Some of these robust responses to warming are already well appreciated, but we gather several together here, partly for pedagogical reasons, and partly with the hope of motivating new observational studies to determine whether those responses, which the models predict are already occurring, are detectable.

As in many discussions of water vapor and global warming, our starting point is the Clausius–Clapeyron (CC) expression for the saturation vapor pressure

$$\frac{d\,\mathrm{Vap}}{dT} = \frac{L}{RT^2} = \alpha T, \qquad (1)$$

where L is the latent heat of vaporization and R is the gas constant. At temperatures typical of the lower troposphere, $\alpha \approx 0.07\ \mathrm{K}^{-1}$; the saturation vapor pressure increases by about 7% for each 1-K increase in temperature. If the equilibrium response of lower-tropospheric temperatures to a doubling of CO_2 is close to the canonical mean value of 3 K, this corresponds to

* Corresponding author address: Dr. Brian J. Soden, Rosenstiel School for Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149.
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GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L06805, doi:10.1029/2006GL028443, 2007

Expansion of the Hadley cell under global warming

Jian Lu,[1,2] Gabriel A. Vecchi,[3] and Thomas Reichler[4]

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[1] A consistent weakening and poleward expansion of the Hadley circulation is diagnosed in the climate change simulations of the IPCC AR4 project. Associated with this widening is a poleward expansion of the subtropical dry zone. Simple scaling analysis supports the notion that the poleward extent of the Hadley cell is set by the location where the thermally driven jet first becomes baroclinically unstable. The expansion of the Hadley cell is caused by an increase in the subtropical static stability, which pushes poleward the baroclinic instability zone and hence the outer edge of the Hadley circulation. **Citation:** Lu, J., G. A. Vecchi and T. Reichler (2007), Expansion of the Hadley cell under global warming, *Geophys. Res. Lett.*, *34*, L06805, doi:10.1029/2006GL028443.

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[1] The Hadley cell (HC) plays a pivotal role in the earth's climate by transporting energy and angular momentum poleward and by organizing the three dimensional tropical atmospheric circulation. The locations of the large-scale subtropical dry zones and the major tropical/subtropical deserts of the globe are largely determined by the subsiding branches of the HC. Thus, understanding how the structure and intensity of the HC and the associated subtropical dry zones may change under the greenhouse gas (GHG)-induced global warming is a topic of substantial interest.

[1] The detailed response of the HC to increasing GHG is complex as the HC is influenced by many processes, including tropical heating processes [e.g., *Mitas and Clement*, 2006], the atmospheric stability [e.g., *Schneider*, 1977], extra-tropical eddy dynamics [e.g., *Walker and Schneider*, 2006], and total atmospheric moisture [*Frierson et al.*, 2006]. To date, studies of the long term behavior of the HC, and the extent to which GHG forcing is relevant remain inconclusive. Atmospheric reanalyses show a statistically significant intensification of their Hadley circulation throughout the second part of the 20th century [*Mitas and Clement*, 2005]. However, this intensification is not found in the reviewed data, nor in most 20th century simulations using both coupled or atmosphere-only general circulation models (GCMs) [*Mitas and Clement*, 2005, 2006]. Meanwhile, simple physical arguments [e.g., *Barnes*, 1998; *Knutson and Manabe*, 1995; *Held and Soden*, 2006] predict a slowdown of the overall tropical overturning circulation under global warming. Such a slowdown seems to be a robust feature in GCMs [*Vecchi and Soden*, 2007], and has been identified in observational analyses of the Walker circulation [*Vecchi et al.*, 2005; *Zhang and Song*, 2006].

[1] However, it remains to be seen whether it also applies to the Hadley circulation. Recent observational Analysis of the satellite observations indicates a poleward expansion of the HC over the past 27 years [*Fu et al.*, 2006]. The extent to which this observed widening of the HC is primarily a response to GHG warming is not clear and warrants further investigation.

[1] Here, we investigate the response of the HC to global warming using 21st century increasing GHG scenarios from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The diversity of the numerical schemes and parameterizations of the AR4 models provides a unique framework for understanding the response of the HC to GHG increases. In this study we show that there is a robust poleward expansion and weakening of the Hadley circulation across all models, and we identify a possible mechanism for this behavior.

2. Data and Methods

[1] Gridded global monthly precipitation, evaporation, surface air temperature, surface wind, temperature, meridional wind, and 500hPa pressure velocity (ω_{500}) were retrieved from the AR4 archive website (available at http://www-pcmdi.llnl.gov), and annual means were formed for the analysis. Most of our analysis was based on output from the A2 scenario which is at the upper end of GHG emission (the CO_2 concentration reaches 800 ppm at the end of the 21st century), two less aggressive scenarios were also explored (A1B with CO_2 stabilization at 720ppm and B1 with CO_2 stabilization at 550ppm). Only the first ensemble member of each GCM for which complete data (the availability of the variables) was used. To identify the climate change response, we compared the first and last twenty years of the 21st century, i.e., (2081–2100) minus (2001–2020).

[1] To determine the poleward edges of the HC, we computed the zonal-mean mass flux stream function (ψ) by vertically integrating the zonal-mean density-weighted meridional wind component from the top model level downward. We first determined the maximum of the absolute value of this stream function at 500 hPa (ψ_{500}), and then identified the edges of the HC as the first latitude poleward of the maximum at which ψ_{500} became zero. An alternative definition of the HC edge as the transition

[1]Climate and Global Dynamics Division, National Center for Atmospheric Research, University Corporation for Atmospheric Research, Boulder, Colorado, USA.

[2]University Corporation for Atmospheric Research Visiting Scientist Program, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton University, Princeton, New Jersey, USA.

[3]Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton University, Princeton, New Jersey, USA.

[4]Department of Meteorology, University of Utah, Salt Lake City, Utah, USA.

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In a warmer climate:

- decrease in convective mass flux
- enhancement in pattern of precipitation - evaporation
- precipitation changes largely reflect poleward expansion of subtropical dry zones
- reasons for expansion of Hadley cell

Take Away

- basic understanding of changes in global precipitation
- be careful summarizing a paper with a catch-phrase
- how you analyze and present your data matters a lot
- ideas of what changes poleward extent of Hadley Cell in warmer climate

5686 JOURNAL OF CLIMATE VOLUME 19

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There remains considerable uncertainty concerning the magnitude of the temperature response to a given increase in greenhouse gases. But there are a number of climatic responses that are tightly coupled to the temperature response. Most of these are related, directly or indirectly, to lower-tropospheric water vapor. We are confident that lower-tropospheric water vapor will increase as the climate warms. We can predict, with nearly as much confidence, that certain other changes will occur that are coupled to this increase in water vapor. In this article we describe some of these robust hydrological responses to warming.

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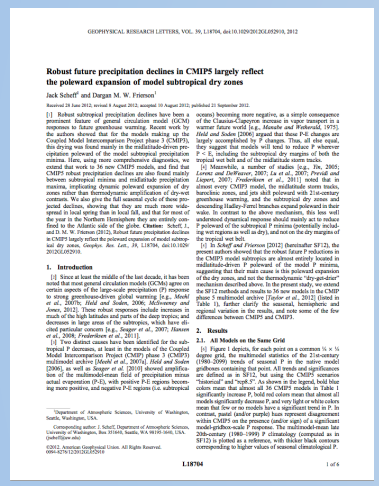

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1. Introduction

[1] The Hadley cell (HC) plays a pivotal role in the earth's climate by transporting energy and angular momentum poleward and by organizing the three dimensional tropical atmospheric circulation. The locations of the large-scale subtropical dry zones and the major tropical/subtropical deserts of the globe are largely determined by the subsiding branches of the HC. Thus, understanding how the structure and intensity of the HC and the associated subtropical dry zones may change under the greenhouse gas (GHG)-induced global warming is a topic of substantial interest.

[1] The detailed response of the HC to increasing GHG is complex as the HC is influenced by many factors, including tropical heating processes [e.g., *Mitas and Clement*, 2006], the atmospheric stability [e.g., *Schneider*, 1977], extra-tropical eddy dynamics [e.g., *Walker and Schneider*, 2006], and total atmospheric moisture [*Frierson et al.*, 2006]. To date, studies of the long term behavior of the HC, and the extent to which GHG forcing is relevant remain inconclusive. Atmospheric reanalyses show a statistically significant intensification of their Hadley circulation throughout the second part of the 20th century [*Mitas and Clement*, 2005]. However, this intensification is not found in the reviewed data, nor in most 20th century simulations using both coupled or atmosphere-only general circulation models (GCMs) [*Mitas and Clement*, 2005, 2006]. Meanwhile, simple physical arguments [e.g., *Bates*, 1998; *Knutson and Manabe*, 1995; *Held and Soden*, 2006] predict a slowdown of the overall tropical overturning circulation under global warming. Such a slowdown seems to be a robust feature in GCMs [*Vecchi and Soden*, 2007], and has been identified in observational analyses of the Walker circulation [*Vecchi et al.*, 2005; *Zhang and Song*, 2006].

[1] However, it remains to be seen whether it also applies to the HC under global warming. Recent observational Analysis of the satellite observations indicates a poleward expansion of the HC over the past 27 years [*Fu et al.*, 2006]. The extent to which this observed widening of the HC is primarily a response to GHG warming is not clear and warrants further investigation.

[1] Here, we investigate the response of the HC to global warming using 21st century increasing GHG scenarios from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The diversity of the numerical schemes and parameterizations of the AR4 models provides a unique framework for understanding the response of the HC to GHG increases. In this study we show that there is a robust poleward expansion and weakening of the Hadley circulation across all models, and we identify a possible mechanism for this behavior.

2. Data and Methods

[1] Gridded global monthly precipitation, evaporation, surface air temperature, surface wind, temperature, meridional wind, and 500hPa pressure velocity (ω_{500}) were retrieved from the AR4 archive website (available at http://www-pcmdi.llnl.gov), and annual means were formed for the analysis. Most of our analysis was based on output from the A2 scenario which is at the upper end of GHG emission (the CO_2 concentration reaches 800 ppm at the end of the 21st century), two less aggressive scenarios were also explored (A1B with CO_2 stabilization at 720ppm and B1 with CO_2 stabilization at 550ppm). Only the first ensemble member of each model in the corresponding scenario (the availability of the variables) was used. To identify the climate change response, we compared the first and last twenty years of the 21st century, i.e., (2081–2100) minus (2001–2020).

[1] To determine the poleward edges of the HC, we computed the zonal-mean mass flux stream function (ψ) by vertically integrating the zonal-mean density-weighted meridional wind component from the top model level downward. We first determined the maximum of the absolute value of this stream function at 500 hPa (ψ_{500}), and then identified the edges of the HC as the first latitude poleward of the maximum at which ψ_{500} became zero. An alternative definition of the HC edge as the transition

[1]Climate and Global Dynamics Division, National Center for Atmospheric Research, University Corporation for Atmospheric Research, Boulder, Colorado, USA.

[2]University Corporation for Atmospheric Research Visiting Scientist Program, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton University, Princeton, New Jersey, USA.

[3]Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton University, Princeton, New Jersey, USA.

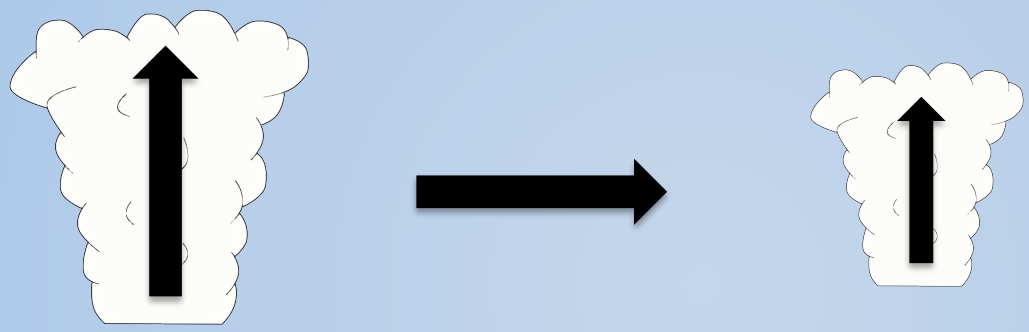
[4]Department of Meteorology, University of Utah, Salt Lake City, Utah, USA.

0094-8276/07/2006GL028443

Held and Soden 2006

As a consequence of the increase in lower-tropospheric water vapor

1.) Decrease in convective mass flux



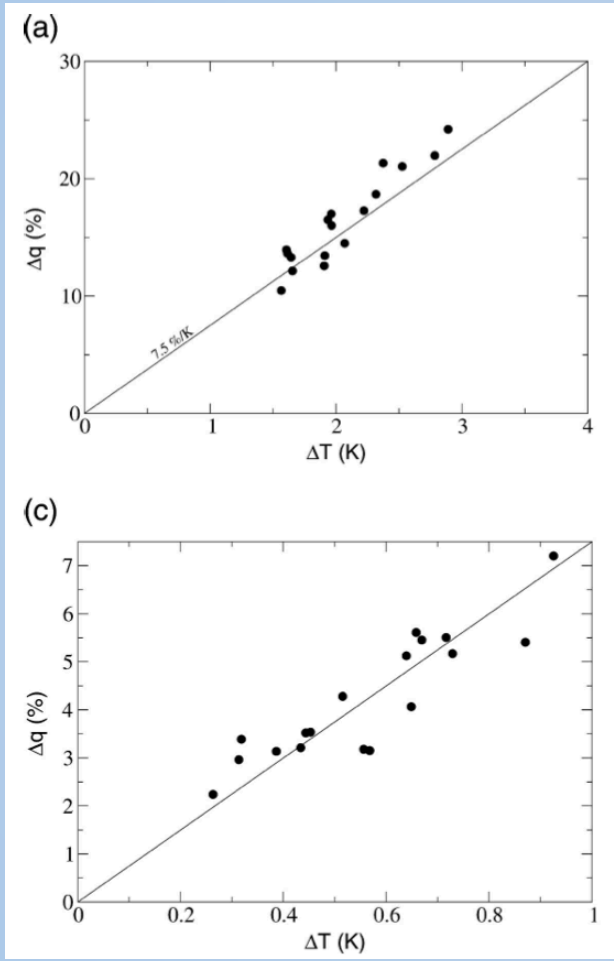
Counterintuitive, seems like a warmer climate system should be more “energetic”

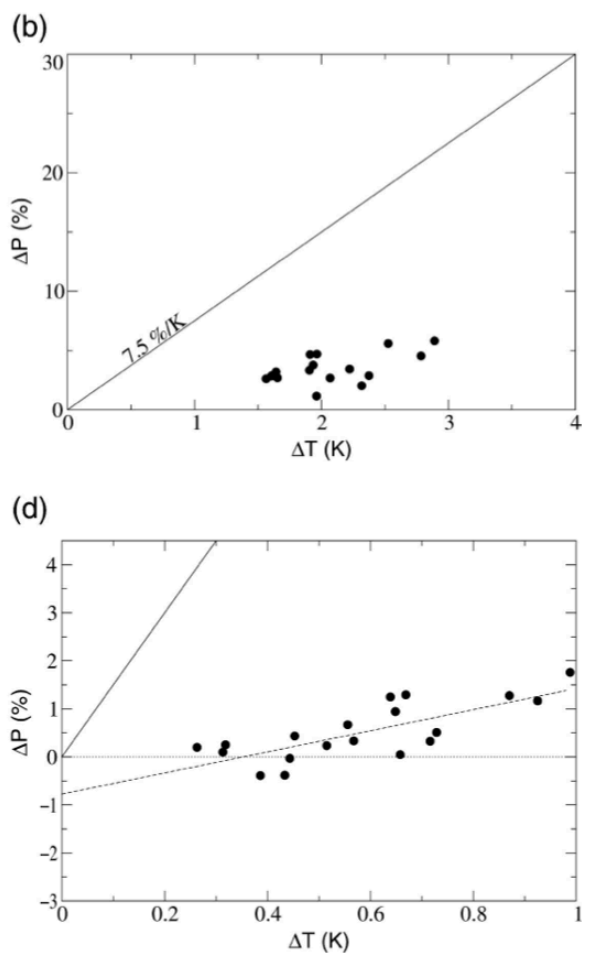
$$P \approx Mq$$

20 AR4 models

(2080 to 2100)
-
(2000 to 2020)

(1980 to 2000)
-
(1860 to 1880)





$$\frac{\delta q}{q} \approx 0.07\delta T$$

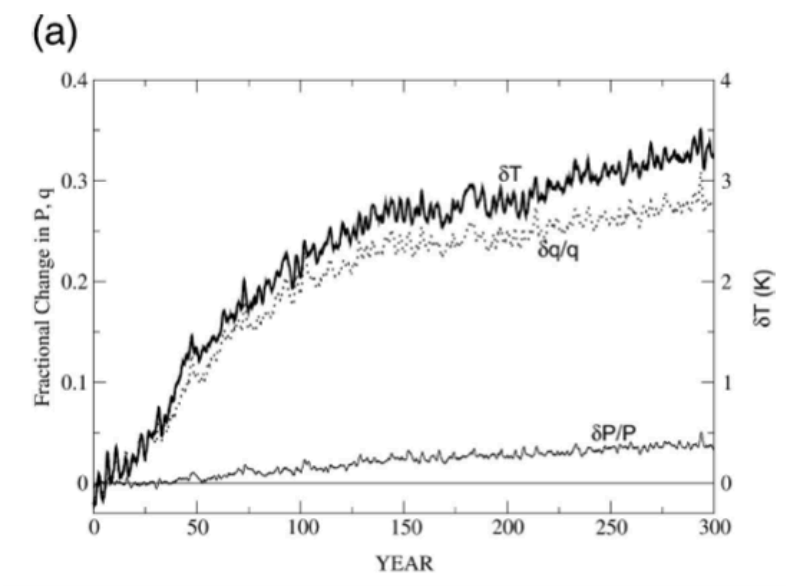
$$\frac{\delta P}{P} \approx 0.02\delta T$$

$$P \approx Mq$$

$$\frac{\delta P}{P} \approx \frac{\delta(Mq)}{Mq} = \frac{\delta M}{M} + \frac{\delta q}{q}$$

$$\frac{\delta M}{M} \approx \frac{\delta P}{P} - \frac{\delta q}{q}$$

$$\frac{\delta M}{M} \approx 0.02\delta T - 0.07\delta T = -0.05\delta T$$

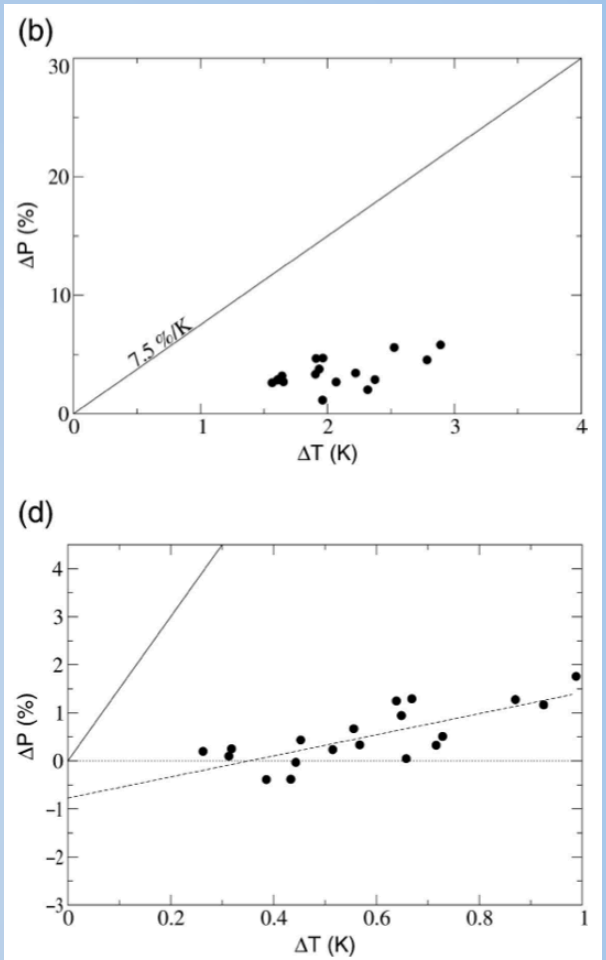


GFDL model

Wait!

This is an argument based on $\frac{\delta P}{P} \approx 0.02 \delta T$

This result is purely model derived $\xrightarrow{\text{AR4}}$



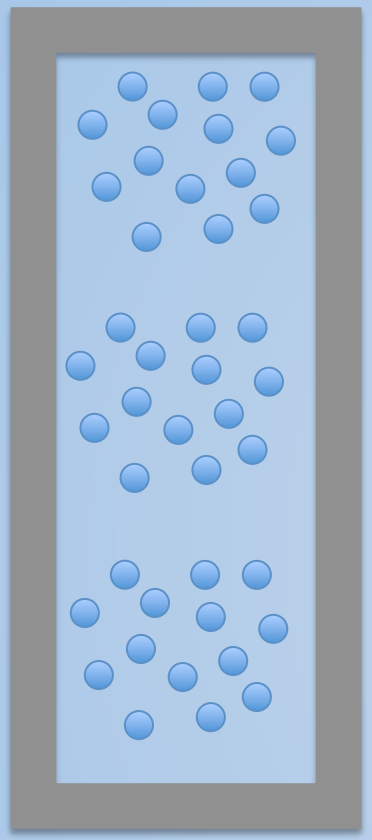
Models use parameterized convection, can we trust them?

Intuitively, if I put 7% more moisture in the atmosphere I expect 7% more precipitation.

This must be bogus!

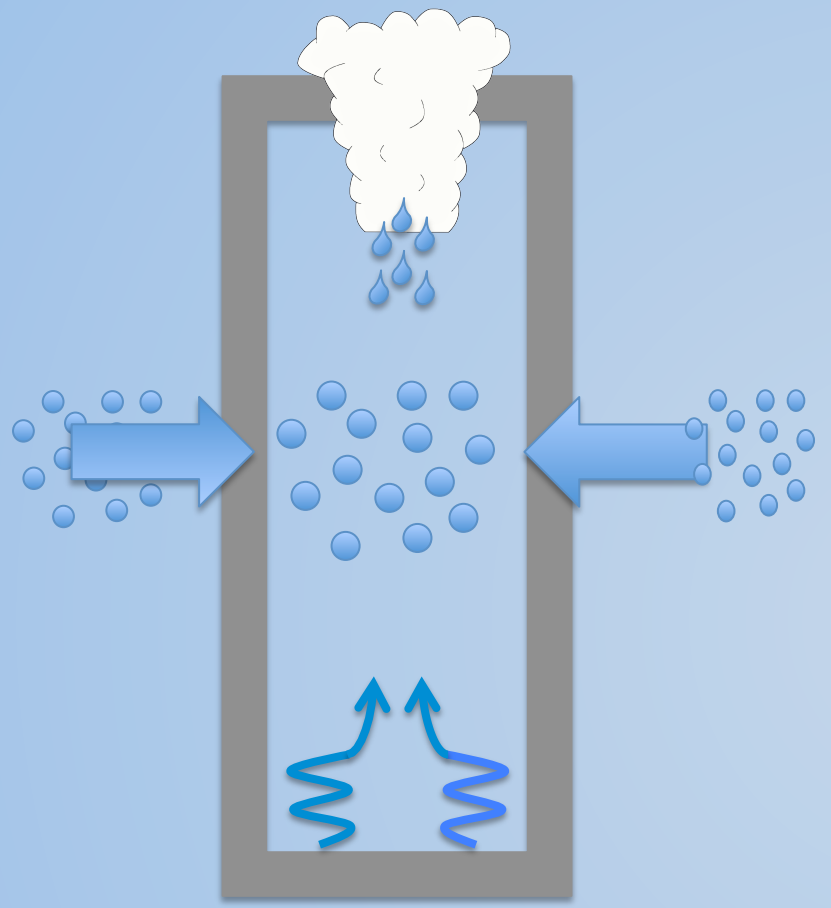
$$\frac{\delta P}{P} \approx 0.02 \delta T$$

Global Average Precipitation



Column moisture: $\left\langle \frac{\partial q}{\partial t} \right\rangle = \frac{1}{L_v} SLHF - P - \left\langle \nabla \circ (q\vec{V}_H) \right\rangle$

Global Average Precipitation



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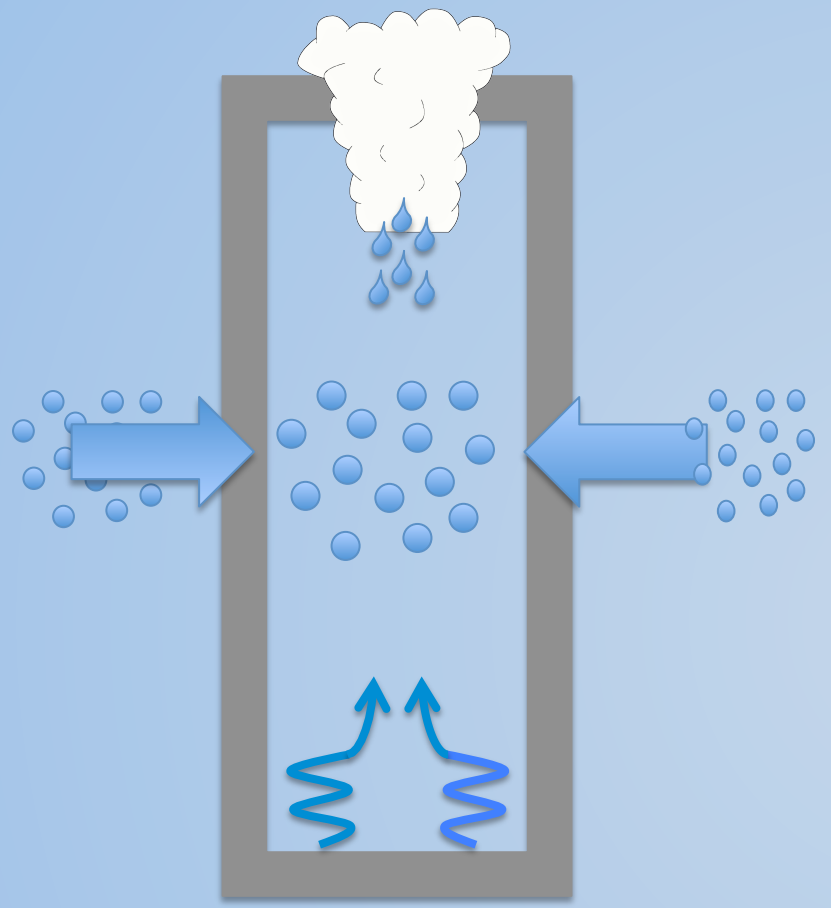
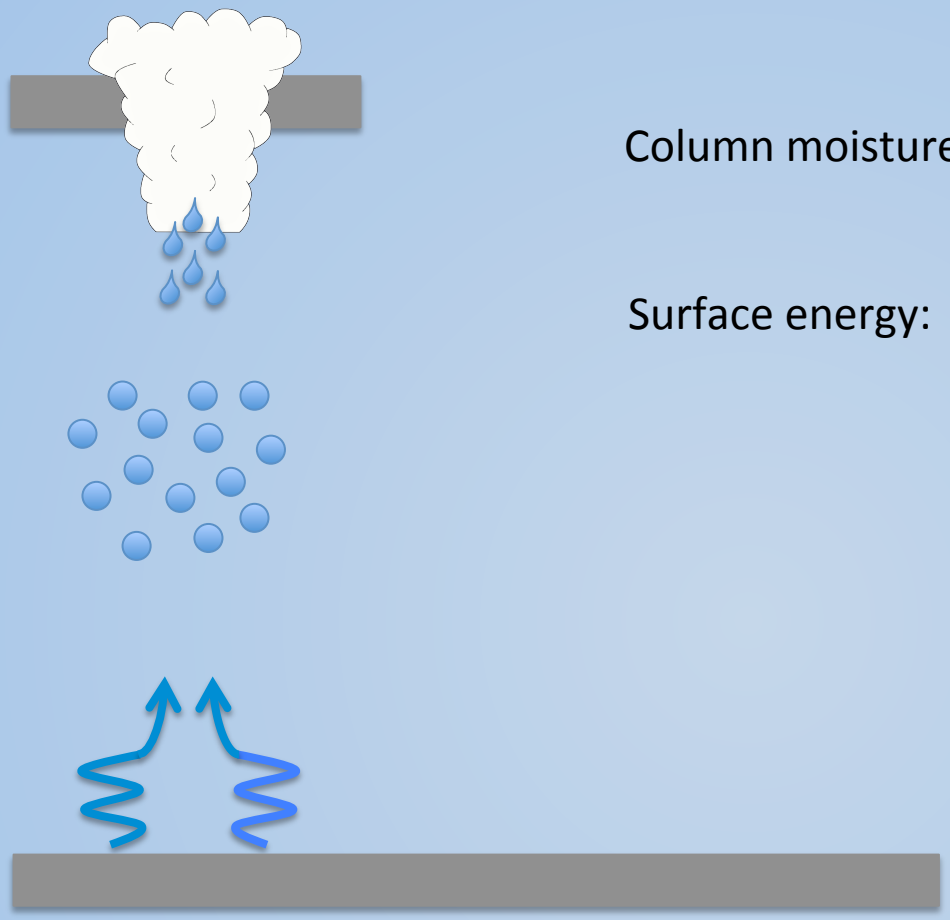
Global Average Precipitation



Column moisture: $\left\langle \frac{\partial q}{\partial t} \right\rangle = \frac{1}{L_v} SLHF - P - \left\langle \nabla \circ (q \vec{V}_H) \right\rangle$

Let's consider **steady state**
and take the **global average**

Global Average Precipitation

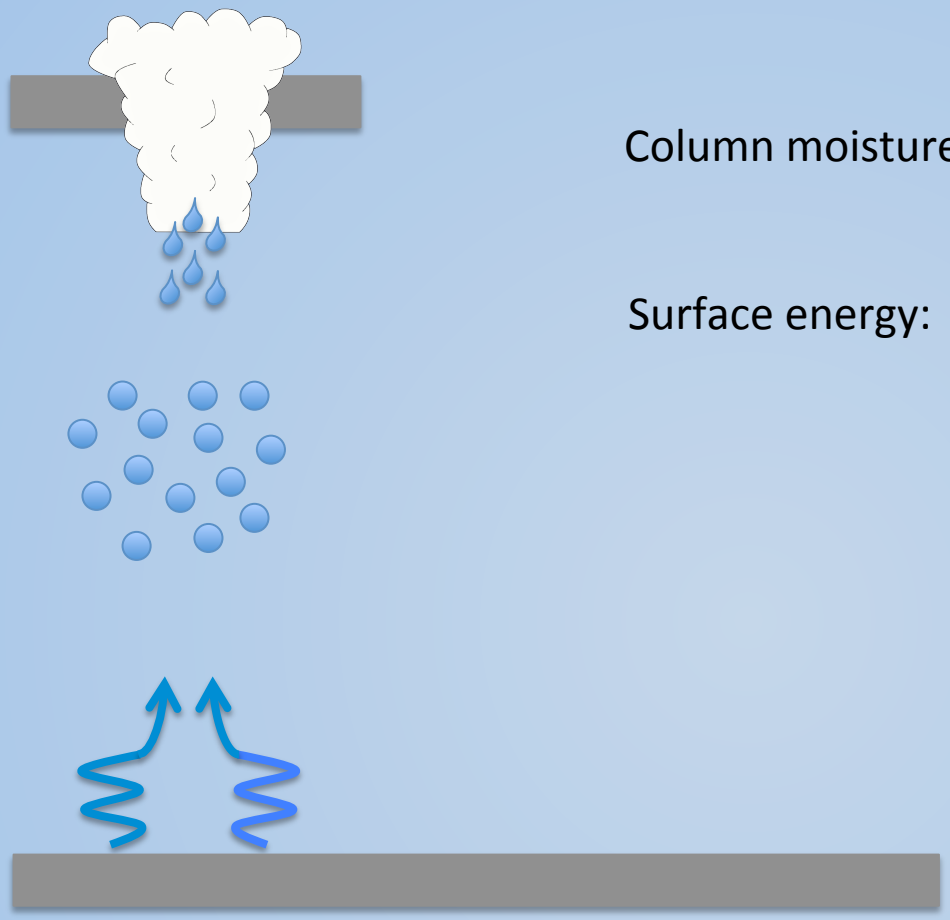


Column moisture: $$P = \frac{1}{L_v} SLHF$$

Surface energy: $$\frac{\partial E_s}{\partial t} = R_s - SLHF - SSHF + \Delta F_{ocean}$$

energy

Global Average Precipitation



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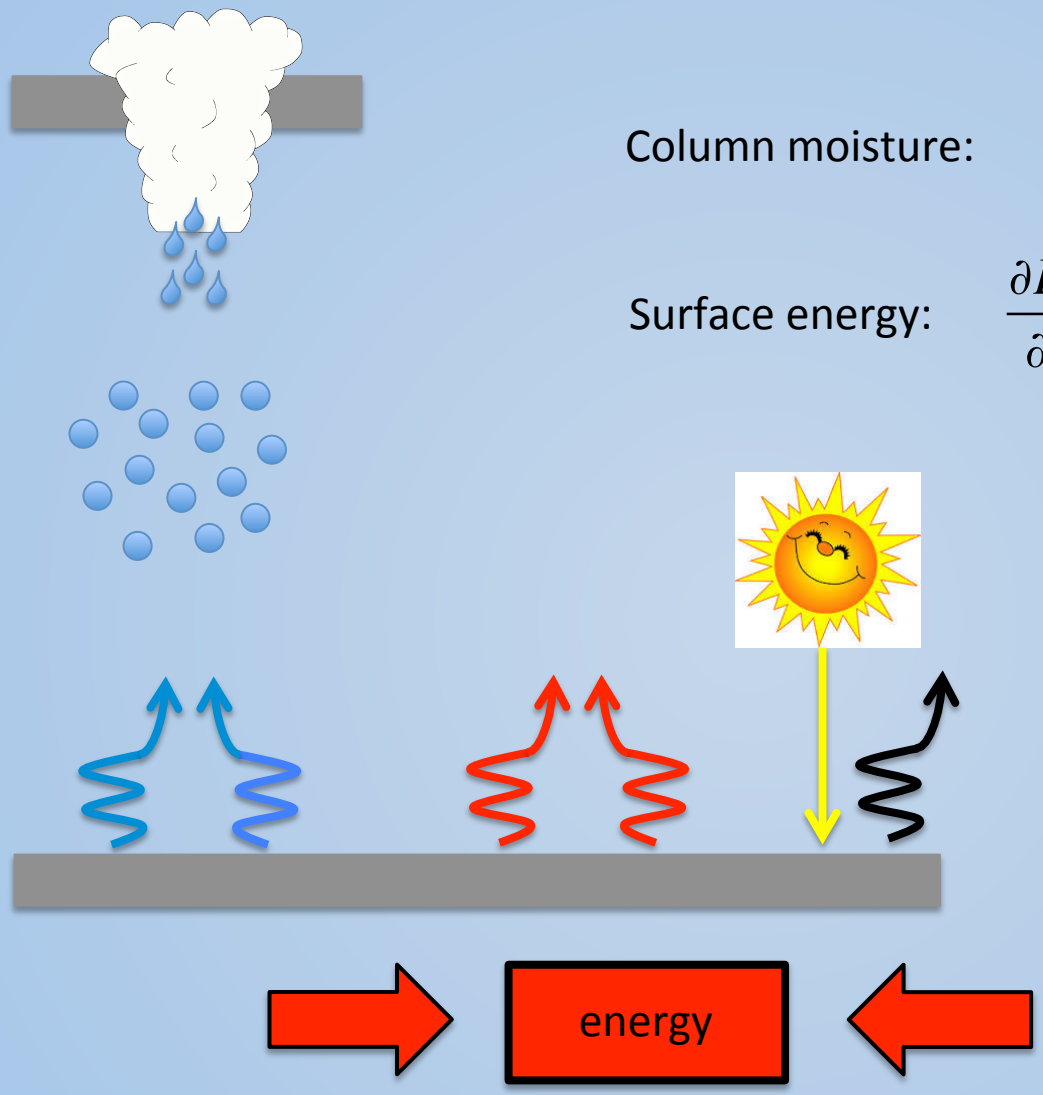
energy

energy

Global Average Precipitation



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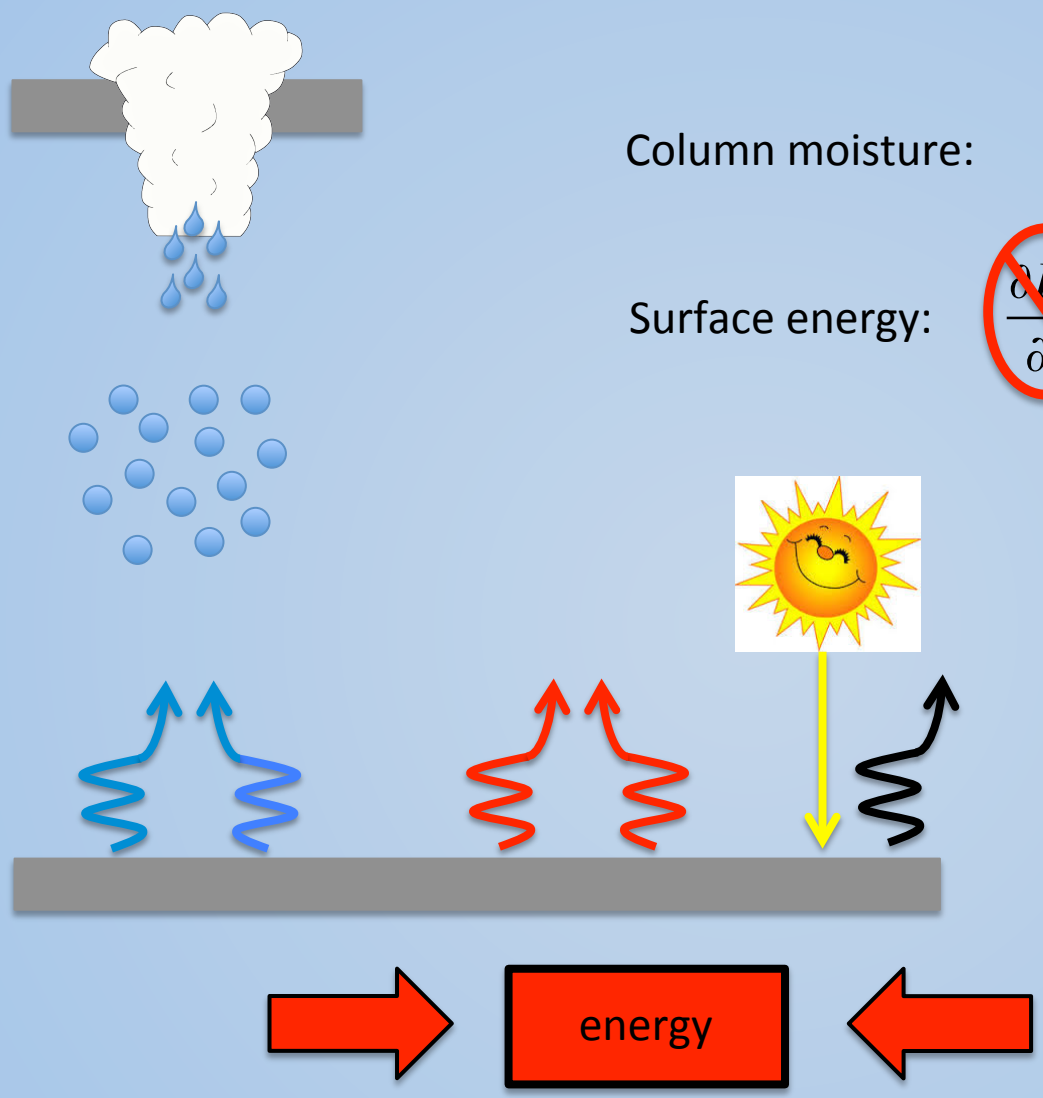
Global Average Precipitation

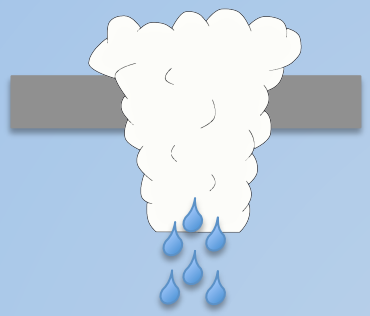


Column moisture: $$P = \frac{1}{L_v} SLHF$$

Surface energy: $$\frac{\partial E_s}{\partial t} = R_s - SLHF - SSHF + \Delta F_{ocean}$$

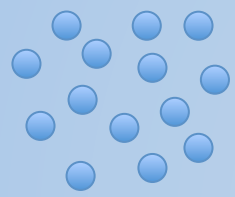
Let's consider **steady state** and take the **global average**

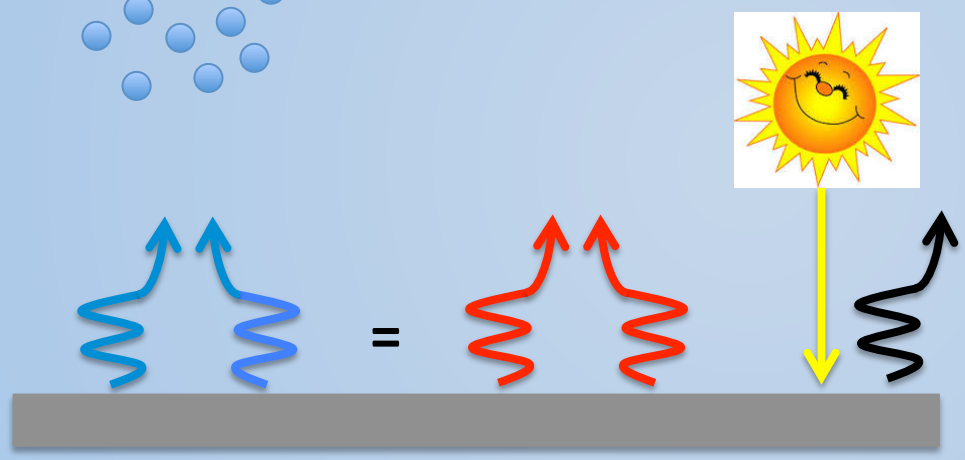
Global Average Precipitation



Column moisture: $P = \frac{1}{L_v} SLHF$

Surface energy: $SLHF = R_s - SSHF$





energy

Global Average Precipitation

Column moisture: $P = \frac{1}{L_v} SLHF$

Surface energy: $SLHF = R_s - SSHF$

$$\boxed{P = \frac{1}{L_v}(R_s - SSHF)}$$

Notice that atmospheric moisture content plays no role in this equation!

Come to same conclusion using other approaches!

Precipitation does not need to scale with CC

Held and Soden address changes in radiation, albedo, and the Bowen ratio in a warming climate, coming to the following conclusion:

"Because the increase in strength of the global hydrological cycle is constrained by relatively small changes in radiative fluxes, it cannot keep up with the rapid increase in water vapor."

CMIP5

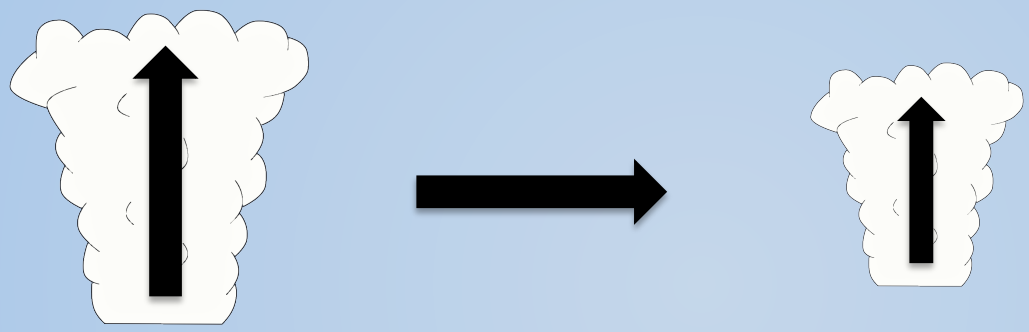
	RCP4.5	RCP8.5
Global	1.0 - 3.0%	1.0 - 2.25 %
Land	-1.5 - 4.0%	0 - 4%
Ocean	0.5 - 3.0%	0.5 - 2.5%

Based on Figure 12.7. Minimum and maximum annual mean precipitation changes (% change/C) from CMIP5.

Held and Soden 2006

As a consequence of the increase in lower-tropospheric water vapor

1.) Decrease in convective mass flux



2.) Pattern of P – E is enhanced → "wet regions get wetter, dry regions get drier"

Column moisture: $\left\langle \frac{\partial q}{\partial t} \right\rangle = \frac{1}{L_v} SLHF - P - \left\langle \nabla \circ (q\vec{V}_H) \right\rangle$

E

Column moisture: $P - E = -\left\langle \nabla \circ (q\vec{V}_H) \right\rangle$

If you assume:

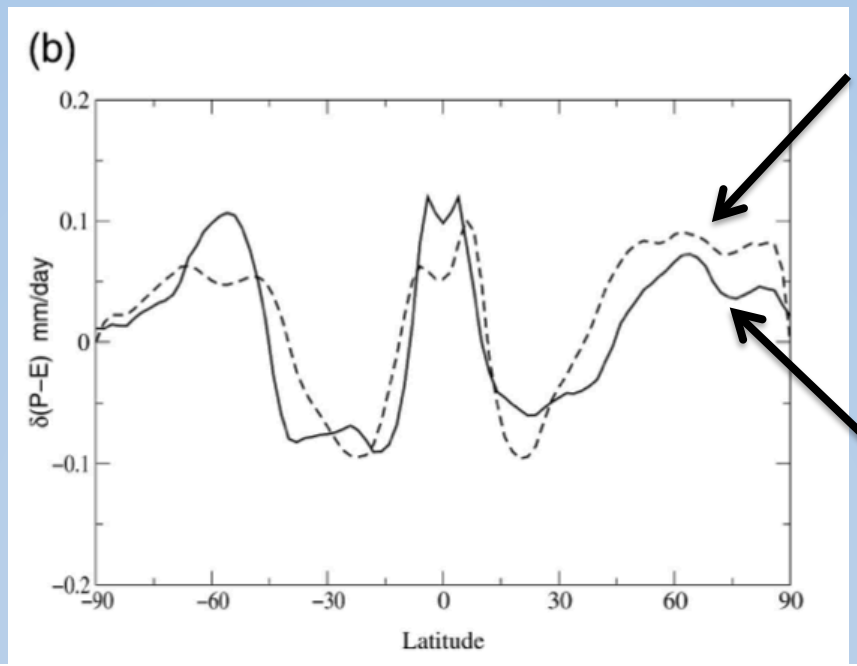
1.) Fixed relative humidity

2.) No changes in the circulation

$$\boxed{\delta(P - E) = 0.07\delta T(P - E)}$$

"The pattern of P-E is simply enhanced, becoming more positive where it is already positive and more negative where it is negative."

AR4 models, A1B Scenario



Prediction from

$$\delta(P-E) = 0.07\delta T(P-E)$$

Model

FIG. 6. The zonal-mean $\delta(P-E)$ from the ensemble mean of PCMDI AR4 models (solid) and the thermodynamic component (dashed) predicted from (6). Results are shown from simulations using the (a) 20C3M, (b) SRES A1B, and (c) 2×CO2 slab equilibrium forcing scenarios.

"The difference between the actual response and this simple fixed flow fixed relative humidity response clearly shows the effects of the poleward movement of the storm tracks in both hemispheres, which displaces the poleward boundary of the dry subtropical zones with P-E < 0 farther poleward."

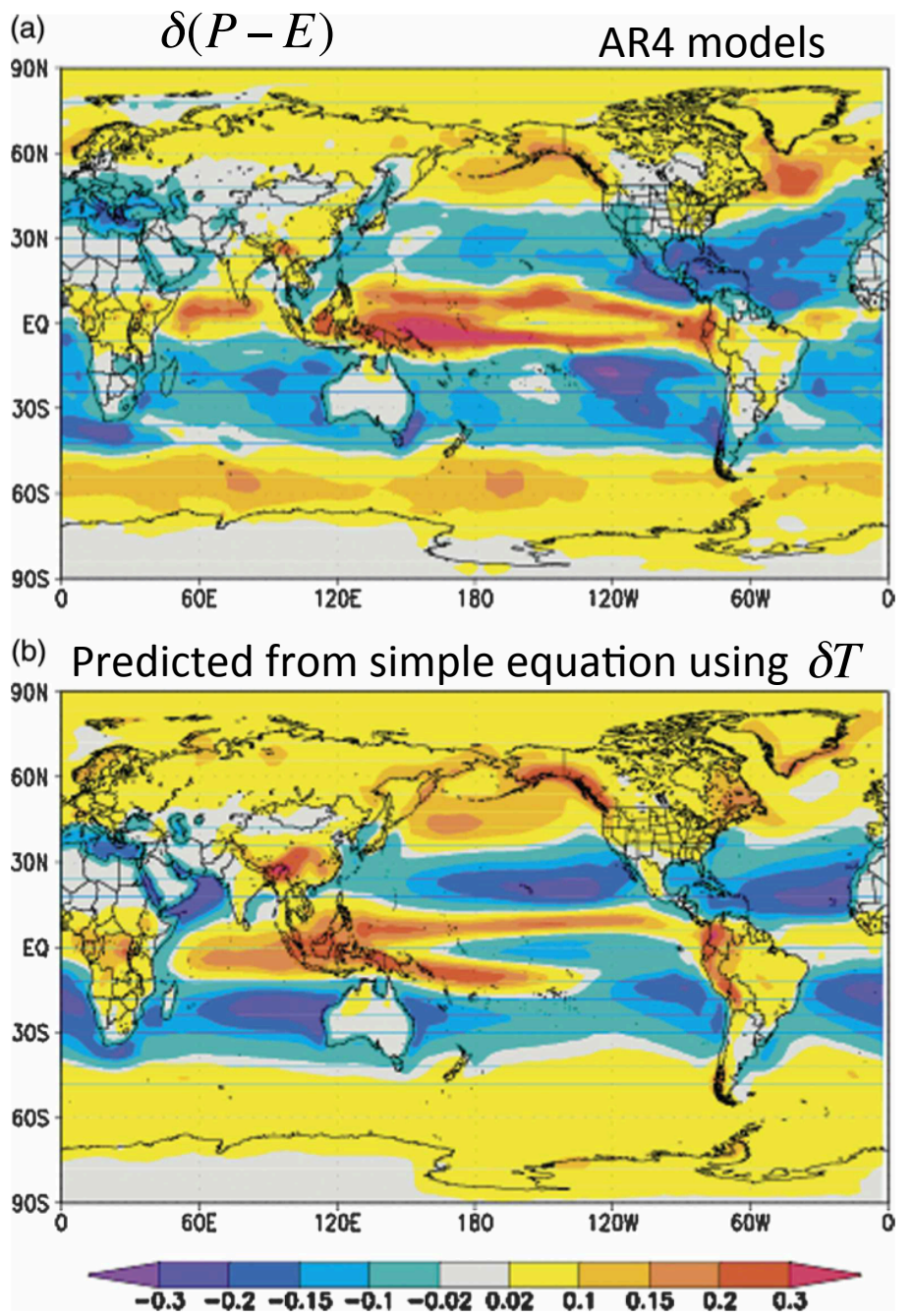


FIG. 7. The annual-mean distribution of $\delta(P-E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

$\delta(P-E)$ not δP

Held and Soden point this out many times

Average over all seasons

Multi-model mean

Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones

Jack Scheff and Dargan M. W. Frierson

Geophysical Resarch Letters, 2012

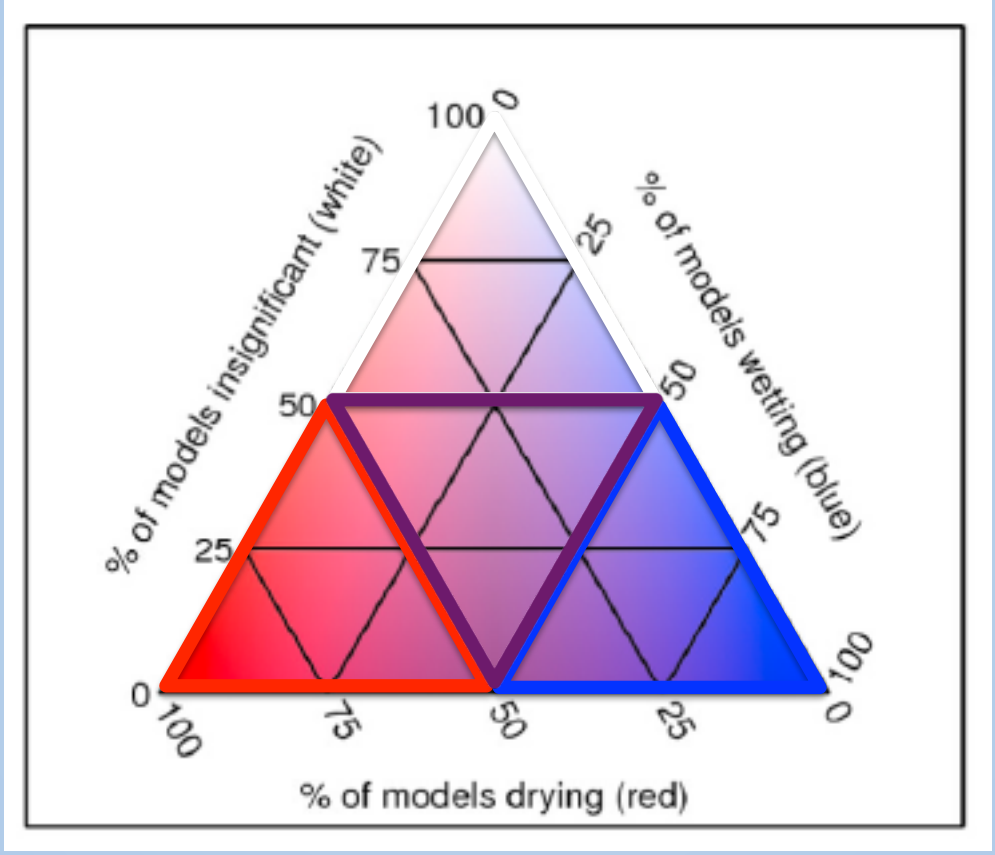
CMIP5 projections have shown a decrease in subtropical precipitation rates. Why?

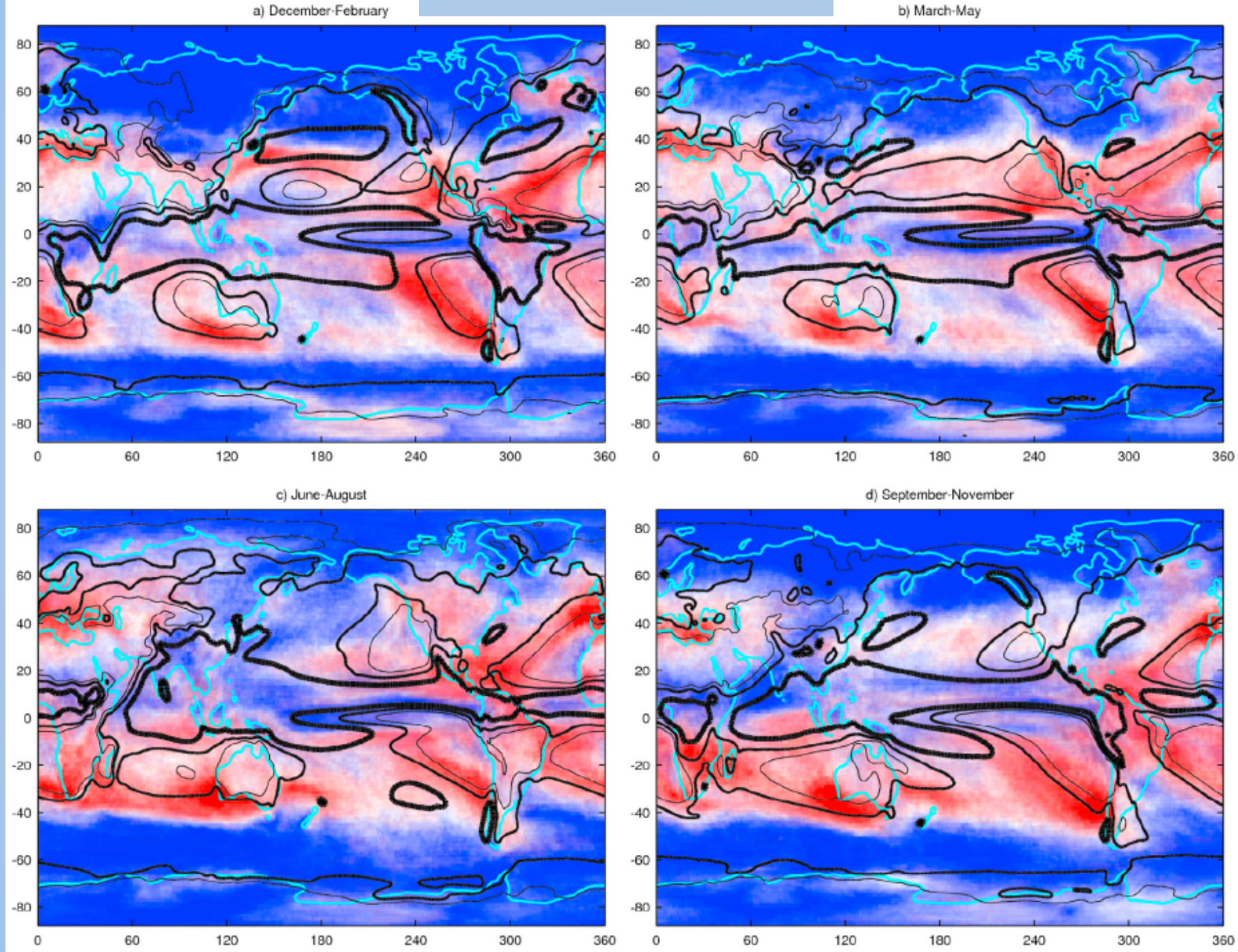
1. Amplification of the current P-E distribution.

   "… since E is tied to the local surface energy supply, which is solar-dominated, E cannot change much—so the bulk of this P - E amplification would be accomplished by changes in P. Thus, roughly, P would increase where and when P - E > 0; and P would decrease where and when P - E < 0 (dry-get-drier)."

   - Scheff and Frierson, 2012 (JoC)

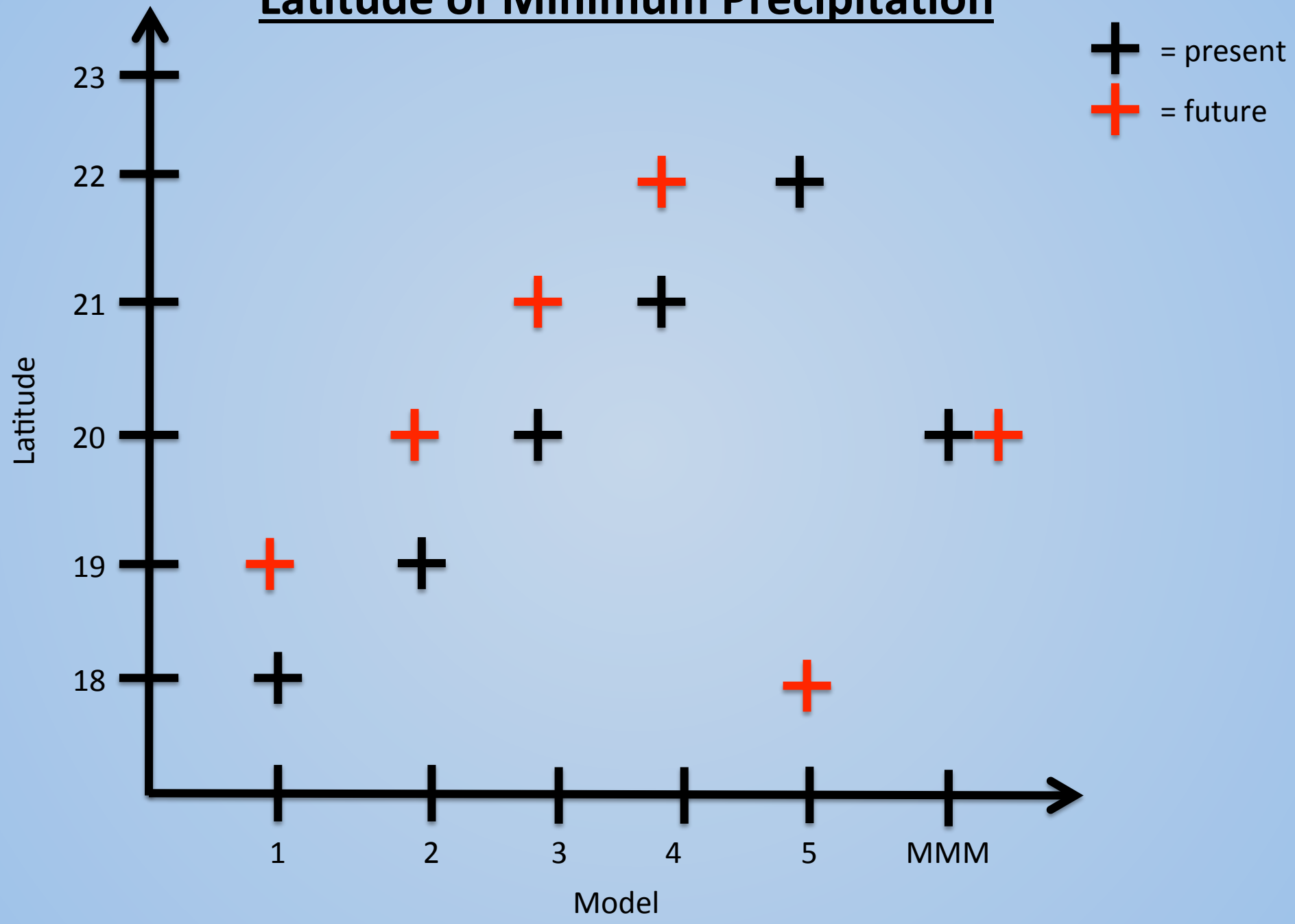
2. Subtropical dry zones are expanding poleward with mid-latitude storm tracks and baroclinic zones.


% of models insignificant (white)
% of models wetting (blue)
% of models drying (red)
100
75
50
25
0
0
25
50
75
100
100
75
50
25
0



Scheff and Frierson, 2012

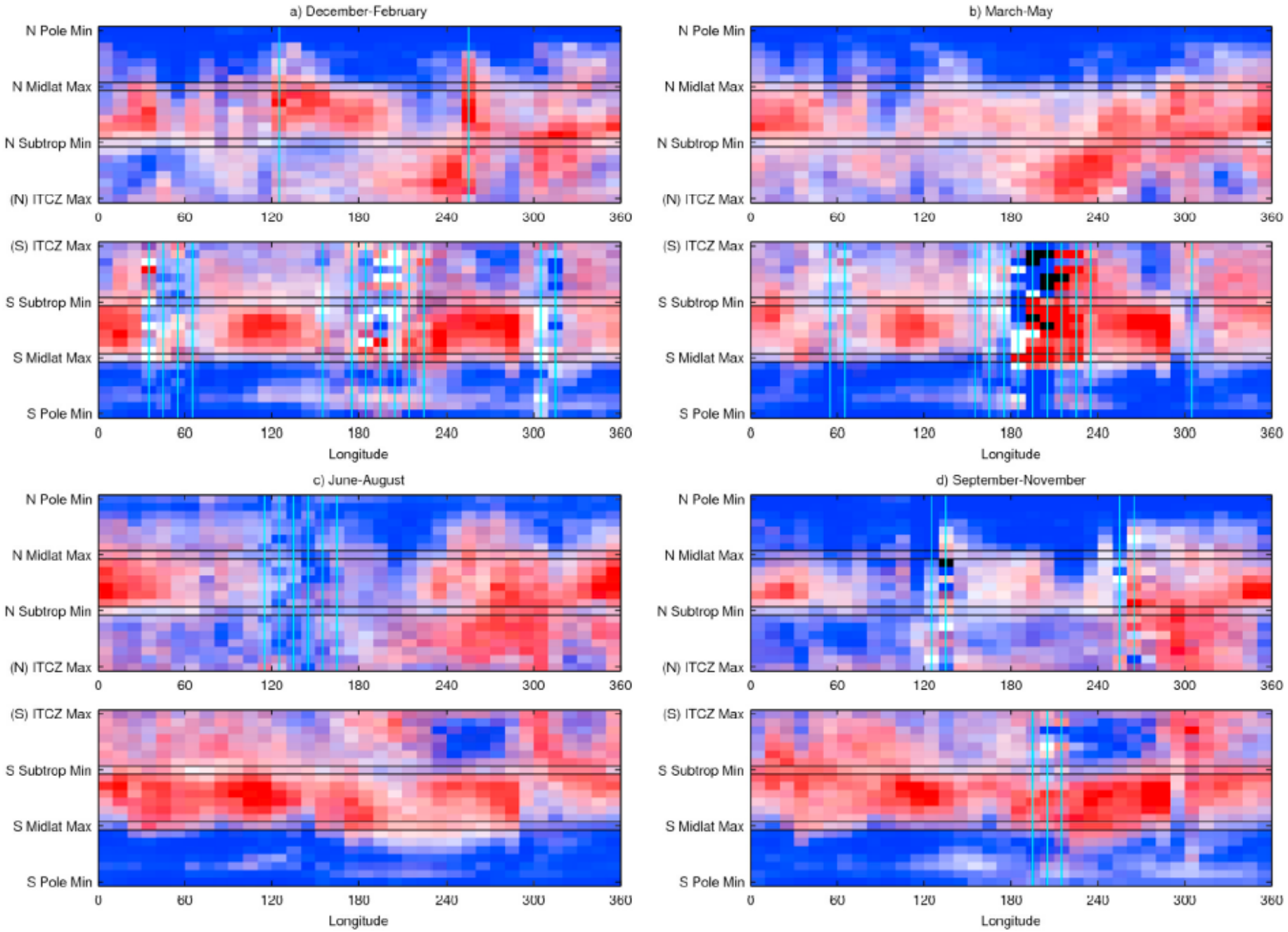
Latitude of Minimum Precipitation



Model-by-model approach

"… introduced a novel system for recording each […] model's seasonal P response pattern relative to the pattern of its own climatology in a uniform fashion that can be collated across many models."

- Scheff and Frierson, 2012



Scheff and Frierson, 2012

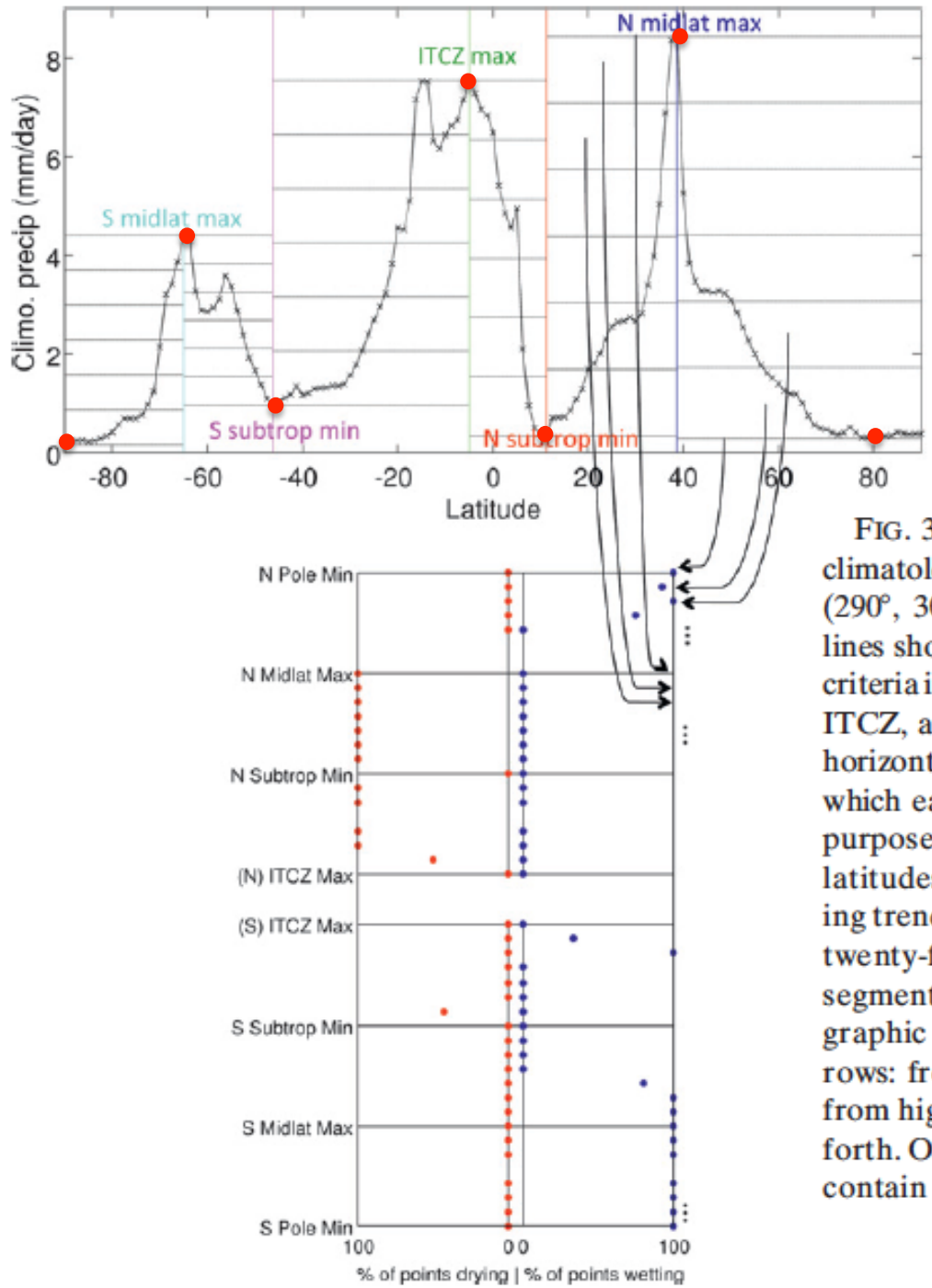
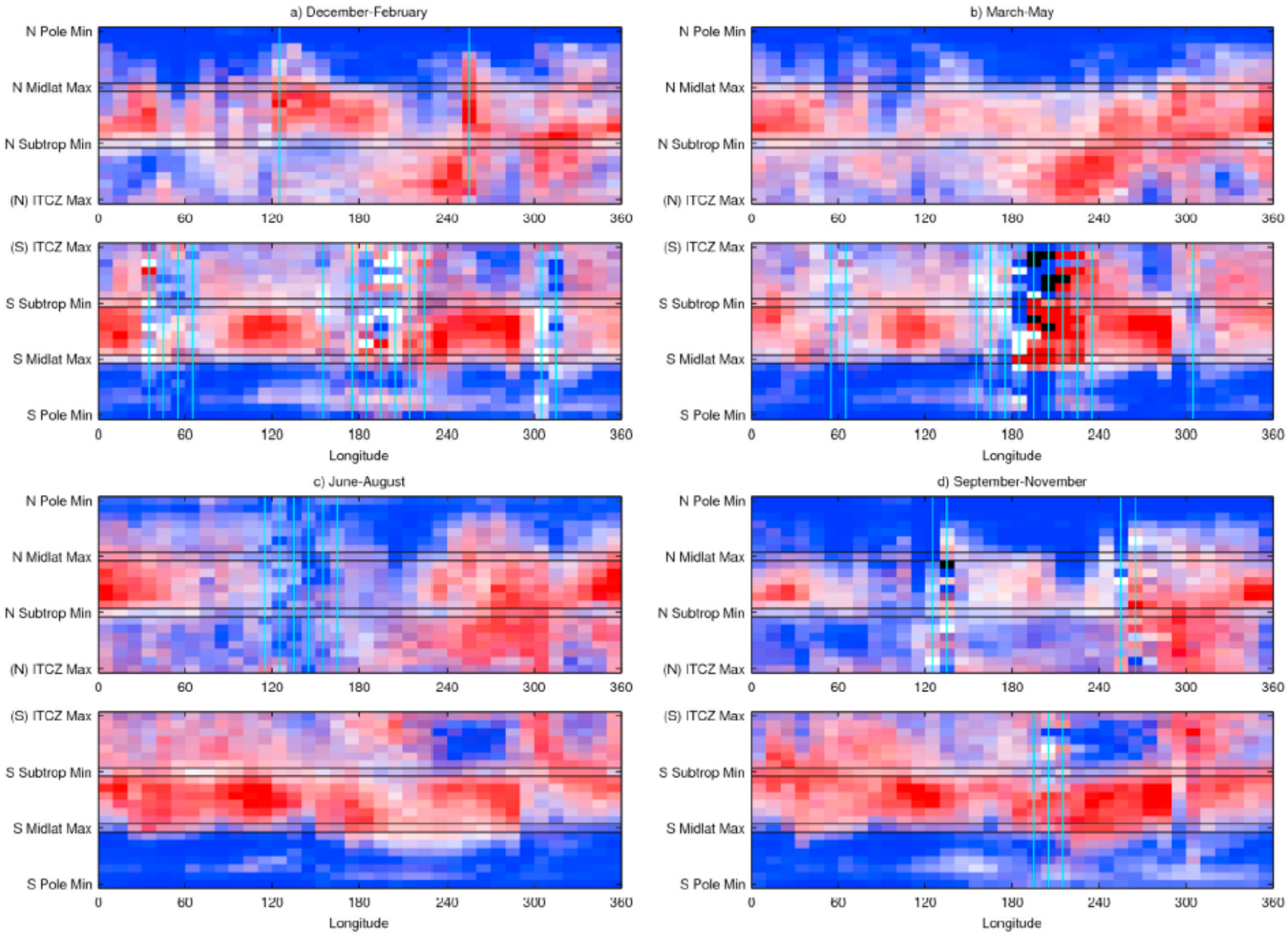


FIG. 3. (top) Black curve shows a sample late twentieth-century climatological P vs latitude profile, from the zonal average of the (290°, 300°E] strip in HadGEM1, March–May. Colored vertical lines show the large-scale features of this profile as defined by the criteria in the appendix (the peak near 15°S is slightly lower than the ITCZ, and thus is not prominent enough to be a feature). Black horizontal lines show the boundaries of the interfeature P bins to which each point of the profile is assigned for response-recording purposes, according to section 4a. (bottom) The percentage d of latitudes with significant twenty-first-century (1980–2099) drying trends in P, and the percentage w of latitudes with significant twenty-first-century wetting trends in P, for each bin of each segment of this profile. The bins are arranged in quasi-geographic order within each segment, illustrated by the black arrows: from lowest P to highest P going down the top segment, from highest P to lowest P going down the next segment, and so forth. Ordinates with missing data correspond to bins that do not contain any points.

Scheff and Frierson, 2012 (JoC)



Scheff and Frierson, 2012

Results and Conclusions

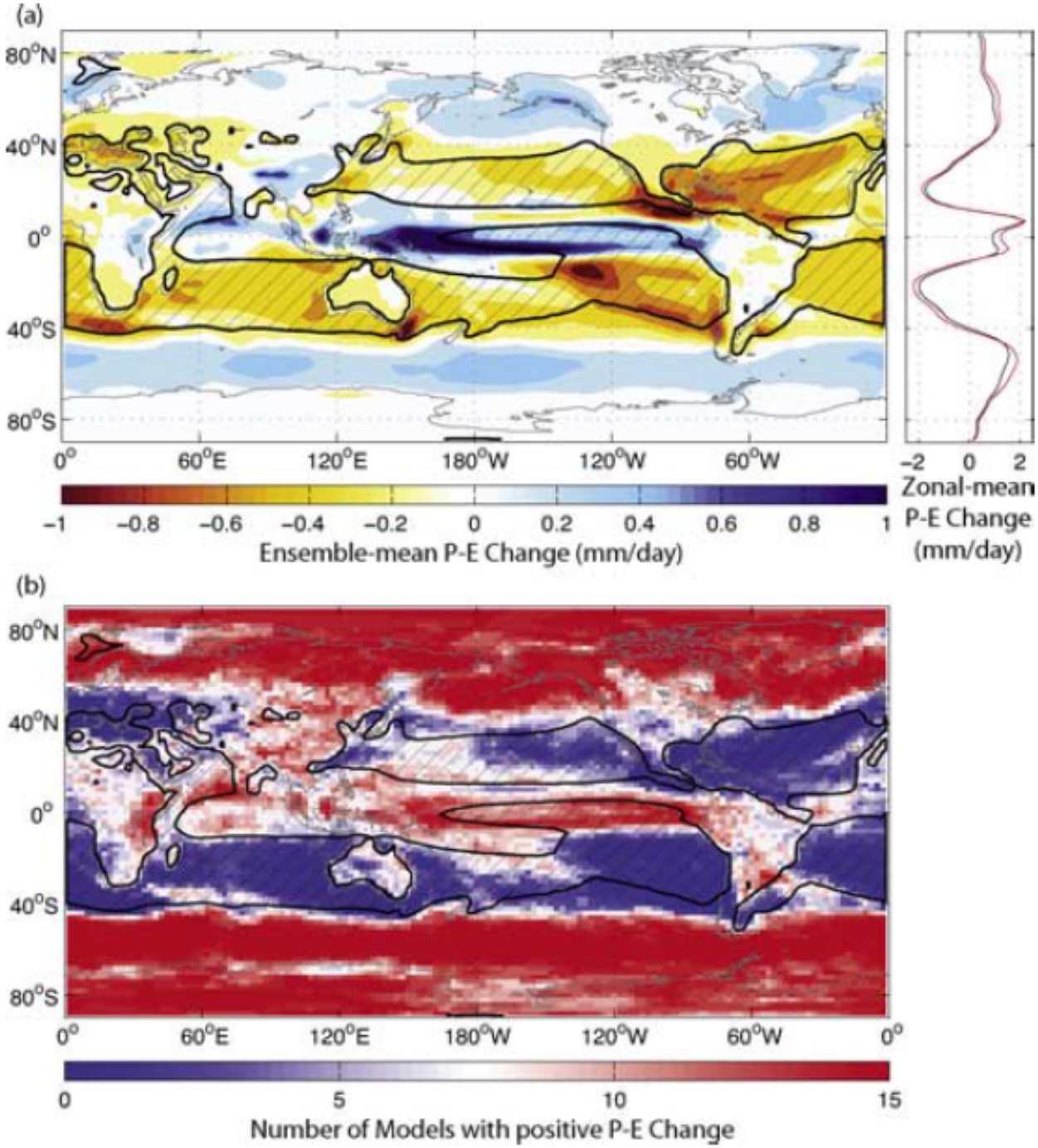
- Drying is expanding into mid-latitudes
- Wetting increased in high latitudes

  ➔ suggest a dynamically-driven precipitation response, linked to poleward shift in midlatitude jets
- Important to consider seasonality; some patterns can be hidden in the annual mean

Expansion of the Hadley cell under global warming

Jian Lu, Gabriel A. Vecchi, and Thomas Reichler

Geophysical Resarch Letters, 2007

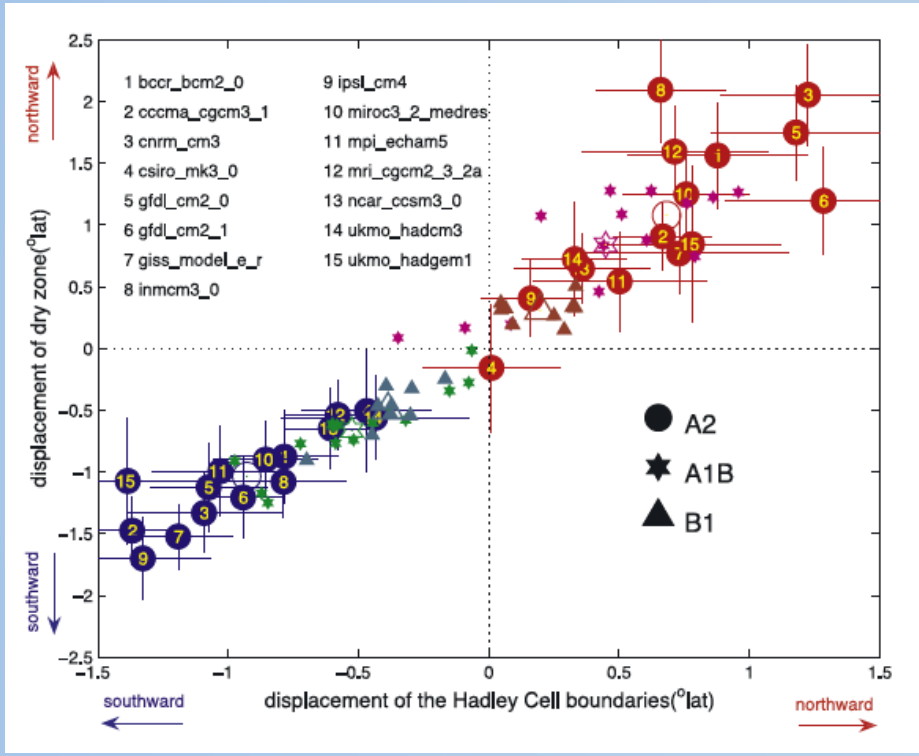

(a)
80°N
40°N
0°
40°S
80°S
0°
60°E
120°E
180°W
120°W
60°W
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Ensemble-mean P-E Change (mm/day)
−2
0
2
Zonal-mean
P-E Change
(mm/day)
(b)
80°N
40°N
0°
40°S
80°S
0°
60°E
120°E
180°W
120°W
60°W
0°
0
5
10
15
Number of Models with positive P-E Change

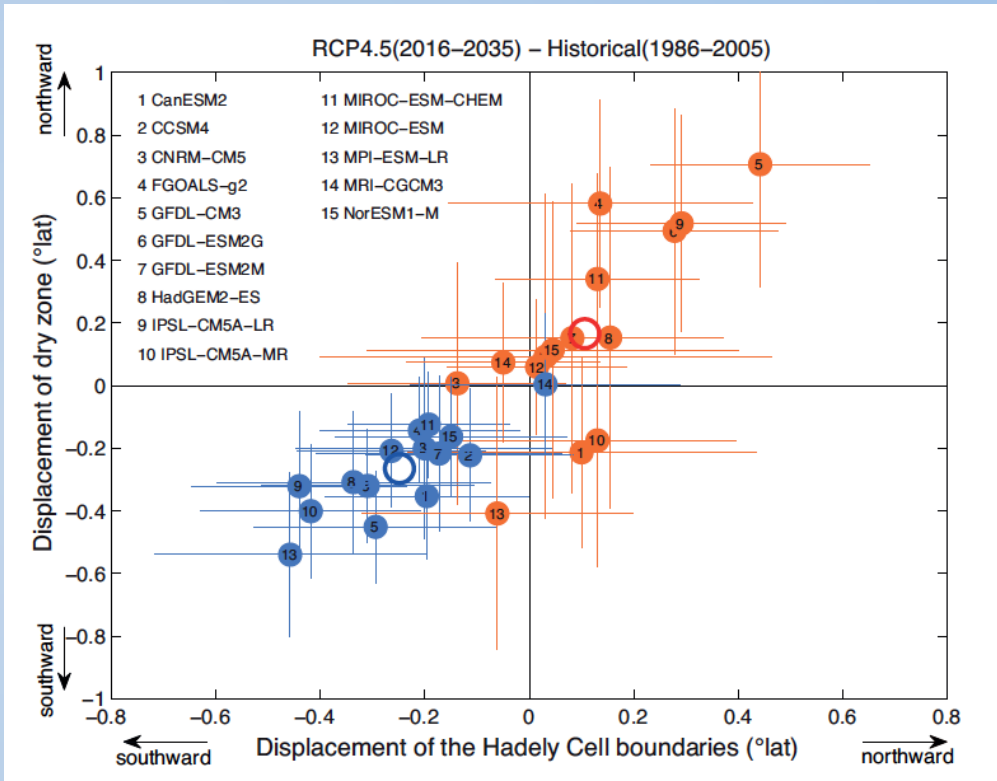
Lu et al., 2007

Does expansion of subtropical dry zone correspond to poleward expansion of the Hadley Cell?

To determine the poleward edges of the Hadley Cell…

- Calculated the zonal-mean mass flux stream function (Ψ) by vertically integrating the zonal-mean density-weighted meridional wind component from the top model level downward
- Calculated the maximum value of Ψ at 500 hPa, Ψ_{500}
- Defined the edge of the HC as the first latitude at which $\Psi_{500} = 0$





Long Term:
2081-2100 – 2001-2010

- 85% in NH and 72% in SH
- Shift of 1°

Lu et al., 2007

Short Term:
2016-2035 – 1986-2005

IPCC AR5, Ch.11

What are the mechanisms of Hadley Cell expansion?

Nearly inviscid theory for axisymmetric circulation

Assumptions:

1. Angular momentum is conserved
2. Hadley Cell is energetically closed

$$\phi_H \sim \left(\frac{\cancel{g} H_t}{\cancel{\Omega^2} \cancel{a^2}} \frac{\Delta_h}{\theta_0} \right)^{\frac{1}{2}}$$

$\phi_H = width\ of\ tropopause$

$g = gravity$

$H_t = height\ of\ Tropical\ tropopause$

$\Omega = angular\ velocity$

$a = earth's\ radius$

$\Delta_h = equator\ to\ pole\ potential\ temperature\ difference$ $in\ radiative\ equilibrium$

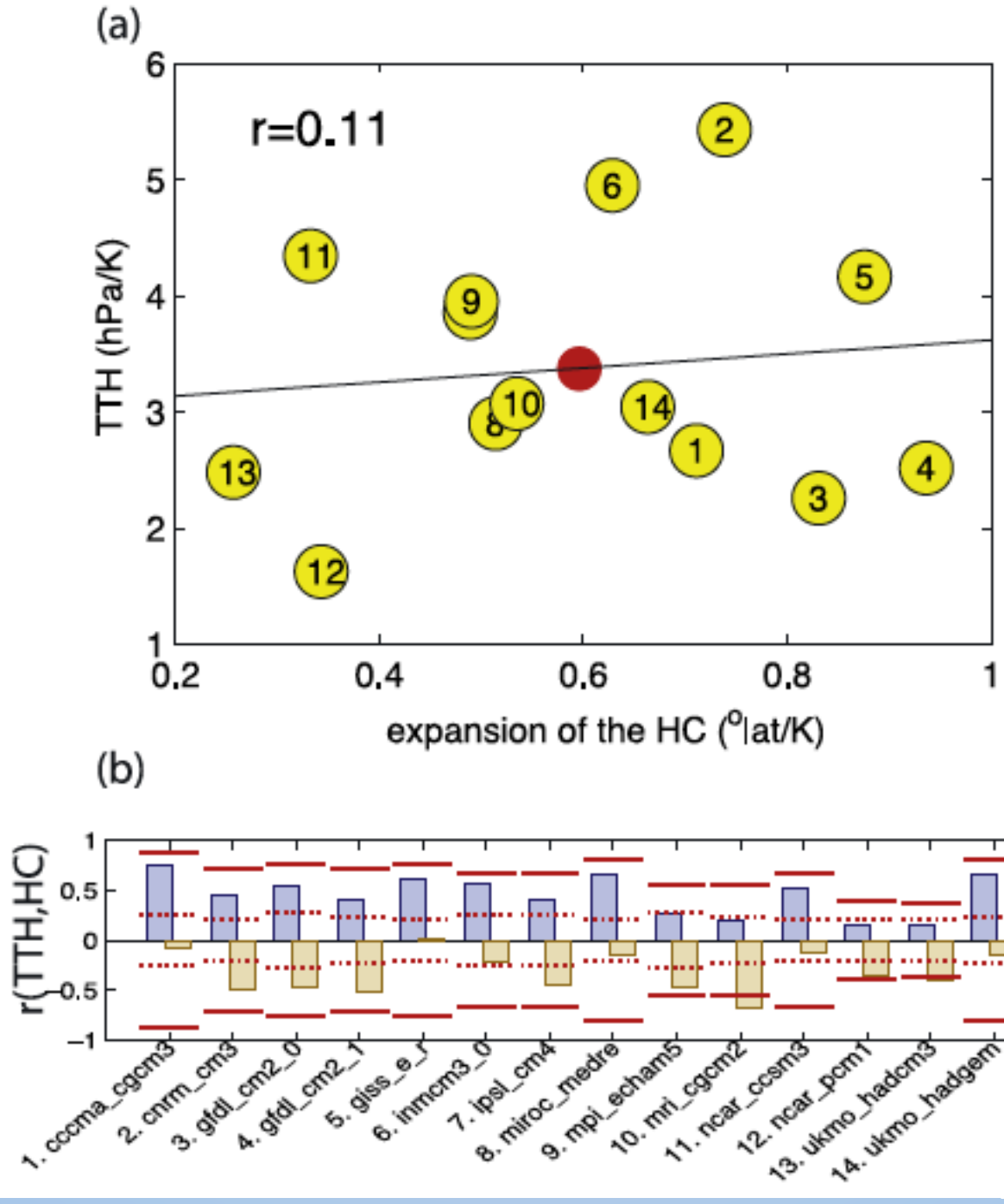
$\theta_0 = global\ mean\ temperature$

$$\phi_H \sim \left(H_t \frac{\Delta_h}{\theta_0} \right)^{\frac{1}{2}}$$

$$\boxed{if\ H_t \uparrow,\ then\ \phi_H \uparrow}$$

$$if\ \Delta_h \uparrow,\ then\ \phi_H \uparrow$$

$$if\ \theta_0 \uparrow,\ then\ \phi_H \downarrow$$


(a)
r=0.11
TTH (hPa/K)
expansion of the HC (°lat/K)
(b)
r(TTH,HC)
1. cccma_cgcm3
2. cnrm_cm3
3. gfdl_cm2_0
4. gfdl_cm2_1
5. giss_e_r
6. inmcm3_0
7. ipsl_cm4
8. miroc_medre
9. mpi_echam5
10. mri_cgcm2
11. ncar_ccsm3
12. ncar_pcm1
13. ukmo_hadcm3
14. ukmo_hadgem

Lu et al., 2007

Considering angular momentum and stability…

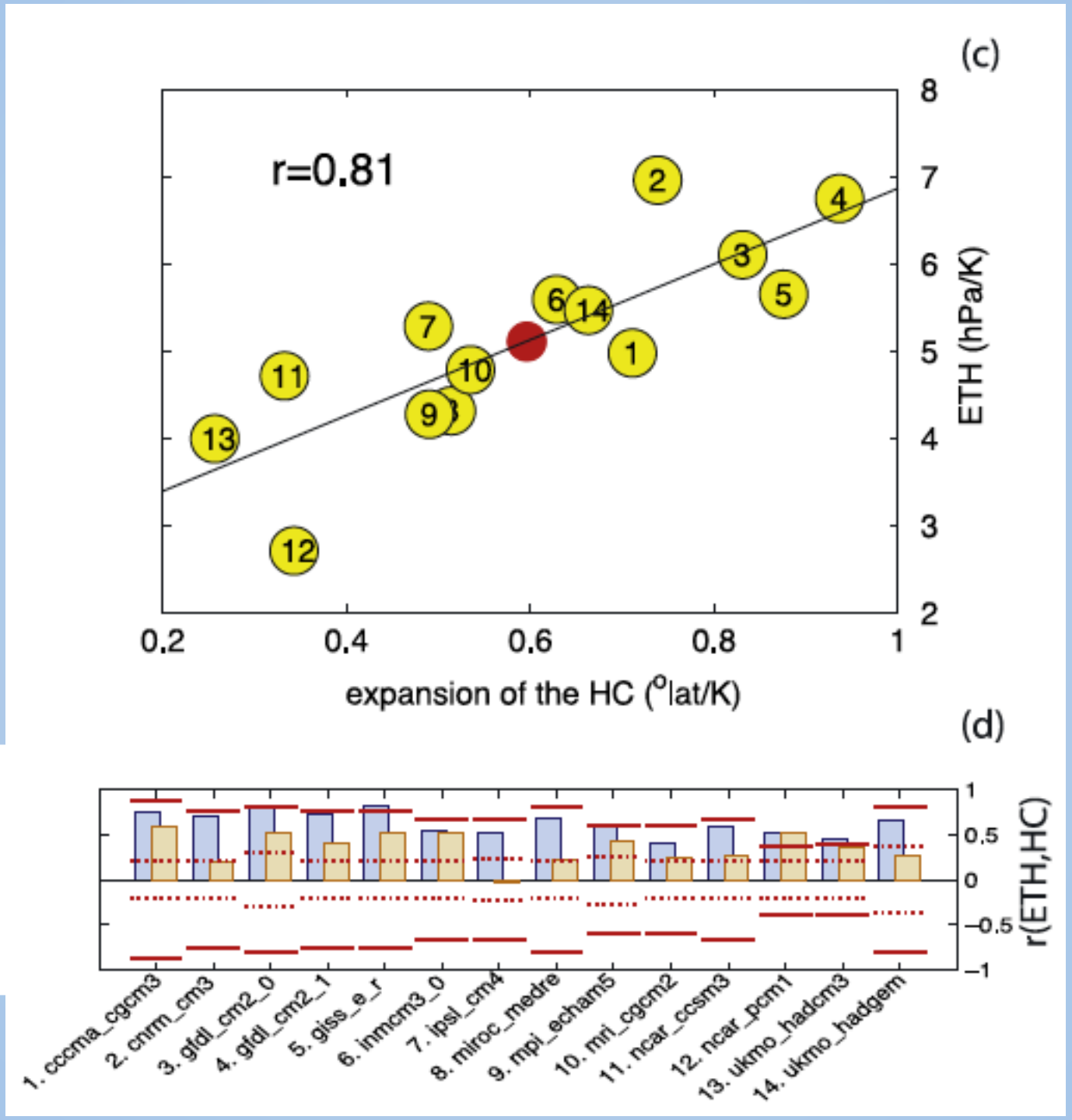
$$\phi_H \propto \left(\frac{NH_e}{\Omega a} \right)^{\frac{1}{2}} \qquad OR \qquad \phi_H \propto \left(\frac{NH_e}{\Omega^2 a} \right)^{\frac{1}{3}}$$

$$N = vertically\ averaged\ Brunt - Vaisala\ frequency$$

$$H_e = local\ tropopause\ height$$

$$\phi_H \propto NH_e$$

$$H_e = ETH\ (35° - 55°\ latitude)$$


(c)
r=0.81
ETH (hPa/K)
expansion of the HC (°lat/K)
(d)
r(ETH,HC)
1. cccma_cgcm3
2. cnrm_cm3
3. gfdl_cm2_0
4. gfdl_cm2_1
5. giss_e_r
6. inmcm3_0
7. ipsl_cm4
8. miroc_medre
9. mpi_echam5
10. mri_cgcm2
11. ncar_ccsm3
12. ncar_pcm1
13. ukmo_hadcm3
14. ukmo_hadgem

Lu et al., 2007

Results and Conclusions

- Subtropical expansion and Hadley Cell expansion are correlated
- TTH and Hadley Cell expansion are not well correlated
- ETH—a good proxy for gross static stability—and Hadley Cell expansion are well correlated

  ➔ suggests that Hadley Cell expansion is largely dynamically driven

Take Away

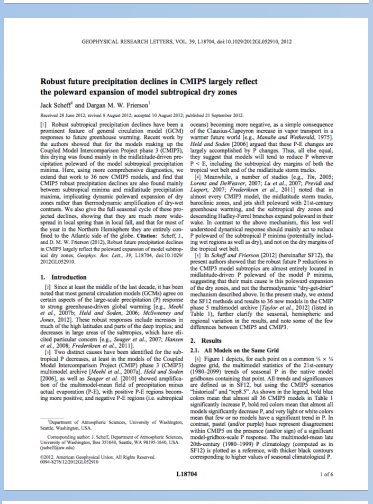
Robust Responses of the Hydrological Cycle to Global Warming

Isaac M. Held

National Oceanic and Atmospheric Administration/Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey

Brian J. Soden

Rosenstiel School for Marine and Atmospheric Science, University of Miami, Miami, Florida



Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones

Jack Scheff and Dargan M. W. Frierson

Expansion of the Hadley cell under global warming

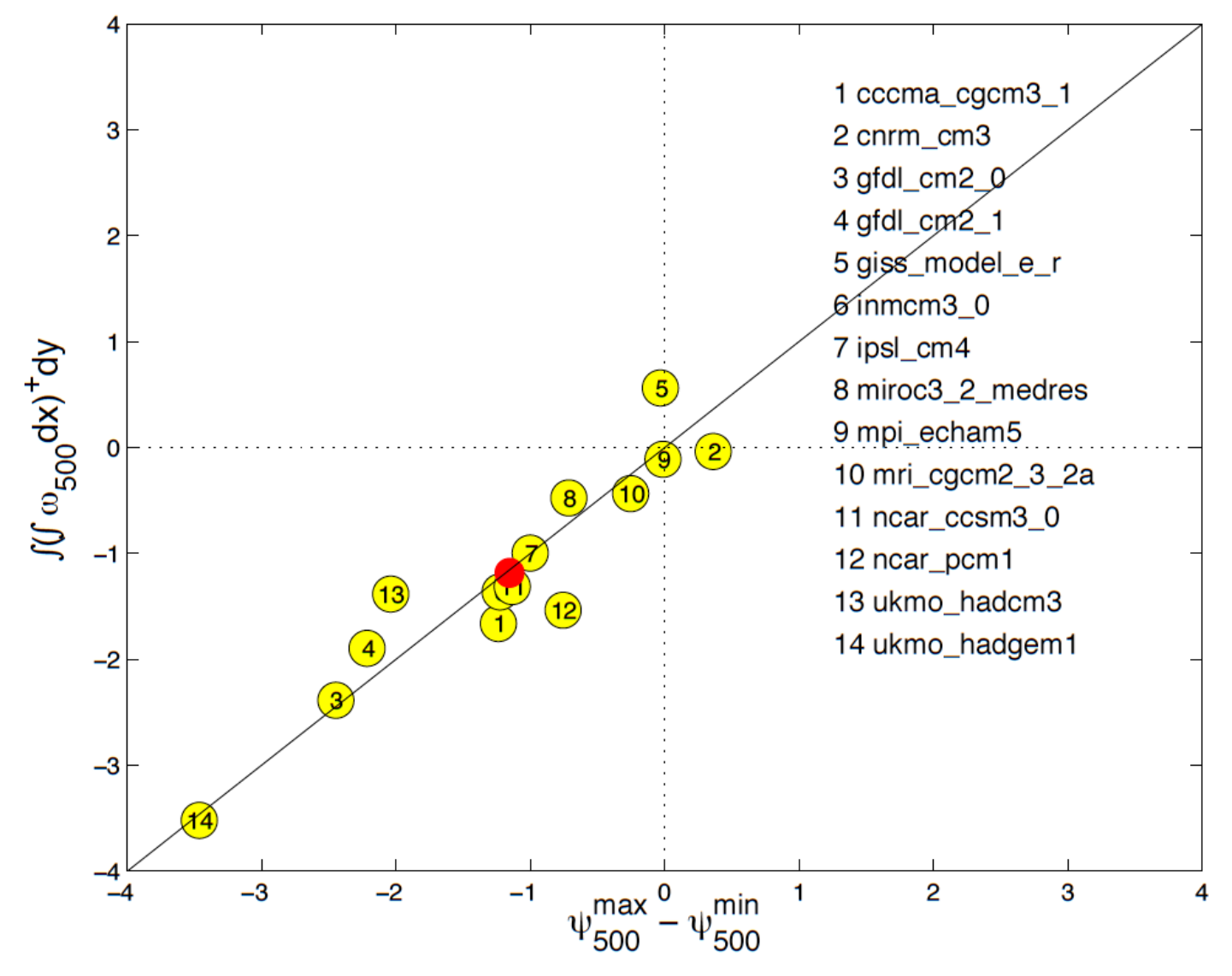
Jian Lu, Gabriel A. Vecchi, and Thomas Reichler

[redacted] wet regions get wetter, dry regions get drier."

- multi-model means can be misleading

- increase in subtropical static stability helps Hadley cell expand poleward

Projected weakening of Hadley circulation (A2)



Lu et al., 2007 (S1)