Changes in Precipitation and the Hadley Cell in a Warming Climate

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

Jack Schuff and Dagan M. W. Frierson

1. Introduction

[1] Since at least the middle of the last decade, it has been noted that most general circulation models (GCMs) agree on certain aspects of the large-scale precipitation (P) response to strong greenhouse-driven global warming (e.g., Mehal et al., 2007; Held and Soden, 2006; McAvaney and Jones, 2012). These robust responses include increases in much of the high latitudes and parts of the dome regions; and decreases in large areas of the subtropics, which have distinct particular concerns (e.g., Gregory et al., 2007; Hansem et al., 2008; Frederiksen et al., 2011).

[1] Two distinct causes have been identified for the subtropical P decreases, at least in the models of the Coupled Model Intercomparison Project (CMIP) phase 3 (CMIP3) multimodel archive (Mashel et al., 2007a); Held and Soden [2006], as well as 34 authors et al. [2010] showed amplification of the multimodel-mean field of precipitation minus actual evaporation (PE), with positive PE regions becoming more positive, and negative PE regions (i.e., subtropical oceans) becoming more negative, as a simple consequence of the Clausius-Clapeyron increase in vapor transport in a warmer future world (e.g., Manabe and Stouffer, 1979). Held and Soden [2006] argued that these PE changes are largely overwhelmed by P changes. Thus, all else equal, they suggest that models will tend to reduce P wherever P − PE increases, e.g., including the subtropical dry margins of both the tropical and middle-latitude storm tracks.

[1] Meanwhile, a number of studies (e.g., 196, 2005; Lorenz and DePuey, 2005; Peterson and Muere, 2007; Frederiksen et al., 2011) noted that in almost every CMIP3 model, the mid-latitude storm tracks, baroclinic zones, and jet stream poleward of 21st-century greenhouse warming, and the subtropical dry zones and descending Hadley-Teleman branches expanded poleward in their wake. In contrast to the above mechanisms, this was well understood dynamical response should simply act to reduce P poleward of the subtropical P maximum (potentially including wet regions as well as dry), and not on the dry margins of the tropical wet belt.

[1] In Schuff and Frierson (2012) (hereinafter SF12), the present authors showed that the robust future precipitation reductions in the CMIP3 model simulations are almost entirely located in midlatitude-driven P poleward of the model P maximum, suggesting that their main cause is this poleward expansion of the dry zones, and not the thermodynamic “dry-wet skier” mechanism described above. In the present study, we revisited the SF12 methods and results from new models in the CMIP3 phase 3 multimodel archive [Taylor et al., 2012] (listed in Table 1), further clarify the seasonal, hemispheric, and regional variations in the results, and note some of the few differences between CMIP3 and CMIP5.

2. Results

2.1. All Models on the Same Grid

[6] Figure 1 depicts, for each model on a common 1° × 1° degree grid, the multimodel statistics of the 21st-century (1880-2009) trends of seasonal P in the native model gridboxes containing that point. All trends and significances are defined as in SF12, but using the CMIP3 scenarios “historical” and “rcp8.5.” As shown in the legend, bold blue colors mean that almost all 34 CMIP3 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, pale (and/or purple) tones correspond to significant differences within CMIP3 on the presence (and/or sign) of a significant model-gridbox-scale P response. The multimodel mean has 20th-century (1880-1999) P climatology (computed as in SF12) plotted as a reference, with thicker black contours corresponding to higher values of seasonal climatological P.
Were they wrong?

Robust responses of the hydrological cycle to global warming
IM Held, BJ Soden - Journal of Climate, 2006 - journals.ametsoc.org
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 ...
Overview

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 Aways

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

\[
\frac{\delta q}{q} \approx 0.07 \delta T
\]

\[
\frac{\delta P}{P} \approx 0.02 \delta T
\]
\[ P \approx Mq \]

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

\[
\frac{\delta M}{M} \approx \frac{\delta P}{P} - \frac{\delta q}{q}
\]

\[
\frac{\delta M}{M} \approx 0.02 \delta T - 0.07 \delta T = -0.05 \delta T
\]
Wait!

This is an argument based on \( \frac{\delta P}{P} \approx 0.02 \delta T \).

This result is purely model derived.

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!
Global Average Precipitation

Column moisture: \[ \left\langle \frac{\partial q}{\partial t} \right\rangle = \frac{1}{L_v} SLHF - P - \left\langle \nabla \cdot (q \vec{V}) \right\rangle \]
Global Average Precipitation

Column moisture: \[ \left\langle \frac{\partial q}{\partial t} \right\rangle = \frac{1}{L_v} SLHF - P - \left\langle \nabla \cdot (q \vec{V}_H) \right\rangle \]
Global Average Precipitation

Column moisture: \( \langle \frac{\partial q}{\partial t} \rangle = \frac{1}{L_v} SLHF - P - \langle \nabla \cdot (q \nabla H) \rangle \)

Let’s consider **steady state** and take the **global average**
Global Average Precipitation

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

Surface energy: \[ \frac{\partial E_s}{\partial t} = R_s - SLHF - SSHF + \Delta F_{ocean} \]
Global Average Precipitation

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Let’s consider steady state and take the global average.
Column moisture: \[ P = \frac{1}{L_v} SLHF \]

Surface energy: \[ SLHF = R_s - SSHF \]
Global Average Precipitation

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

Surface energy: \[ SLHF = R_s - SSHF \]

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

<table>
<thead>
<tr>
<th></th>
<th>RCP4.5</th>
<th>RCP8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Global</strong></td>
<td>1.0 - 3.0%</td>
<td>1.0 - 2.25 %</td>
</tr>
<tr>
<td><strong>Land</strong></td>
<td>-1.5 - 4.0%</td>
<td>0 - 4%</td>
</tr>
<tr>
<td><strong>Ocean</strong></td>
<td>0.5 - 3.0%</td>
<td>0.5 - 2.5%</td>
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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:
\[
\frac{\partial q}{\partial t} = \frac{1}{L_v} SLHF - P - \langle \nabla \cdot (q \vec{V}_H) \rangle
\]
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

\[ \delta(P - E) = 0.07 \delta T (P - E) \]

“The pattern of P-E is simply enhanced, becoming more positive where it is already positive and more negative where it is negative.”
“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.”
\[ \delta(P - E) \]

AR4 models

Predicted from simple equation using \( \delta T \)

Average over all seasons

Multi-model mean

Held and Soden point this out many times

\[ \delta(P - E) \text{ not } \delta P \]
Robust future precipitation declines in CMIP5 largely reflect the poleward expansion of model subtropical dry zones

Jack Scheff and Dargan M. W. Frierson
Geophysical Research 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.
Latitude of Minimum Precipitation

+= present
+= future

Model

<table>
<thead>
<tr>
<th>Latitude</th>
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<tbody>
<tr>
<td>23</td>
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<td>22</td>
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<td>21</td>
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<td>20</td>
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<td>19</td>
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<td>18</td>
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</tbody>
</table>

Model

1  2  3  4  5  MMM
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
FIG. 3. (top) Black curve shows a sample late twentieth-century climatological $P$ vs latitude profile, from the zonal average of the $(290^\circ, 300^\circ\text{E})$ 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 $15^\circ\text{S}$ 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.
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 Research Letters, 2007
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 ($\Psi$) by vertically integrating the zonal-mean density-weighted meridional wind component from the top model level downward
- Calculated the maximum value of $\Psi$ at 500 hPa, $\Psi_{500}$
- 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

\[ \phi_H \sim \left( \frac{gH_t}{\Omega^2 a^2 \theta_0} \right)^{\frac{1}{2}} \]

- \( \phi_H = \text{width of tropopause} \)
- \( g = \text{gravity} \)
- \( H_t = \text{height of Tropical tropopause} \)
- \( \Omega = \text{angular velocity} \)
- \( a = \text{earth's radius} \)
- \( \Delta_h = \text{equator to pole potential temperature difference in radiative equilibrium} \)
- \( \theta_0 = \text{global mean temperature} \)
\[ \phi_H \sim \left( H_t \frac{\Delta_h}{\theta_0} \right)^{\frac{1}{2}} \]

- if \( H_t \uparrow \), then \( \phi_H \uparrow \)
- if \( \Delta_h \uparrow \), then \( \phi_H \uparrow \)
- if \( \theta_0 \uparrow \), then \( \phi_H \downarrow \)
Lu et al., 2007

(a) 

$\text{r} = 0.11$

(b)
Considering angular momentum and stability...

\[ \phi_H \propto \left( \frac{NH_e}{\Omega a} \right)^{\frac{1}{2}} \quad OR \quad \phi_H \propto \left( \frac{NH_e}{\Omega^2 a} \right)^{\frac{1}{3}} \]

\[ N = \text{vertically averaged Brunt–Vaisala frequency} \]

\[ H_e = \text{local tropopause height} \]
$$\phi_H \propto NH_e$$

$$H_e = ETH \ (35^\circ - 55^\circ \text{ latitude})$$
Lu et al., 2007

(c) 

\[ r = 0.81 \]

Expansion of the HC (°lat/K)

ETH (hPa/K)

(d) 

\([\text{ETH,HC}]^2\)
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
- multi-model means can be misleading

- increase in subtropical static stability helps Hadley cell expand poleward
Projected weakening of Hadley circulation (A2)