Understanding Recent and Projected Changes in the Atmospheric Water Cycle

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I. Water Vapor
CMIP3 Models (20C3M)

\[ \Delta q \text{ (\%)} \]

\[ \Delta T \text{ (K)} \]

Held and Soden 2006
Comparison with Observations

(A) 2σ confidence interval
1σ confidence interval
Average of 12 ALL models
Observations (SSM/I)

(B) Stratospheric aerosol optical depth

Santer et al. 2007
Response to Eruption of Mount Pinatubo

Soden et al. 2002
Response to Eruption of Mount Pinatubo

Soden et al. 2002
The Clausius–Clapeyron Equation

\[
\frac{d \ln e_s}{dT} = \frac{L_v}{R_v T^2} \equiv \alpha(T)
\]
The Clausius–Clapeyron Equation

Saturation vapor pressure: caps amount of water vapor

\[
\frac{d \ln e_s}{dT} = \frac{L_v}{R_v T^2} \equiv \alpha(T)
\]
The Clausius–Clapeyron Equation

\[ \frac{d \ln e_s}{dT} = \frac{L_v}{R_v T^2} \]

- Saturation vapor pressure
- Latent heat of vaporization (~2.5 × 10^6 J kg\(^{-1}\))
- Gas constant for water vapor (461 J K\(^{-1}\) kg\(^{-1}\))
- Temperature (~280 K)
The Clausius–Clapeyron Equation

\[ \frac{d \ln e_s}{dT} = \frac{L_v}{R_v T^2} \sim 7\% \text{ K}^{-1} \]
<table>
<thead>
<tr>
<th>( \Delta \text{WV} )</th>
<th>Column WV</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3% K(^{-1}) (6.5–8.2% K(^{-1}))</td>
<td>21(^{st}) century</td>
<td>CMIP3 Models (A1B–20C3M) O’Gorman &amp; Muller 2010</td>
</tr>
<tr>
<td>7.4% K(^{-1}) (6.3–8.5% K(^{-1}))</td>
<td>Constant RH</td>
<td>CMIP3 Models (A1B–20C3M) O’Gorman &amp; Muller 2010</td>
</tr>
<tr>
<td>7.9% K(^{-1}) (6.6–9.3% K(^{-1}))</td>
<td>Saturation</td>
<td>CMIP3 Models (A1B–20C3M) O’Gorman &amp; Muller 2010</td>
</tr>
<tr>
<td>6.9±3.6% K(^{-1})</td>
<td>1988–2006</td>
<td>SSMI Santer et al., 2007</td>
</tr>
<tr>
<td>6.6±0.4% K(^{-1})</td>
<td>1989–2008</td>
<td>SSMI/ERA-Interim O’Gorman et al. 2012</td>
</tr>
</tbody>
</table>
Zonal Mean Specific Humidity Change

O’Gorman and Muller 2010
Zonal Mean Relative Humidity Changes

Wright et al. 2010
Zonal Mean Relative Humidity Changes

Temperature Change

Circulation Change

Wright et al. 2010
The Zonal Mean Tropical Circulation
The Zonal Mean Tropical Circulation

Wright et al. 2010
Regional Relative Humidity Changes

(a) Relative humidity (%) at 500hPa

(b) Change in relative humidity (%K$^{-1}$) at 500hPa

(c) Surface relative humidity (%)

(d) Change in surface relative humidity (%K$^{-1}$)

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O’Gorman and Muller 2010
<table>
<thead>
<tr>
<th>ΔWV</th>
<th>Surface WV</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.7% K(^{-1})</td>
<td>21(^{st}) century</td>
<td>CMIP3 Models (A1B–20C3M) O’Gorman &amp; Muller 2010</td>
</tr>
<tr>
<td>(5.2–6.2% K(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.9% K(^{-1})</td>
<td>Saturation</td>
<td>CMIP3 Models (A1B–20C3M) O’Gorman &amp; Muller 2010</td>
</tr>
<tr>
<td>(5.2–6.4% K(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.4±1.0% K(^{-1})</td>
<td>1973–1999</td>
<td>HadCRUH Willett et al. 2010</td>
</tr>
</tbody>
</table>

Willett et al. 2010
Regional Specific Humidity Changes

Willett et al. 2010
Summary

• Changes in global mean water vapor are tightly constrained by changes in temperature

• These changes can be understood in the context of constant global mean relative humidity

• There are significant regional departures from constant relative humidity

• Climate model and observational estimates of water vapor change are largely consistent

• Future changes in water vapor appear likely to be similar to changes in the recent past
II. Precipitation
Simulated Precipitation Change (2×CO₂)
<table>
<thead>
<tr>
<th>$\Delta P$</th>
<th>Precipitation</th>
<th>source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim 3.4% K^{-1}$</td>
<td>$2 \times CO_2$</td>
<td>CMIP2 Models (slab ocean) Allen &amp; Ingram 2002</td>
</tr>
<tr>
<td>$\sim 2.2% K^{-1}$</td>
<td>$20^{\text{th}}$ century</td>
<td>CMIP3 Models (20C3M) Held &amp; Soden 2006</td>
</tr>
<tr>
<td>$\sim 1.7% K^{-1}$</td>
<td>$21^{\text{st}}$ century</td>
<td>CMIP3 Models (A1B) Held &amp; Soden 2006</td>
</tr>
<tr>
<td>$7.0 \pm 2.5% K^{-1}$</td>
<td>1988–2006</td>
<td>SSMI/GPCPv2 Wentz et al. 2007</td>
</tr>
<tr>
<td>$2.5% K^{-1}$</td>
<td>1900–2000</td>
<td>CCA (Smith et al. 2009) Arkin et al. 2010</td>
</tr>
<tr>
<td>$1.3 \pm 2.0% K^{-1}$</td>
<td>1988–2009</td>
<td>GPCP v2.1 Li et al. 2011</td>
</tr>
<tr>
<td>$3.4 \pm 0.9% K^{-1}$</td>
<td>1989–2008</td>
<td>GPCP v2.2 O’Gorman et al. 2012</td>
</tr>
</tbody>
</table>
Atmospheric Energy Balance

\[ L_v P = R_{TOA} - R_{SFC} - SH \]
Atmospheric Energy Balance

\[ L_v P = R_{TOA} - R_{SFC} - SH \]

- **net radiative flux at the top of the atmosphere**
- **sensible heat flux into the atmosphere**
- **latent heating of the atmosphere**
- **net radiative flux at the base of the atmosphere**

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Atmospheric Energy Balance

CMIP3 1pctto2x Simulations

$\Delta P (W \cdot m^{-2})$

$\Delta R_{net} (W \cdot m^{-2})$

Stephens and Ellis 2008
Atmospheric Energy Balance

\[ L_v P = R_{TOA} - R_{LCL} \]
Atmospheric Energy Balance

(a) Greenhouse Gas Forcing
- SW absorbed (SFC)
- Net radiative loss (atmosphere)
- Net radiative loss (free atmosphere)

(b) Solar Forcing

Precipitation (mm day⁻¹)
Surface air temperature (K)

O’Gorman et al. 2012
Decomposing the Precipitation Response

Feedback strength (W m\(^{-2}\) K\(^{-1}\))

-2.0  -1.5  -1.0  -0.5  0.0  0.5  1.0

WV  LR  WV+LR  PI  C  SH  ALL

RH fixed

O’Gorman et al. 2012
Different Sensitivity to Different Forcings

Andrews et al. 2009
Decomposing the Precipitation Response

(a)

- Total
- Slow

```
dP/dT (% K⁻¹)
```

- CO₂
- Solar
- SO₄
- BC

O’Gorman et al. 2012
Decomposing the Precipitation Response

(b) $-\delta AA$, $L\delta P$, $-\delta SH$, $k_r \delta T$

$\sigma$-level at which BC added

$W m^{-2}$

O’Gorman et al. 2012
Water Vapor Fluxes and Precipitation

\[ F = \rho V L_v q \]
Water Vapor Fluxes and Precipitation

\[ F = \rho V L_v q \]

- **density**
- **meridional velocity**
- **specific humidity [kg kg\(^{-1}\)]**
Water Vapor Fluxes and Precipitation

\[ F = \rho V_L \nu q \]

- Density
- Meridional velocity
- Specific humidity [kg kg\(^{-1}\)]

\[ \frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T \]
Projected Changes in Water Vapor Flux

Full model ensemble mean

Thermodynamic estimate based on $\alpha \delta T$

Held and Soden 2006
Simulated Precipitation Change (2×CO$_2$)

Allen and Ingram 2002
Observed Precipitation Change (1979–2007)

Zhou et al. 2011
The Energetics of Regional Precipitation Change

\[ L_v P = R_{\text{NET}} - SH + \cdots \]
The Energetics of Regional Precipitation Change

Muller and O’Gorman 2011
The Energetics of Regional Precipitation Change

\[ L_v P = R_{\text{NET}} - SH + H \]
The Energetics of Regional Precipitation Change

Muller and O’Gorman 2011
The Energetics of Regional Precipitation Change

Muller and O’Gorman 2011
Simulated Mean and Extreme Precipitation Changes

Emori and Brown 2011
Summary

• Global mean precipitation changes are not tightly constrained by temperature, although temperature changes appear to dominate water vapor flux changes.

• Changes in precipitation are constrained by the energy budget of the atmosphere, especially the free atmosphere.

• There are substantial differences between climate model and observational estimates of precipitation changes, as well as between different observational estimates.

• Regional changes in precipitation appear to reinforce existing patterns: wet regions get wetter, while dry regions get drier.