Changes in the distribution of rain frequency and intensity in response to warming

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Changes in the distribution of rain

1. Introduction
   – Why the distribution would change

2. Theory
   – Shift and increase modes of change

3. Response to CO$_2$ increase in CMIP5 models
   – Shift + Increase modes
   – Extreme mode
Moisture increases, Precipitation increases less

Moisture increases at 7%/K

Precipitation increases at 1-3%/K

Held and Soden (2006)
Extreme precipitation increases with moisture

Allen and Ingram (2002)
Rain distribution should change shape

- Global-mean rainfall increases by 2 \( \%K^{-1} \)
- Extreme rain rate increases by around 7 \( \%K^{-1} \)

- The distribution must change
  - Less frequent, more intense rainfall

Trenberth (1999)
How can we quantify the relationships among changes in global-mean rainfall, extreme rain rate, and the rest of the distribution of rain?
Daily precipitation data

- Rain rate in mm/day

- Climate model simulations
  - CMIP5 Carbon dioxide increase (1pctCO2)
  - 22 models

- Observations
  - Global Precipitation Climatology Project (GPCP) 1 Degree Daily
  - 1997-2012
Methodology

• Calculate both rain frequency and rain amount distributions

• Average globally

• Dry threshold of less than 0.1 mm/d

• Logarithmic rain rate axis
Rain rate \( r \) is in mm d\(^{-1}\), though we log coordinate so it. The cumulative distribution of rain amount \( P(r) \) is,
\[
P(r) = \int_{\ln r_{\text{min}}}^{\ln r} p(ln ˙r) \, d\ln ˙r,
\]
where \( p(ln r) \) is the precipitation density function. Dots indicate functions. The units of \( P \) are mm d\(^{-1}\), and \( p = \frac{dP}{d\ln r} \). The total rainfall (the global mean precipitation) is \( P(\infty) = P(r_{\text{max}}) \). The dry day threshold is \( r_{\text{min}} \), and the maximum daily rainfall in our dataset is \( r_{\text{max}} \). We assume \( P(r_{\text{min}}) = 0 \). The cumulative distribution of rain amount \( F(r) \) is,
\[
F(r) = \int_{-\infty}^{\ln r} f(ln ˙r) \, d\ln ˙r = F_{\text{dry}} + \int_{\ln r_{\text{min}}}^{\ln r} f(ln ˙r) \, d\ln ˙r,
\]
where \( f(ln r) \) is the probability density function for rain, and \( F(\infty) = F(r_{\text{max}}) = 1 \). \( F_{\text{dry}} = F(r_{\text{min}}) \) is the dry day frequency. The rainfall amount (\( p \)) and rain frequency (\( f \)) distributions are related by,
\[
p(ln r) = rf(ln r),
\]
and

\[
\begin{align*}
\text{Rain frequency} & \quad \text{Rain amount} \\
\begin{array}{c}
\begin{array}{c}
\text{Rain rate (mm/d)}
\end{array}
\end{array} & \begin{array}{c}
\begin{array}{c}
\text{Rain amount (mm/d)}
\end{array}
\end{array}
\end{align*}
\]

\[
\begin{array}{c}
\begin{array}{c}
\text{Multi−model mean}
\end{array}
\end{array} & \begin{array}{c}
\begin{array}{c}
\text{Model 95% confidence}
\end{array}
\end{array} & \begin{array}{c}
\begin{array}{c}
\text{GPCP}
\end{array}
\end{array}
\end{align*}
\]
Models vary in their fidelity to observations

Rain amount

- MPI–ESM–LR
- IPSL–CM5A–LR
- BCC–CSM1.1

Model
Observations

Rain rate (mm/d)
How could the distribution of precipitation change?

- It could rain more often (and be dry less often)

**Increase mode**

- Rain frequency and amount increase by the same fraction at all rain rates

\[ p'(\ln r) = (1 + a)p(\ln r) \]

\[ f'(\ln r) = (1 + a)f(\ln r) \]

- Total rain increases
How else could the distribution of precipitation change?

- It could rain harder

**Shift mode**
- The same amount of rain falls at higher rain rates

\[
p'(\ln r) = p(\ln r - b)
\]
\[
f'(\ln r) = e^{-b}f(\ln r - b)
\]
- Total rain **does not** change
Figure 12.41: Patterns of temperature (left column) and percent precipitation change (right column) by the end of the 21st century (2081–2100 vs 1986–2005), for the CMIP3 models average (first row) and CMIP5 models average (second row), scaled by the corresponding global average temperature changes.

Shifts in space

IPCC AR5 WG1 Fig. 12.41
Multi-model mean rain distribution response to CO$_2$ increase

Rain amount

Rain rate (mm/d)
Fit the shift and increase modes
Best fit shift-plus-increase

\[
\begin{align*}
    \text{a} & \quad \text{Increase: } 0.9 \ \% K^{-1} \\
    \text{b} & \quad \text{Shift: } \quad 3.3 \ \% K^{-1}
\end{align*}
\]
Repeat for every model

Average of models

- Shift 3.3 %K⁻¹
- Increase 1.1 %K⁻¹
Change in extreme rain:
Multi-model mean response to CO$_2$ increase

Figure 4.8: Extreme precipitation response (% K$^{-1}$) for CMIP5 multi-model mean CO$_2$ doubling (black) and the shift-plus-increase (magenta). Percent change in rain rate per degree warming by percentile of the cumulative frequency distribution. Gray lines show 95% confidence of the multi-model mean response.
Models have different responses

- MPI–ESM–LR
  - Model response
  - Shift+increase

- IPSL–CM5A–LR
  - Model response
  - Shift+increase

- GFDL–ESM2G
  - Model response
  - Shift+increase

Rain rate change (%/K)

Percentile

Rain rate (%/K)
Extreme mode falls as resolved precipitation increases.

Figure 4.12: MPI-ESM-LR (top), IPSL-CM5A-LR (middle), and GFDL-ESM2G (bottom) showing the change in rain amount and rain rate for RCP8.5. The model response is shown in black, the shift+increase in pink, and the unresolved precipitation change in orange.

Conclusions

• Most of the increase in total rainfall in response to global warming comes as the increase mode—a uniform increase at all rain rates.
  – Some of the rest comes from the extreme mode, which occurs in only some models.

• The increase in extreme rain occurs as a shift of the distribution to higher rain rates in some models
  – In other models it occurs as an extreme mode.
Read more:
• Submitted to *Journal of Climate*
  – Drafts at www.atmos.washington.edu/~angie

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