Global Warming without Global Mean Precipitation Increase?

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Global Hydrological Cycle

Higher surface temperature $\rightarrow$ increased evaporation $\rightarrow$ more precipitation?

Yes □

No □
Global Hydrological Cycle

for CO₂ increase global models yield

- ∼7% increase water vapor mixing ratio per kelvin temperature increase (in agreement with expectation according to Clausius-Clapeyron relation)

- ∼2% increase in surface precipitation per kelvin temperature increase ("muted response")
Global Hydrological Cycle

- $q_{vapor}$: planetary boundary layer
- M: upward mass flux
- P: precipitation
Global Hydrological Cycle

\[ P = Mq \]

- Precipitation
- Upward mass flux out of the boundary layer
- Water vapor mixing ratio in the boundary layer
Global Hydrological Cycle

for CO$_2$ increase global models yield

- $\sim 7\%$ increase in water vapor mixing ratio per Kelvin temperature increase (in agreement with expectation according to Clausius-Clapeyron relation)

- $\sim 2\%$ increase in surface precipitation per Kelvin temperature increase ("muted response")

- overall circulation slowdown

Held and Soden, J. Climate, 2006

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Global Tropospheric Heat Budget

if sensible heat flux is assumed to remain constant:

\[ \Delta R_n = L \Delta P \]

- perturbation radiative cooling
- precipitation perturbation

- precipitation change limited by capability of the troposphere to radiate away heat
Response to CO$_2$ increase

- CO$_2$ absorbs terrestrial radiation
- makes it harder to radiate away heat directly
- expect slowdown of subsiding branch of Hadley circulation
- adding CO$_2$ at fixed surface temperature leads to precipitation decrease
- found out long ago in some of the very early atmosphere-only model runs
Response to CO$_2$ increase

- CO$_2$ radiative effect dampens precipitation response to surface warming
Response to Aerosols

- Aerosols mainly scatter and/or absorb solar radiation
- Expect weaker damping
- Expect larger hydrological sensitivity
Coupled Climate Model Data

Coupled Model Intercomparison Project, Phase 5 (CMIP5)

- single-forcing runs from 15 models:
  - only greenhouse anthropogenic gases (historicalGHG, 46 runs)
  - only anthropogenic aerosols (historicalAero, 28 runs, only 8 models)
- all forcings (historical, 71 runs)
Surface Temperature Change

CMIP5 pre-industrial to near present day

ΔT_a (K)

GHG

all forcings

eaerosol
cold

medium

warm
Precipitation Change

- CMIP5 pre-industrial to near present day

\[
\Delta pr \text{ (mm day}^{-1}\text{)}
\]

- GHG
- all forcings
- aerosol

- cold
- medium
- warm
Hydrological Sensitivity

\[ hs = \frac{\delta P (\text{in } \%) }{\delta T} \]

- percentage change of precipitation per K warming or cooling
Hydrological Sensitivity

- CMIP5 pre-industrial to near present day

\( \frac{\Delta p_r}{\Delta T_a} \) (% K\(^{-1}\))

- aerosol
- GHG
- all forcings

cold  medium  warm
Hydrological Sensitivity - Result

- only GHG: $1.7 \pm 0.4\%K^{-1}$
- only Aerosol: $3.6 \pm 0.5\%K^{-1}$
Hydrological Sensitivity - Result

- Hydrological sensitivity for aerosol is roughly twice as large as that for GHG.

- Similar to the one for temperature surface increase only.

- But still smaller than the $7\% \cdot K^{-1}$ vapor increase (consistent with water vapor radiative feedback).
Strange Formula

since $\Delta T = \Delta T_G + \Delta T_A$ and $\Delta P = \Delta P_G + \Delta P_A$:

$$\frac{\delta P}{\delta T} = \frac{\Delta P_G + \Delta P_A}{\Delta T_G + \Delta T_A}$$

and thus:

$$\Delta P = \frac{\delta P}{\delta T} \Delta T = \left(\frac{\delta P}{\delta T}\right)_G \Delta T_G + \left(\frac{\delta P}{\delta T}\right)_A \Delta T_A$$

where $\left(\frac{\delta P}{\delta T}\right)_G$ and $\left(\frac{\delta P}{\delta T}\right)_A$ are the hydrological sensitivities from the single forcing experiments.
Schematic: changes pre-industrial to recent past

based on CMIP5 models with a realistic 20th century warming
But: effects do not cancel regionally!

- a) GHG
- b) aerosol
- c) all
- d) sum

∆P mm day⁻¹

Future?

- $\Delta T_a$ (K)
- $\Delta pr$ (mm day$^{-1}$)
- $\Delta pr/\Delta T_a$ (% K$^{-1}$)

RCP8.5
RCP4.5

Schematic: future changes

only GHG  only aerosol  sum

light colors: informed guess

temperature  precipitation
Summary

- robust response of the hydrological cycle to aerosol cooling
- models with realistic 20th century warming show almost vanishingly small precipitation increase
- as future will be dominated by CO$_2$ warming clear signal will emerge
thank you!


U.S. contributions:

- contributions to CMIP5 from modeling groups at NOAA, NASA, NCAR
- analysis software: NCL (UCAR/NCAR/CISL/TDD)
- software for data distribution (ESG) from PCMDI/DOE

ongoing mission by NASA and JAXA with other international collaborators: Global Precipitation Measurement (GPM) mission
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Global mean circulation

![Graph](https://example.com/graph.png)
Global Tropospheric Heat Budget

\[ LW_{emi} = SW_{abs} + LW_{abs} + LHF + SHF \]

- Emission of terrestrial radiation
- Absorption of solar radiation
- Absorption of terrestrial radiation
- Latent heat flux
- Sensible heat flux
Global Tropospheric Heat Budget

net radiation balanced by LHF and SHF

\[ R_{net} = LW_{emi} - SW_{abs} - LW_{abs} = LHF + SHF \]

or since globally \( LHF = L P \):

\[ R_{net} = L P + SHF \]

where

- \( L \) latent heat of evaporation
- \( P \) precipitation
Model classification

![Graph showing model classification results](image)


- Y-axis: \( \Delta T_{mod} - \Delta T_{obs} \)
- X-axis: List of models

The graph illustrates the deviation of model predictions (\( \Delta T_{mod} \)) from observed data (\( \Delta T_{obs} \)) for various climate models. The models are color-coded and shown with error bars indicating the range of values.