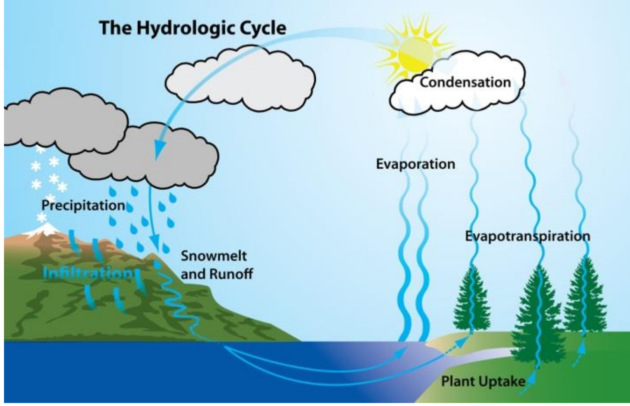

Climate Change and the Hydrological Cycle

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EXPECT

AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL066795

Key Points:

- The fast response to cirrus cloud thinning is qualitatively opposite to that of CO_2 increase
- Cirrus cloud thinning avoids the weakening of the hydrological cycle in solar radiation management
- We present a methodologically simple way to carry out studies of cirrus cloud thinning

Supporting Information:

- Figures S14 and Table S1

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Citation:
Kristjánsson, J. E., H. Muri, and H. Schmidt (2015), The hydrological cycle response to cirrus cloud thinning, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL066795.

Received 29 OCT 2015
Accepted 21 NOV 2015
Accepted article online 25 NOV 2015

The hydrological cycle response to cirrus cloud thinning

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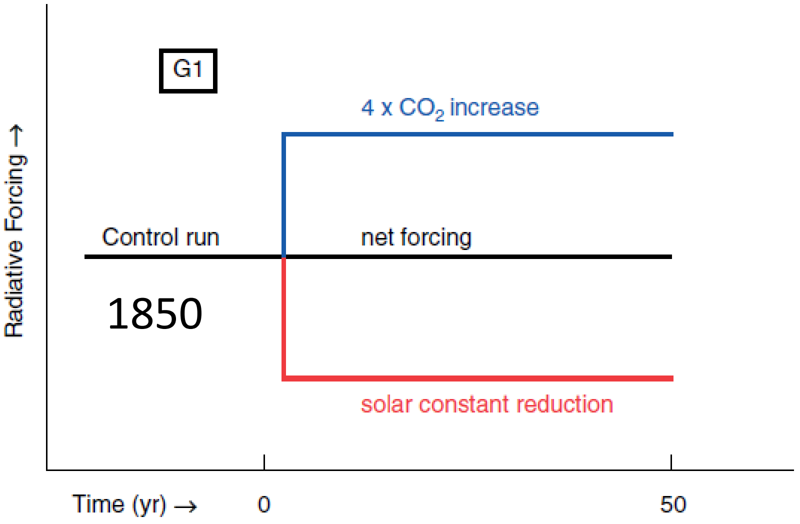
Abstract Recent multimodel studies have shown that if one attempts to cancel increasing CO_2 concentrations by reducing absorbed solar radiation, the hydrological cycle will weaken if global temperature is kept unchanged. Using a global climate model, we investigate the hydrological cycle response to "cirrus cloud thinning (CCT)," which is a proposed climate engineering technique that seeks to enhance outgoing longwave radiation. Investigations of the "fast response" in experiments with fixed sea surface temperatures reveal that CCT causes a significant enhancement of the latent heat flux and precipitation. This is due to enhanced radiative cooling of the troposphere, which is opposite to the effect of increased CO_2 concentrations. By combining CCT with CO_2 increase in multidecadal simulations with a slab ocean, we demonstrate a systematic enhancement of the hydrological cycle due to CCT. This leads to enhanced moisture availability in low-latitude land regions and a strengthening of the Indian monsoon.

1. Introduction

Due to slow progress in reducing anthropogenic greenhouse gas emissions and growing concern about the consequences of global warming, increasing attention is being paid to alternative ways of cooling down the climate [e.g., *Crutzen*, 2006; *Schäfer et al.*, 2015]. These so-called "climate engineering" (CE) or "geoengineering" techniques are often divided into two fundamentally different sets of approaches: greenhouse gas removal and solar radiation management (SRM). Cirrus cloud thinning is a form of radiation management (RM), which is different from SRM, because it is the longwave part of the electromagnetic spectrum that is targeted, as opposed to the shortwave.

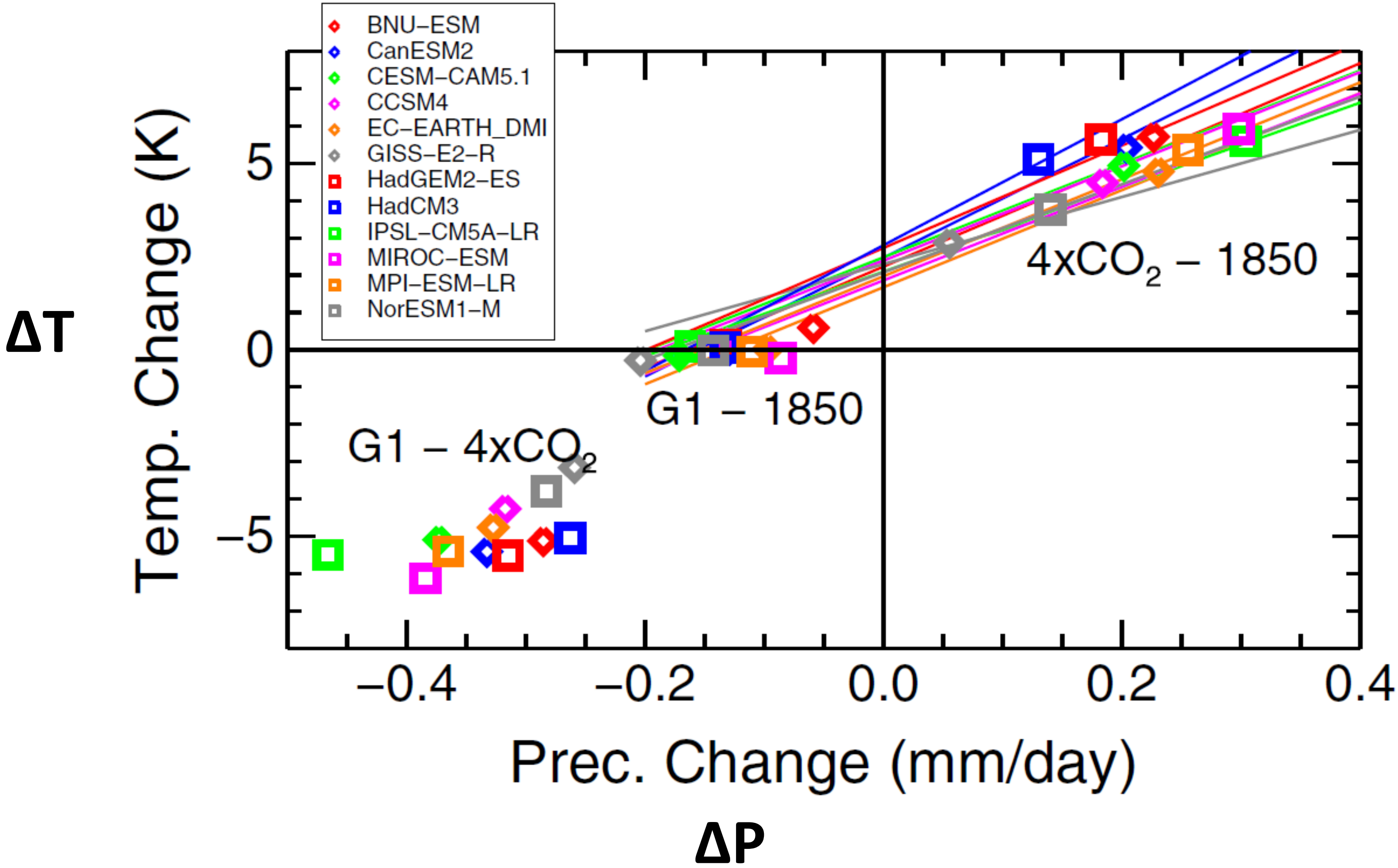
GeoMIP: Idealized Climate Engineering experiments with GCMs

- The **GeoMIP G1** experiment



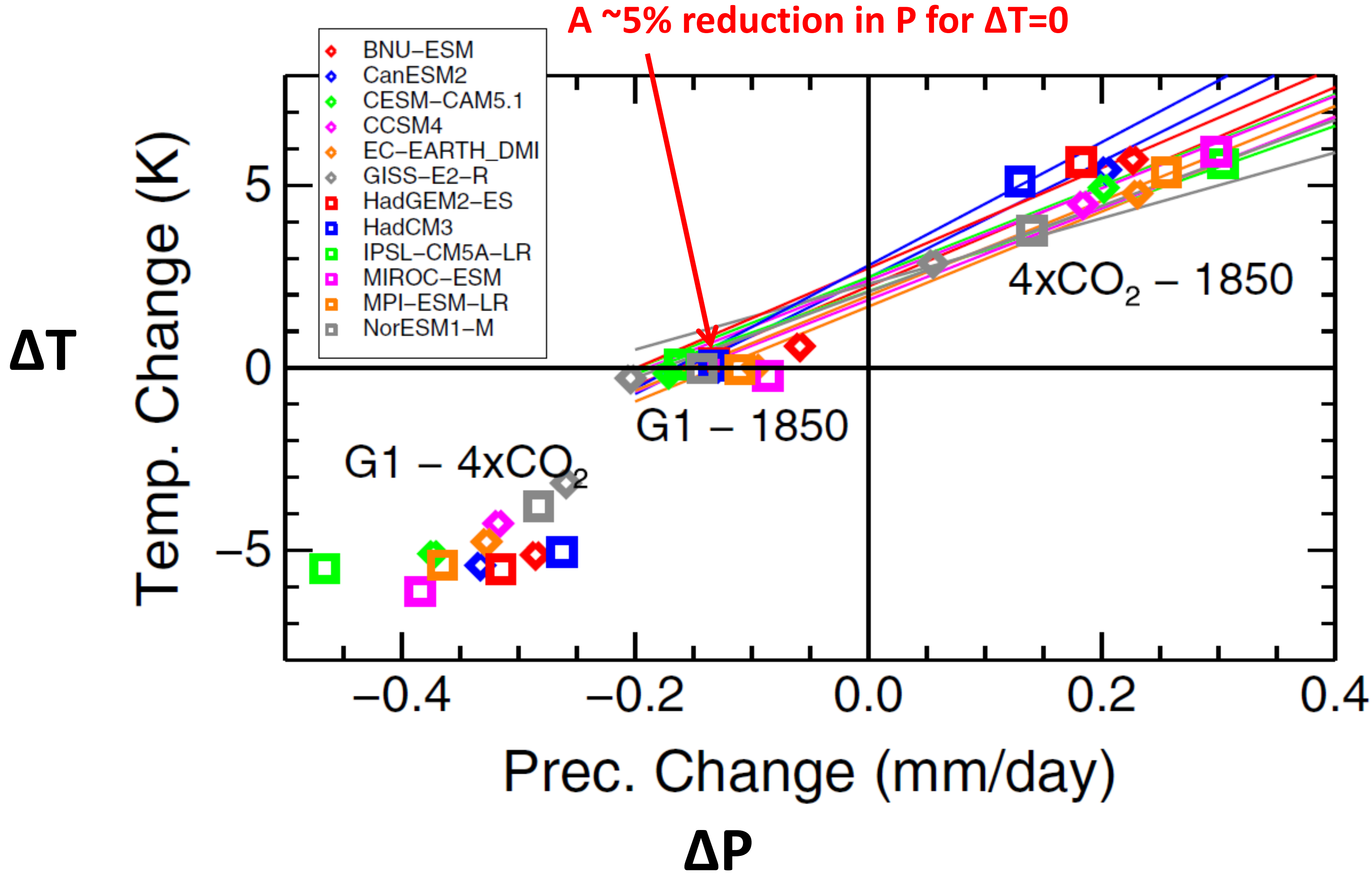
Kravitz et al. (2011: ASL)

Hydrological Sensitivity in G1 experiments with 12 GCMs



Tilmes et al. (2013: JGR)

Hydrological Sensitivity in G1 experiments with 12 GCMs



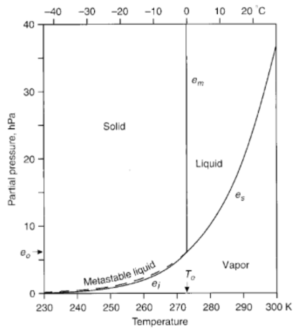
Tilmes et al. (2013: JGR)

How does the hydrological cycle change in a warmer climate?

Naïve expectation:

- (1) **Water vapor** increases according to the Clausius-Clapeyron equation:

$$\frac{de_s}{dT} = \frac{Le_s}{R_v T}$$

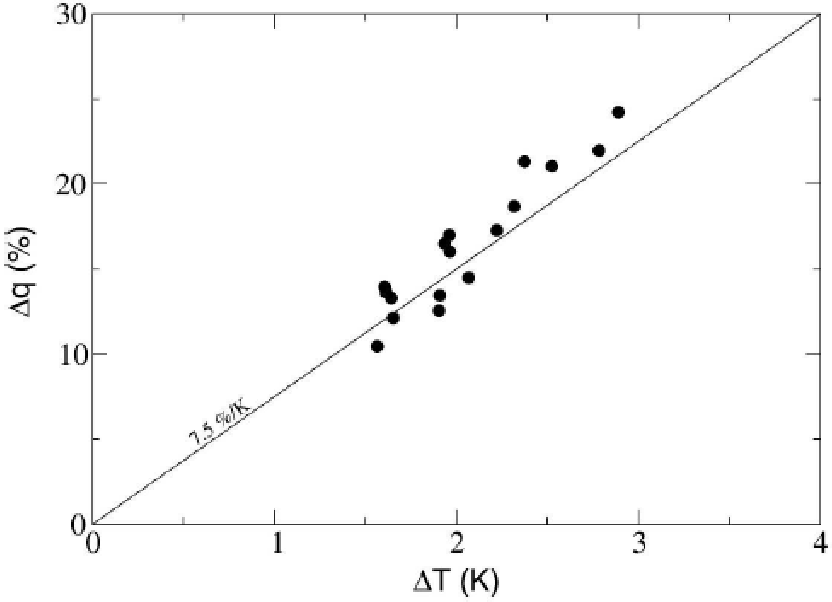


which corresponds to approximately 7% K^{-1}

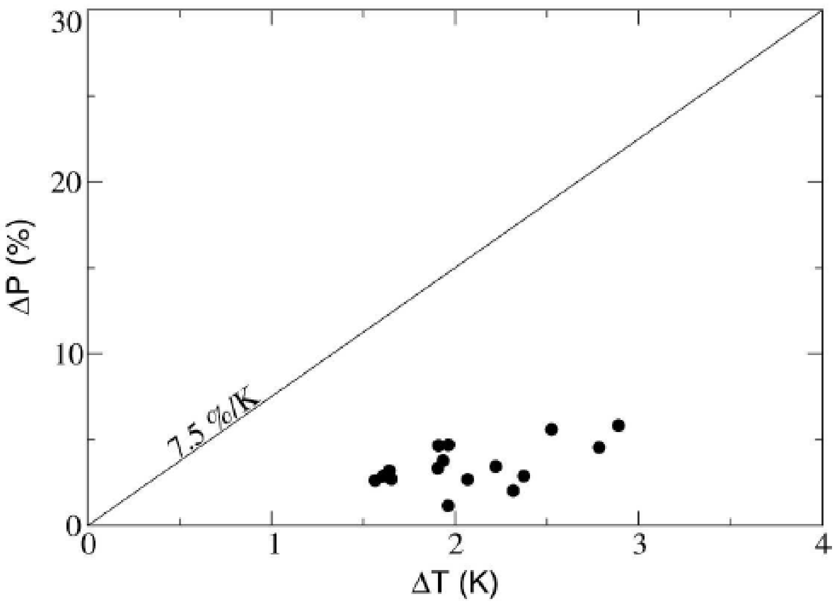
- (2) **Precipitation** also increases by approximately 7% K^{-1}

CMIP4 models: 21st century (A1B scenario)

Water vapor vs Temperature

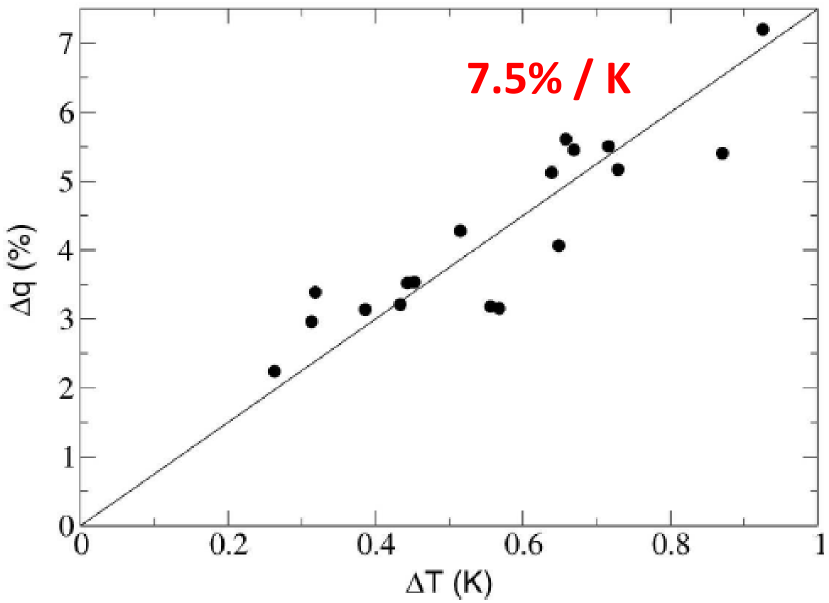


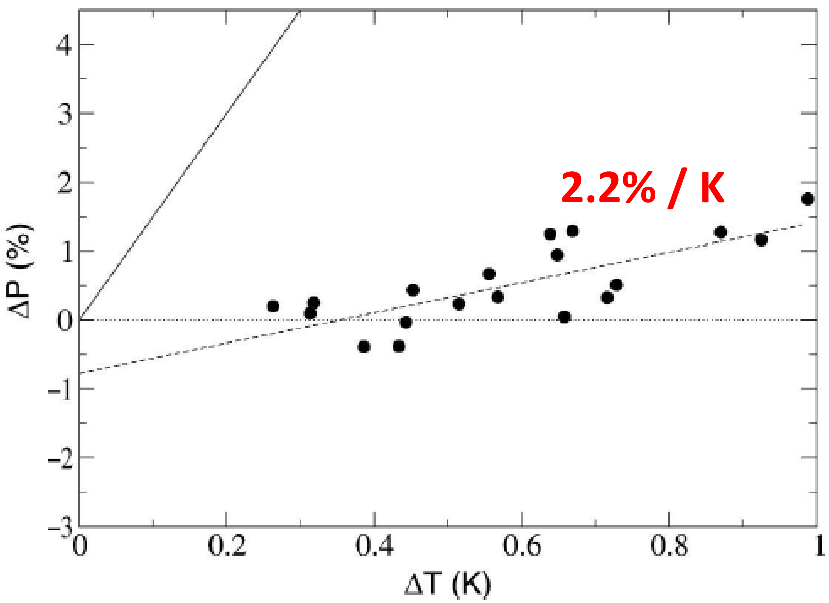
Precipitation vs Temperature



Held & Soden (2006; J.Climate)

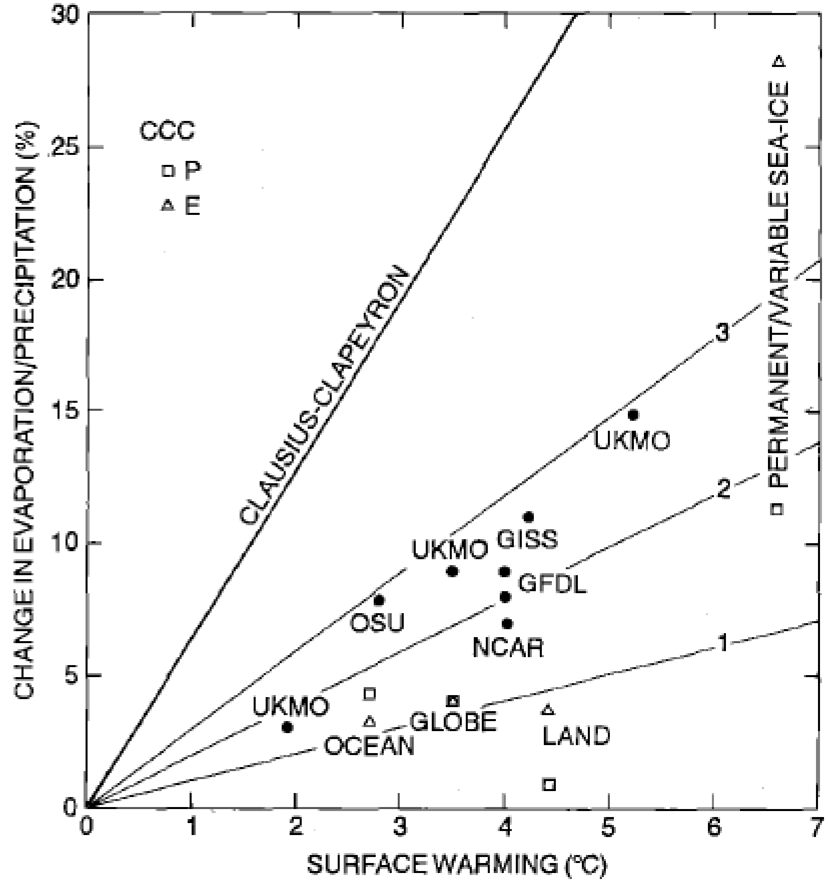
CMIP4 models: 20th century (20C3M runs)





Held & Soden (2006; J.Climate)

Precipitation Changes in Global Climate Models



Boer (1993; Clim.Dyn.)

How does the hydrological cycle change in a warmer climate?

Naïve expectation:

- (1) **Water vapor** increases according to the Clausius-Clapeyron equation:

$$\frac{de_s}{dT} = \frac{Le_s}{R_v T}$$

Correct!

which corresponds to approximately 7% K^{-1}

- (2) **Precipitation** also increases by approximately 7% K^{-1} **Wrong!**

Why does precipitation not follow a simple Clausius-Clapeyron relationship?

- Fundamentally, changes in precipitation (or, equivalently, evaporation) are not controlled by the availability of water, but the availability of energy (Allen & Ingram, 2002: Nature)

Energetics of the Hydrological Cycle

- The atmosphere is in **Energy Balance**, but **not in Radiative Balance**
- **Radiative Cooling** is balanced by Release of **Latent Heat** (~80%) + **Sensible Heat** (~20%)

$$\dot{Q}_{atm} = LH + SH + F_{TOA}^{\downarrow} - F_{TOA}^{\uparrow} - F_{surf}^{\downarrow} + F_{surf}^{\uparrow}$$

- $\dot{Q}_{atm}$: Change in atmospheric heat content
- $LH + SH$: Fluxes of **latent** and sensible **heat** (from surface to atmosphere)
- $F_{TOA}^{\downarrow} - F_{TOA}^{\uparrow}$: Net downwelling radiative flux at TOA (LW + SW)
- $- F_{surf}^{\downarrow} + F_{surf}^{\uparrow}$: Net downwelling radiative flux at the surface (LW + SW)

Fast Response, the **nature of the forcing** dominates

$$\Delta LH + \Delta SH = \Delta F^{\downarrow}_{surf} - \Delta F^{\uparrow}_{surf} - \Delta F^{\downarrow}_{TOA} + \Delta F^{\uparrow}_{TOA} + \Delta \dot{Q}_{atm}$$

Stable Climate ⇒ $\dot{Q}_{atm} \approx 0$

CO_2 doubling ⇒ $\Delta F^{\uparrow}_{TOA,LW} << 0$, $\Delta F^{\downarrow}_{surf,LW} > 0$

(Less Radiative Cooling of the Atmosphere)

⇒ LH + SH reduced ⇒ **Less Precipitation**

Slow Response, the **climate change** dominates

$$\Delta LH + \Delta SH = \Delta F_{surf}^{\downarrow} - \Delta F_{surf}^{\uparrow} - \Delta F_{TOA}^{\downarrow} + \Delta F_{TOA}^{\uparrow} + \Delta \dot{Q}_{atm}$$

Warmer Climate ⇒ $\Delta F_{surf,LW}^{\uparrow} >> 0,$

$\Delta F_{surf,LW}^{\downarrow} > 0$

$\Delta F_{TOA,LW}^{\uparrow} >> 0$

$\Delta \dot{Q}_{atm} > 0$

LH + SH increased

⇓

More Precipitation

What does this mean for the **Hydrological Cycle**?

- **Total** Response = **Fast** Response + **Slow** Response

- Doubling of CO_2 leads to an **increase in precipitation** (due to global warming), but the increase is **smaller than** e.g. **for** a **solar forcing** of the same magnitude

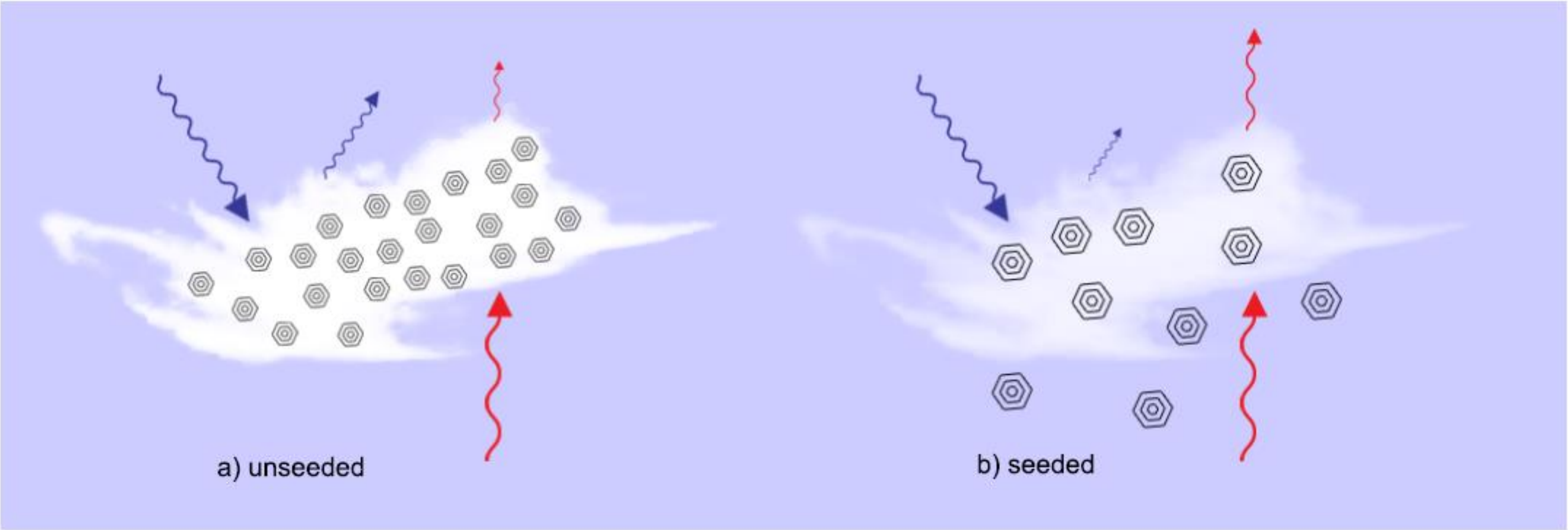
So, what if .....

- we design climate engineering - not through reduced incoming solar radiation, but by opposing the atmospheric radiative warming effect of CO_2?

- OK; but how would we do that?

Cirrus Cloud Thinning

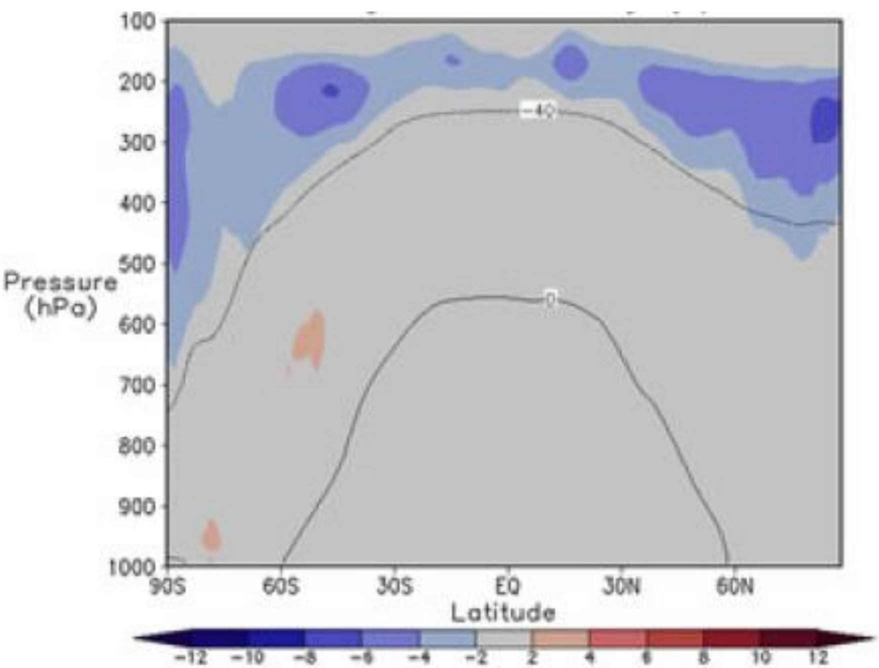
Conceptual Idea



Storelvmo et al. (2013: GRL)

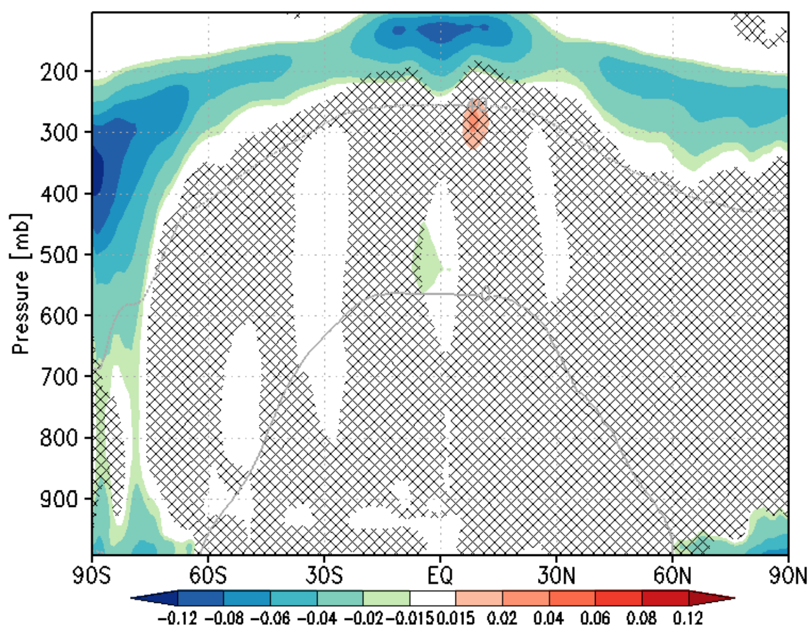
Comparison between simulations with **detailed microphysics** and simple **fall speed** changes

Cloud Cover Change



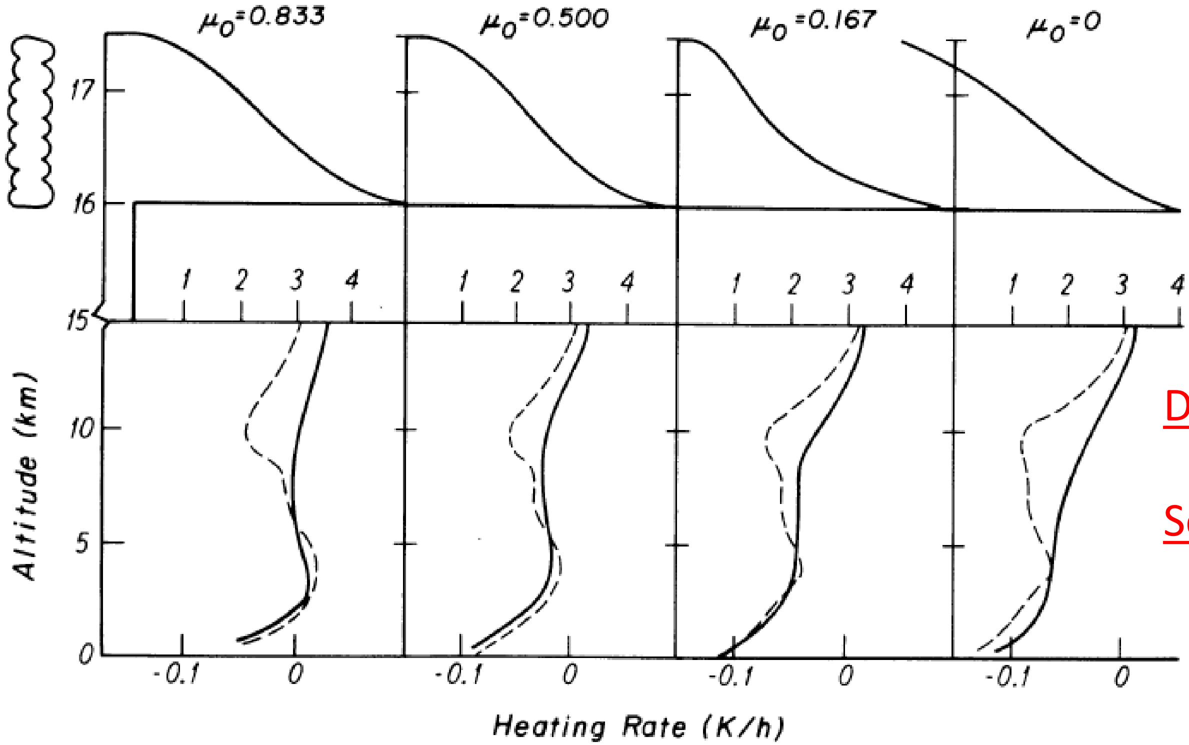
Storelvmo et al. (2013: GRL)

Cloud Cover Change



Muri et al. (2014: JGR)

Cirrus heat the troposphere radiatively



Dashed: Clear sky

Solid: With cirrus

FIG. 5.23 Net heating rate (solar plus ir) profiles in a tropical atmosphere with and without the presence of a cirrostratus with a base height of 16 km and a thickness of 1.5 km. Four solar zenith angles are used. $\mu_0 = 0$ represents the nighttime condition. The upper scales are for heating rates within the cloud.

Liou (1992; Ac.Press)

Two Sets of Simulations

- Fast Response: 30 yr NorESM1 simulations with fixed-SST
- Full Climate Response: 50 yr simulations with a mixed-layer ocean, last 30 yrs used for analysis

Simulations with NorESM1-M

- A set of 8 cases were done with **fixed SSTs** with **slab ocean**.

Fast Response **Total Response**

1. PI control – *ref*
2. Cirrus cloud thinning- *thin2*
3. Cirrus cloud thinning- *thin8*
4. Cirrus cloud thickening- *thick8*
5. Doubling of [CO_2]- *2xCO2*
6. Cirrus cloud thinning*8 and doubling of CO_2- *thin8+2xCO2*
7. Cirrus cloud thinning*2 and doubling of CO_2- *thin2+2xCO2*
8. Cirrus cloud thinning*2 and 1.5xCO_2- *thin2+1.5xCO2*.

- Cirrus cloud thinning (thickening) was done by multiplying (dividing) the ice crystal fall speed by 2 or 8 at temperatures colder than -38°C.

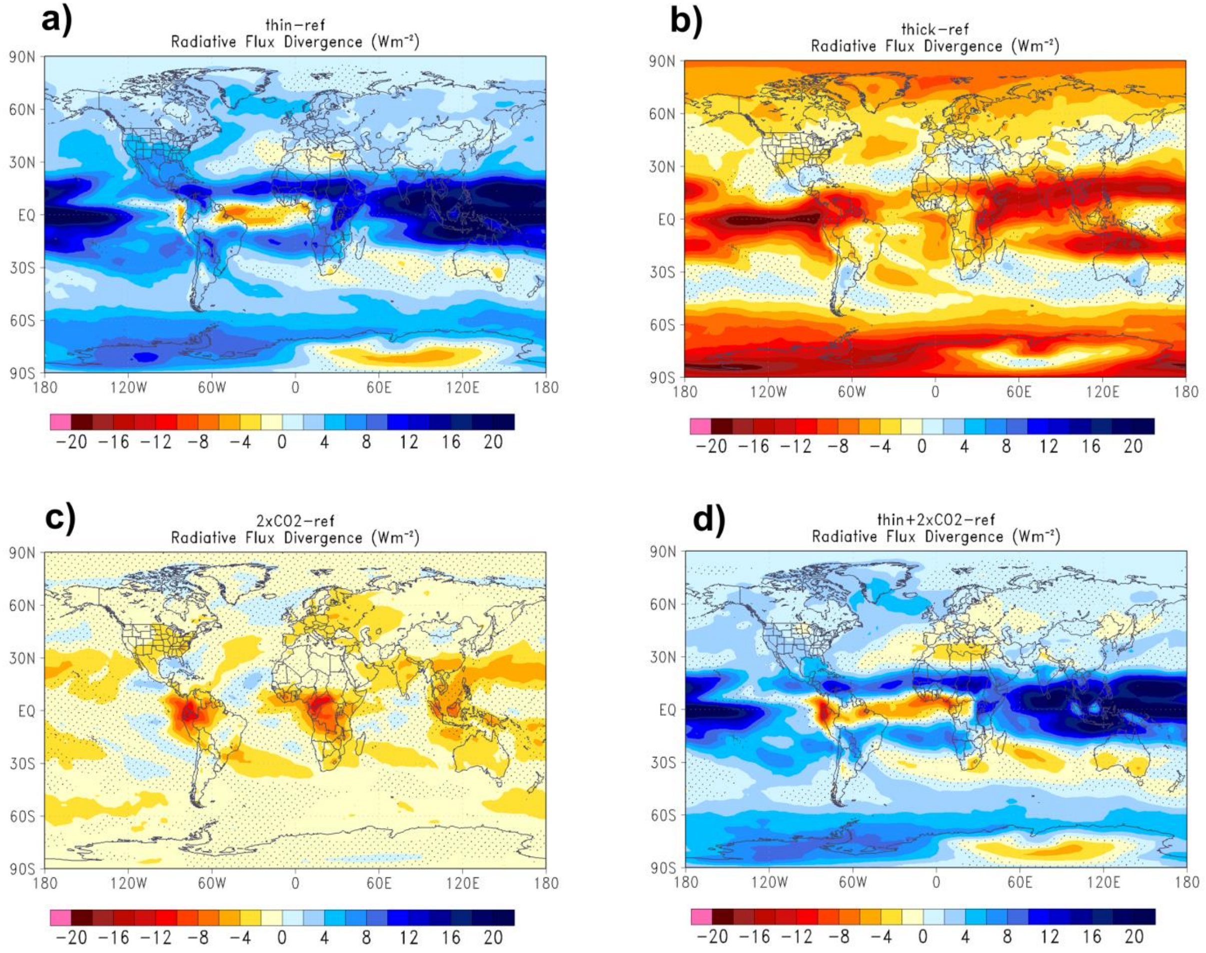
Fast Response: Radiative Flux Divergence

Cirrus Thinning (CCT)

Cirrus Thickening

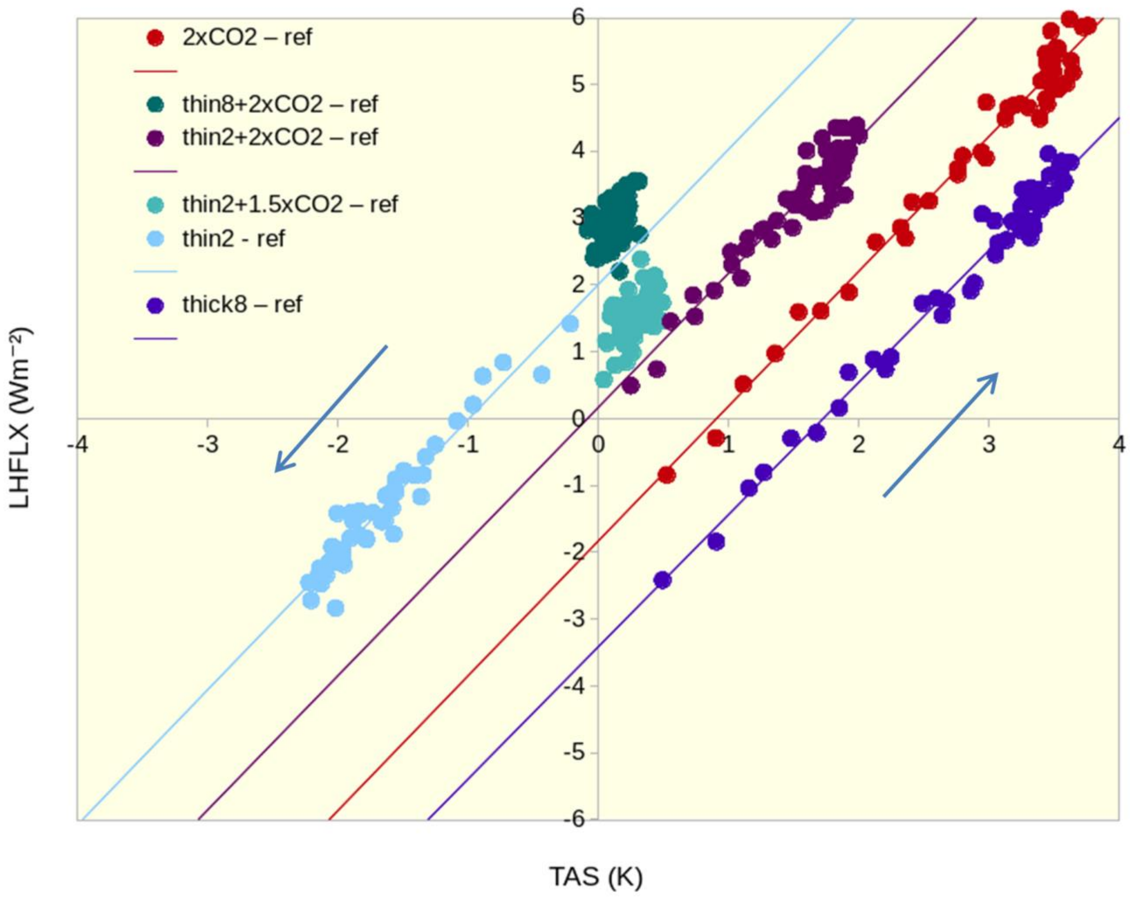
$2xCO_2$

CCT + $2xCO_2$



Kristjánsson et al. (2015: GRL, in press)

Changes in Latent Heat Flux vs Surface Temperature



Kristjánsson et al. (2015: GRL, in press)

Measures of water availability

P: Precipitation, **E**: Evapotranspiration,

PET: Potential Evapotranspiration

- P — Problem: In a warmer climate, more precipitation is needed, so P alone is insufficient
- P – E — Problem: Under dry conditions, E → 0, so P – E becomes irrelevant
- P – PET / P / PET — Measures Evaporative Demand of the Atmosphere. Widely used in Aridity Studies

JJAS Changes in *P - PET*

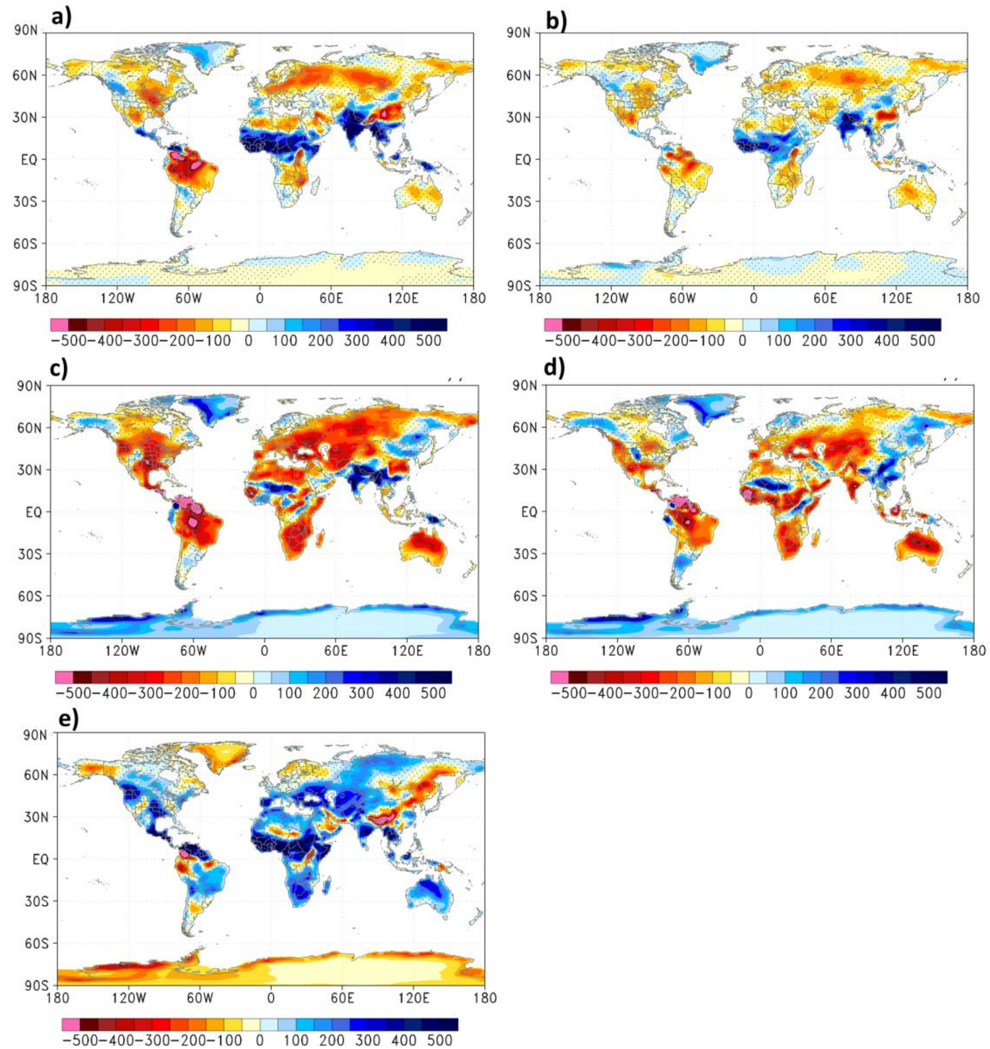
thin8 + $2xCO_2$

thin2 + $1.5xCO_2$

$2xCO_2$

thick8

thin8



Kristjánsson et al. (2015: GRL, in press)

Summary

- In a $2xCO_2$ climate, the amount of water vapor in the atmosphere increases according to the Clausius-Clapeyron equation (~7% K^{-1})
- However, for precipitation, the increase is much weaker
- This is because increased CO_2 – by itself – warms the troposphere, suppressing the flux of latent heat from the surface
- Consequently, **S**olar **R**adiation **M**anagement inevitably weakens the hydrological cycle, even though it restores global temperature
- **C**irrus **C**loud **T**hinning: Operates in the LW => Avoids the suppression of hydrological cycle

Thank you!

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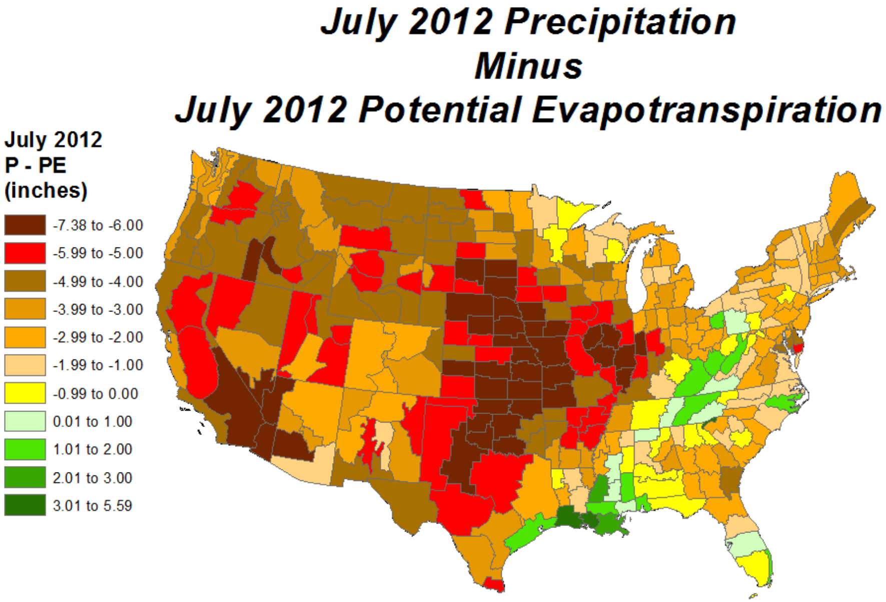
Increased Aridity in a Warmer Climate

- **Potential Evapotranspiration (PET):** the amount of evaporation that would occur if sufficient water were available

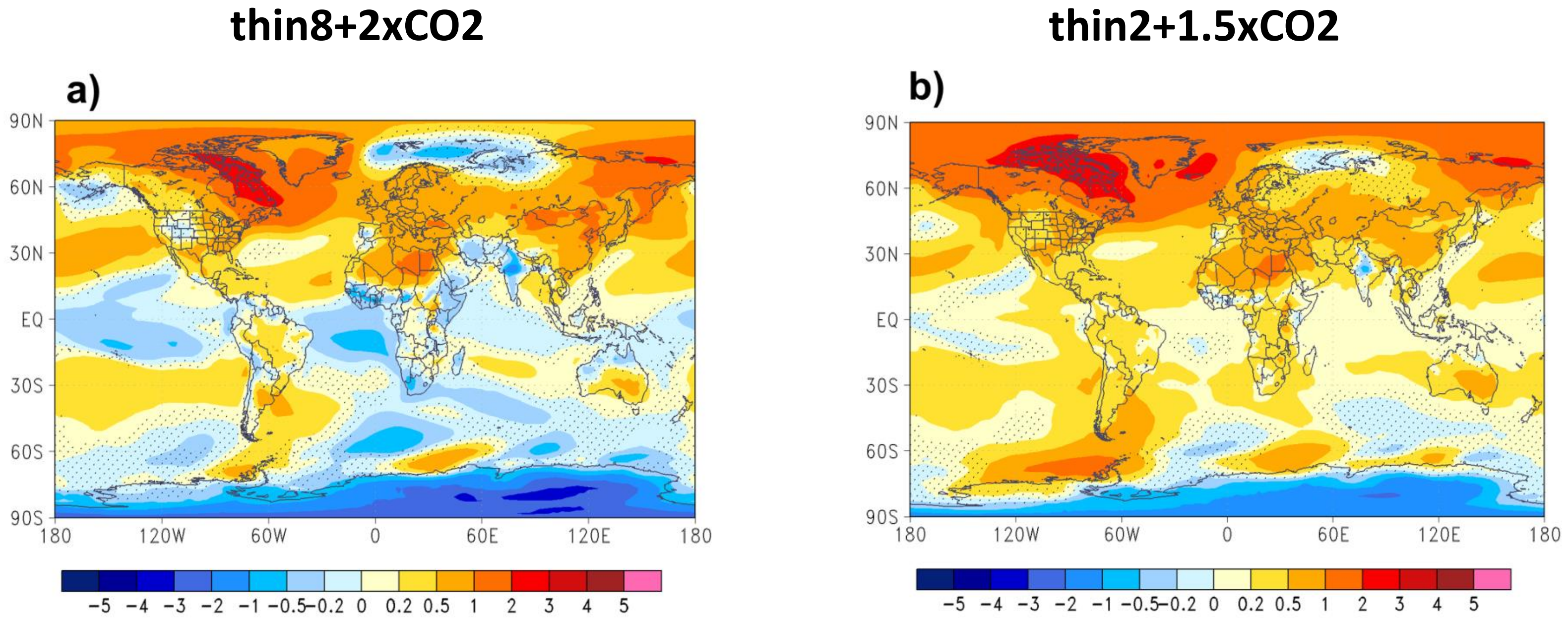


Source: NCDC

- **P – PET < 0 => Dry Climate**

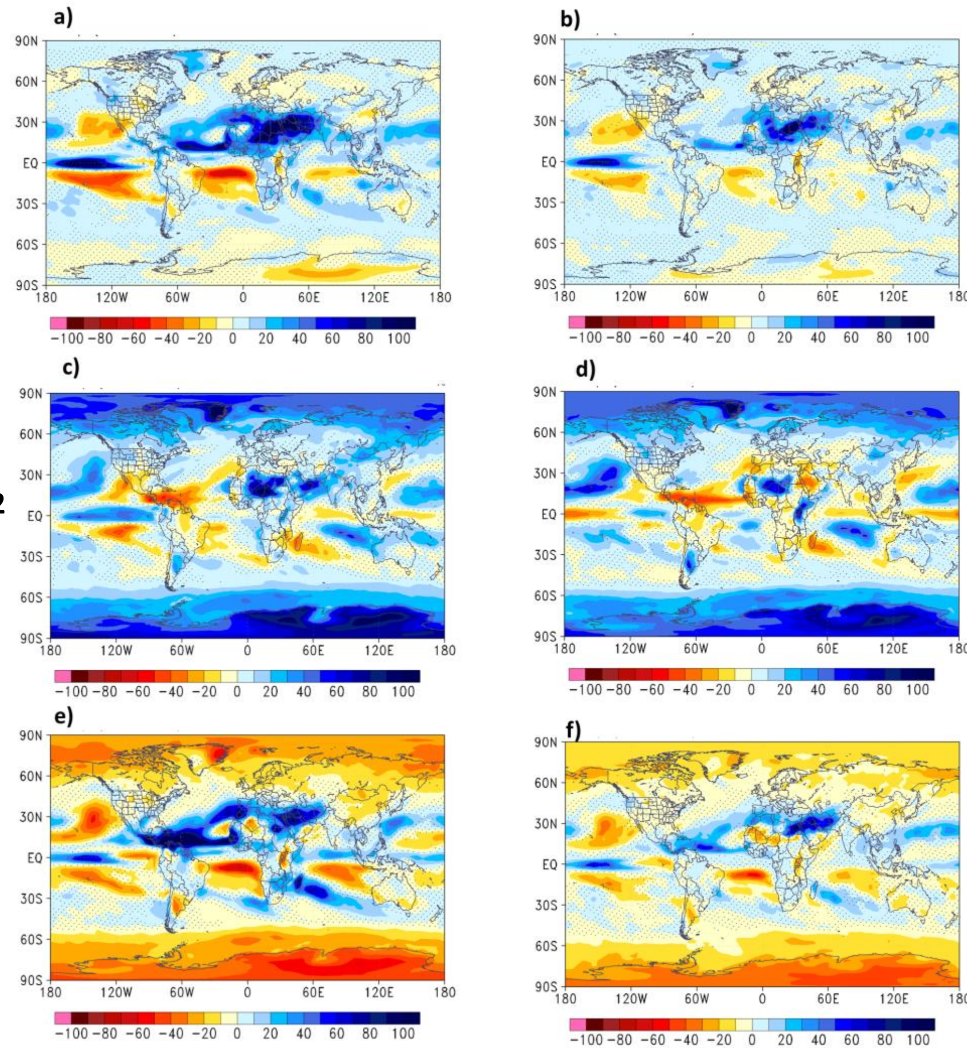
- **P / PET < 0.65: Dry Lands**

Temperature Change in CCT+CO_2 simulations



Kristjánsson et al. (2015: GRL, in press)

Annual Changes in Precipitation



thin8 + $2xCO_2$

thin2 + $1.5xCO_2$

$2xCO_2$

thick8

thin8

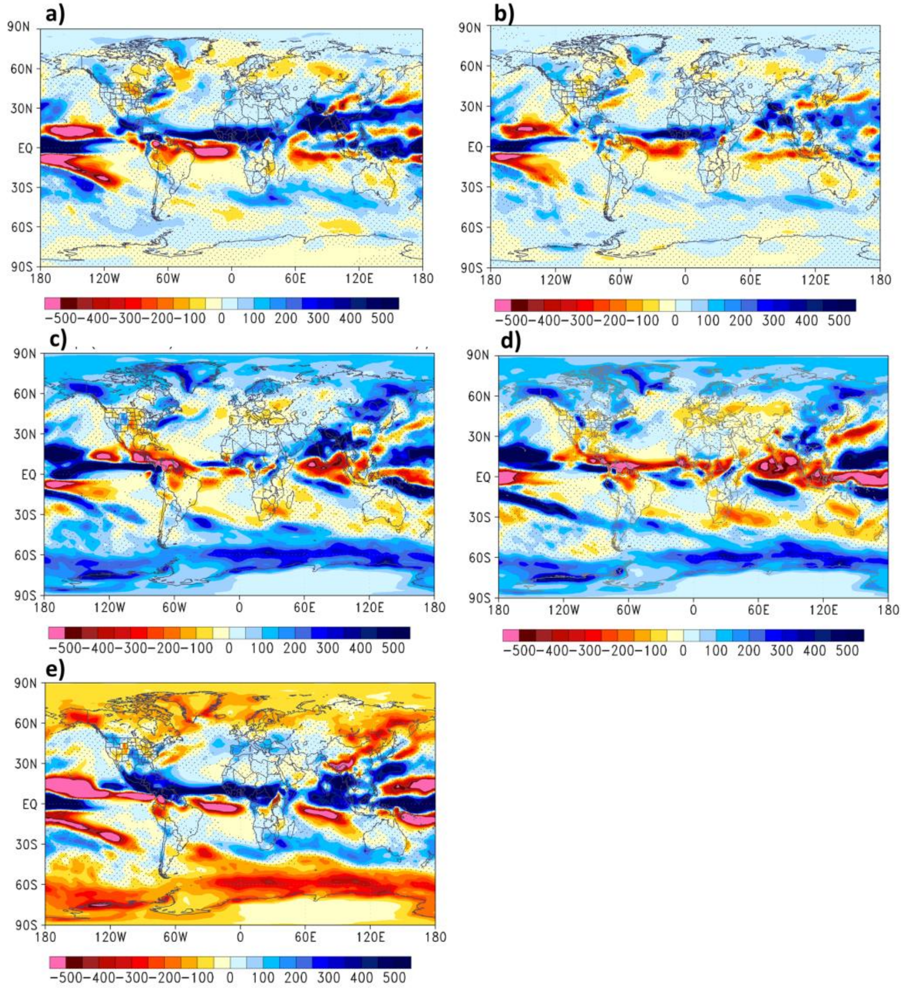
thin2

Kristjánsson et al. (2015: GRL, in press)

JJAS Changes in Precipitation

thin8 + 2xCO_2

thin2 + 1.5xCO_2



2xCO_2

thick8

thin8

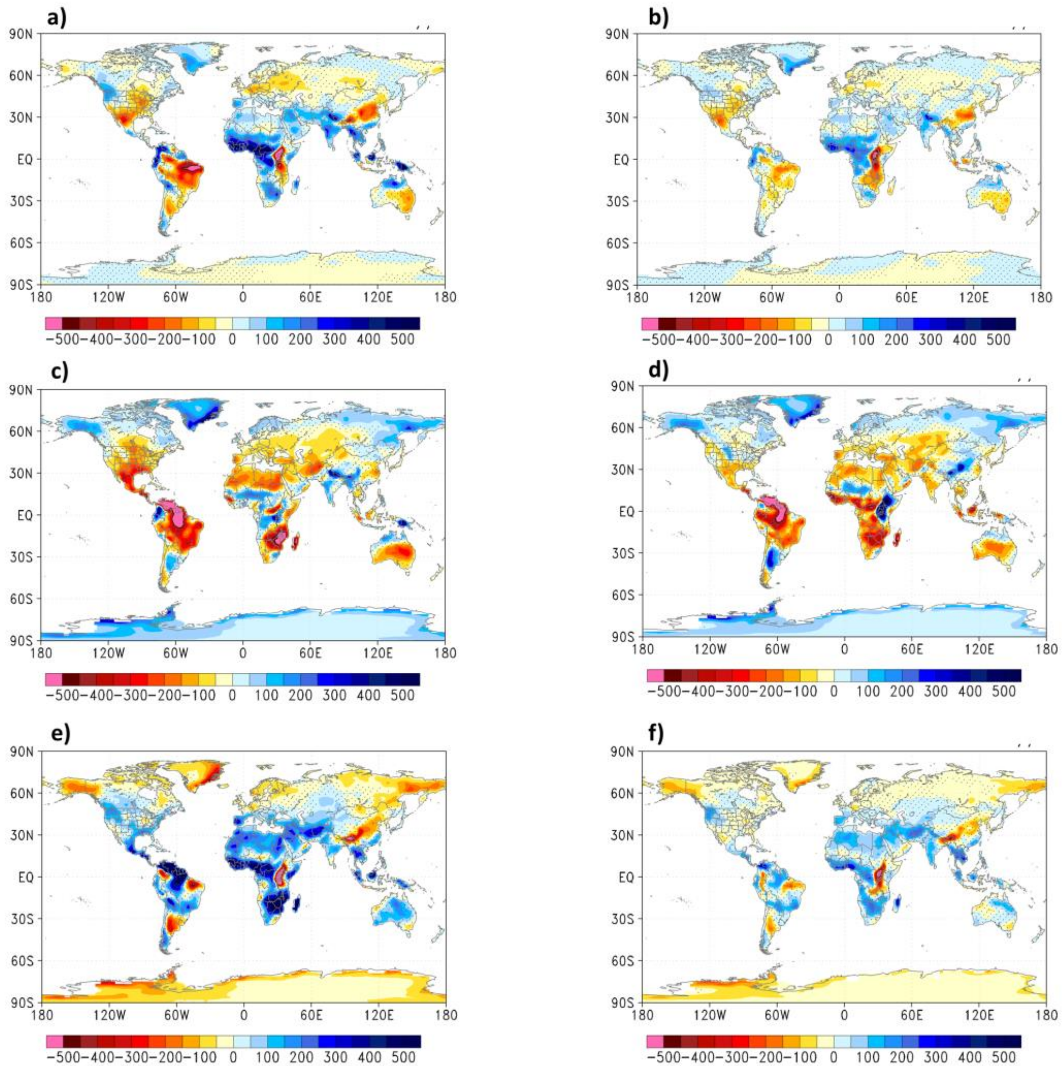
Kristjánsson et al. (2015: GRL, in press)

Annual Changes in *P - PET*

thin8 + $2xCO_2$ | **thin2 + $1.5xCO_2$**

$2xCO_2$ | **thick8**

thin8 | **thin2**



Kristjánsson et al. (2015: GRL, in press)

Fast Response

	thin8 minus *ref*	*thick8* minus *ref*	*2xCO2* minus *ref*	*thin8+2xCO2* minus *ref*	*thin2+1.5xCO2* minus *ref*
RFDIV ($W\ m^{-2}$)	+5.69 ± 0.22	- 4.63 ± 0.20	- 1.73 ± 0.19	+ 3.91 ± 0.20	+ 1.50 ± 0.21
LH ($W\ m^{-2}$)	+4.65 ± 0.24	- 3.82 ± 0.26	- 2.03 ± 0.25	+ 2.63 ± 0.28	+ 0.92 ± 0.25
Precipitation ($mm\ day^{-1}$)	+ 0.161 ± 0.008	- 0.132 ± 0.009	- 0.070 ± 0.008	+ 0.091 ± 0.009	+ 0.032 ± 0.009
T_s (K)	- 0.30 ± 0.051	+ 0.30 ± 0.046	+ 0.27 ± 0.047	- 0.021 ± 0.046	+ 0.016 ± 0.047
RTOA ($W\ m^{-2}$)	- 3.4 ± 0.35	+ 3.5 ± 0.25	+ 3.4 ± 0.29	+ 0.11 ± 0.39	+ 0.22 ± 0.31

Kristjánsson et al. (2015: GRL, in press)

Full Climate Response

	thin2 minus *ref*	*thick8* minus *ref*	*2xCO2* minus *ref*	*thin8+2xCO2* minus *ref*	*thin2+1.5xCO2* minus *ref*
T_s (K)	-1.96	+ 3.38	+ 3.48	+ 0.17	+ 0.36
LH (W m^{-2})	-1.96	+ 3.28	+ 5.19	+ 3.03	+ 1.69
Precipitation (mm day^{-1})	-0.068	+ 0.114	+ 0.180	+ 0.105	+ 0.058
WV column (g m^{-2})	-2.65	+ 5.45	+ 4.94	- 0.82	+ 0.03
NH Sea ice fraction	+0.03	- 0.14	- 0.16	- 0.02	- 0.02

Kristjánsson et al. (2015: GRL, in press)

Hydrological Sensitivity

- Can be defined as
  H = ΔP / ΔT
- H depends on the nature of the forcing
- H is larger for solar forcing than GHG forcing
- Balancing GHG by Solar leads to a reduction in P (and E)

	Temperature (K)	Water vapor content (% K^{-1})	Evaporation and precipitation (% K^{-1})
AP	−0.87	5.7	3.9
GHG	+1.7	7.8	1.5
GHG–AP	+0.57	7.8	−1.9

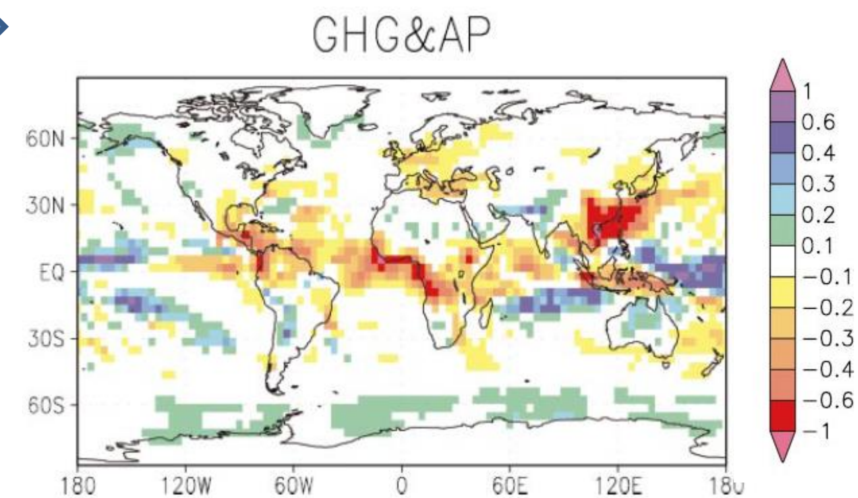


FIG. 5. Annual mean precipitation differences (mm day^{-1}) between PD and PI

Feichter et al. (2004; J.Climate)

Changes in Atmospheric Heating Rates

TABLE 7. ESTIMATED CHANGES IN RADIATIVE FLUXES AND ATMOSPHERIC HEATING RATES DUE TO CHANGES IN CO_2, WATER VAPOUR AND TEMPERATURE ($W\,m^{-2}$)

Radiative component		Contribution to changes				
		CO_2	H_2O	Temperature	All	(GCM)
Net downward long-wave flux	Top	2·1	3·7	−8·8	−2·4	−2·6
	Surface	1·2	5·4	−2·5	4·3	4·2
LW	Heating	0·9	−1·7	−6·3	−6·7	−6·8
Solar	Heating	0·6	2·0	0·0	2·6	2·6
Net	Heating	1·5	−0·3	−6·3	−4·1	−4·2

The changes diagnosed during the model simulation are given in the final column. The contributions to the long-wave components were estimated by taking the annual mean profile at each grid point, running the radiation code with the changes applied one at a time, and globally averaging the results. The contributions to solar heating were estimated using a globally averaged single-column model.

Mitchell et al. (1987; QJRMS)