The linear additivity of the forcings' responses in the energy and water cycles

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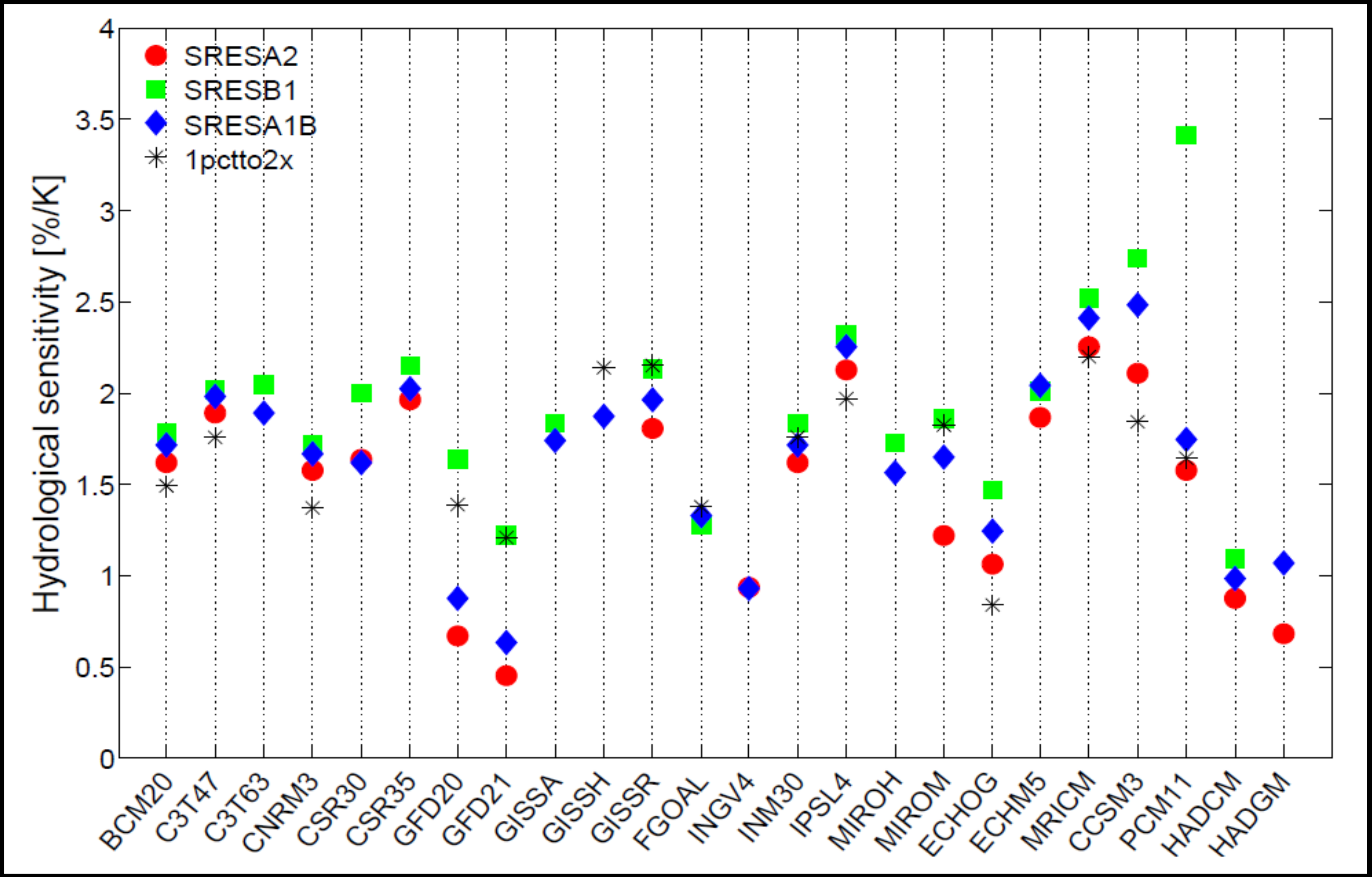
Motivation

• How will precipitation change in a warmer climate?



Model simulations

NCAR CCSM3.5 with fully coupled ocean:

- **2x** : 1%/yr to 2xCO_2
- **4x** : 2%/yr to 4xCO_2
- **37** : 3.7 W/m^2 increase in solar forcing
- **74** : 7.4 W/m^2 increase in solar forcing
- **372x** : 1%/yr to 2xCO_2 + 3.7 W/m^2 solar forcing

} Forcing ends at year 70

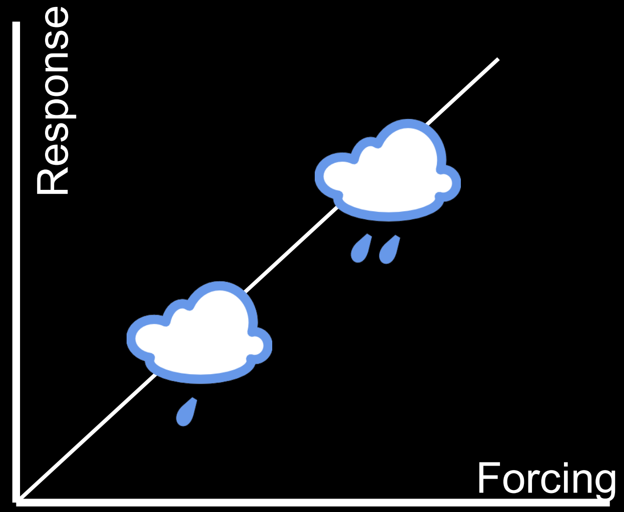
5 runs x 100 yrs for each simulation

Anomalies: years 71-100 vs. years 400-499 in control run

Research questions

a) Can we add the responses to individual forcings to estimate the combined response to all forcings?

2x * 2 = 4x
37 * 2 = 74
2x + 37 = 372x



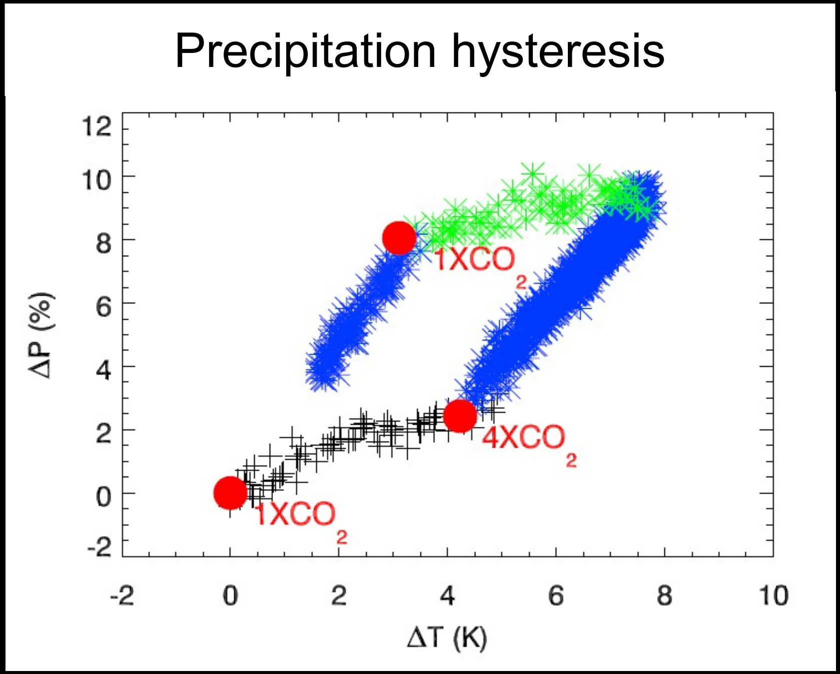
b) Can we explain the different responses to CO_2 and solar forcings in terms of different physical processes?

4x vs. 74

Results a)

- Linear additivity assumption is not valid for years 71-100:

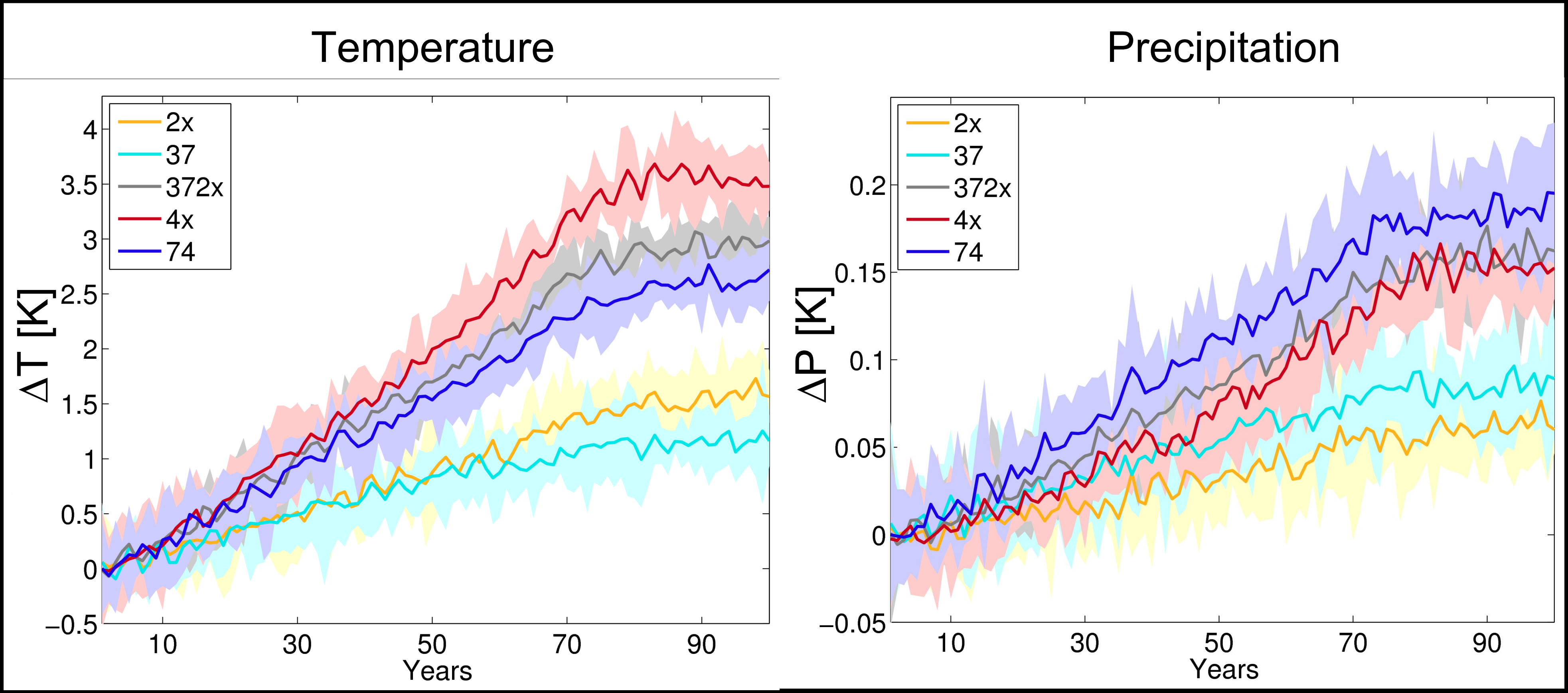
	CO_2	Solar	CO_2+solar
TOA SW	53%	6%	9%
TOA LW	-51%	9%	21%
Temperature	16%	12%	9%
Precipitation	25%	10%	11%



Wu et al., 2010

Results b)

• Hydrological sensitivity larger in solar simulations:



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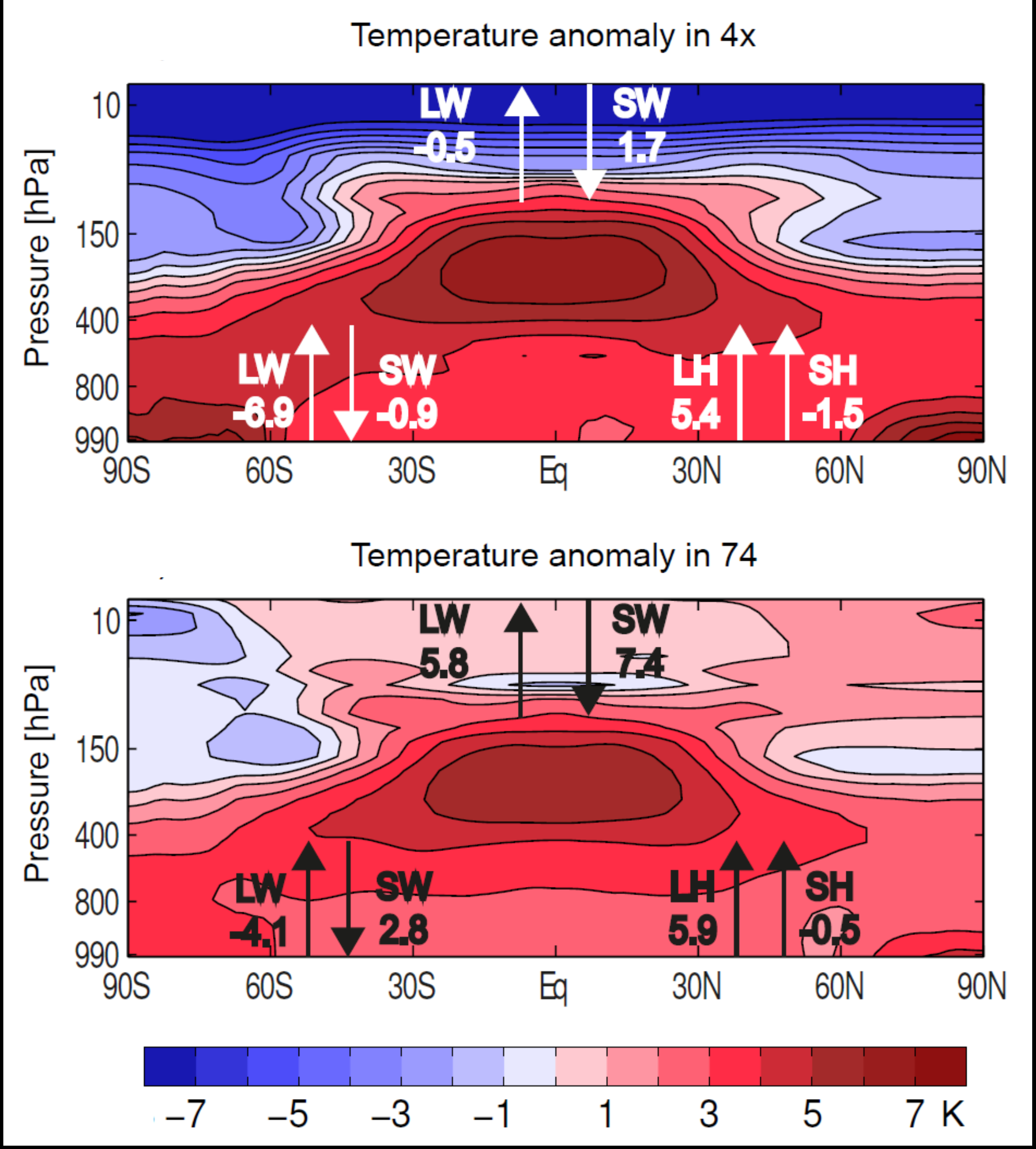
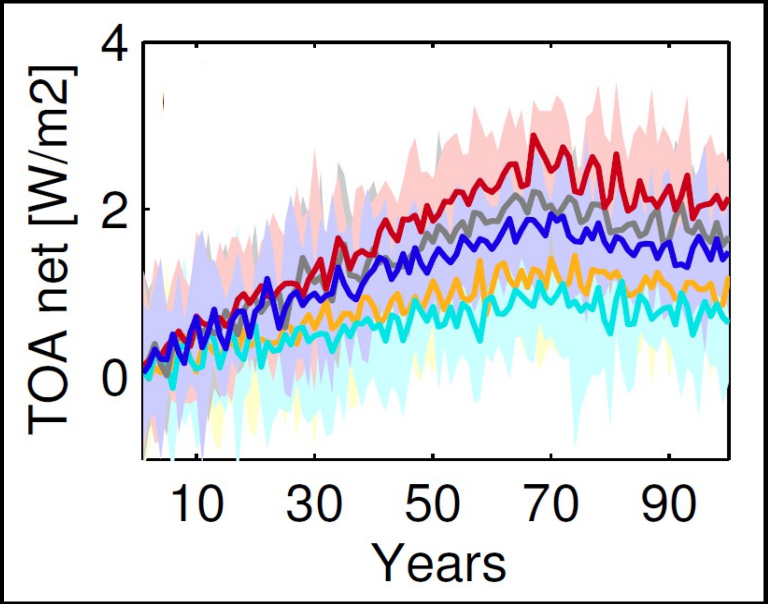
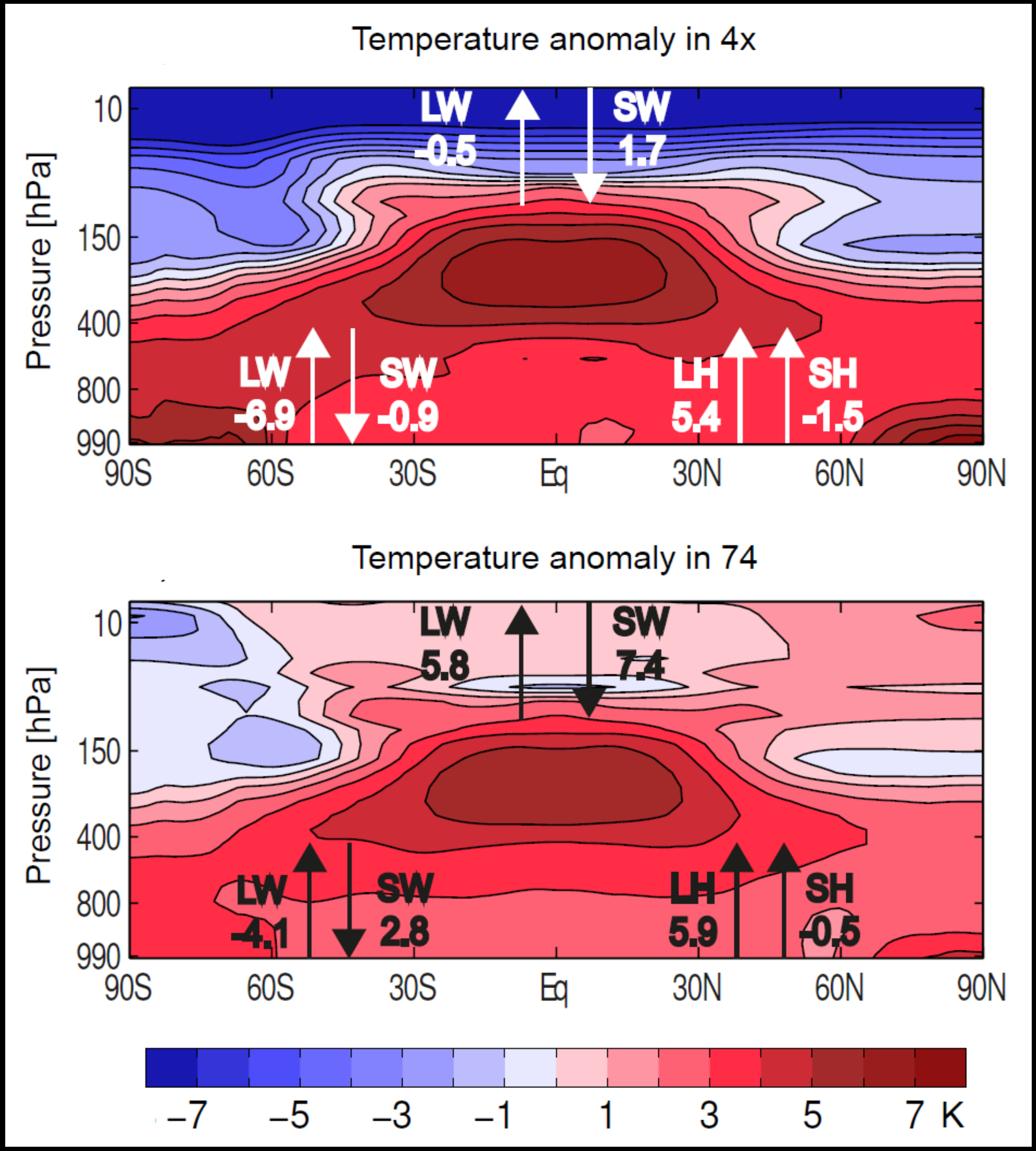
Results b)



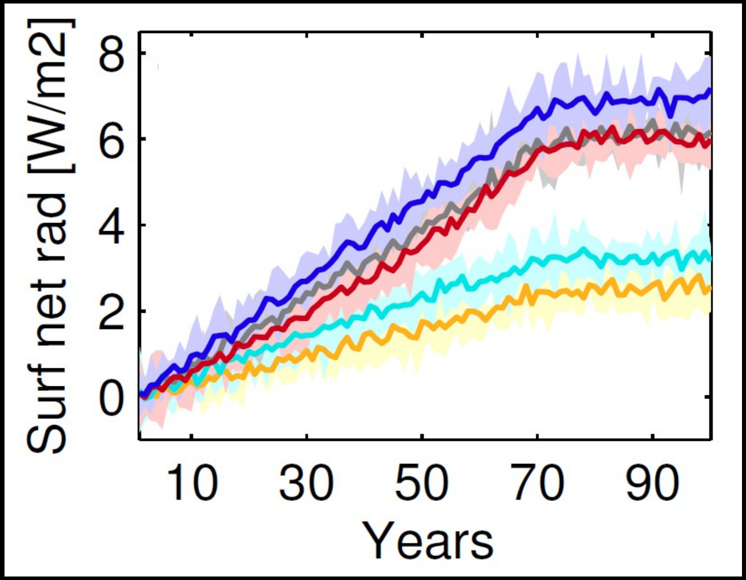
Energy imbalance:



Results b)

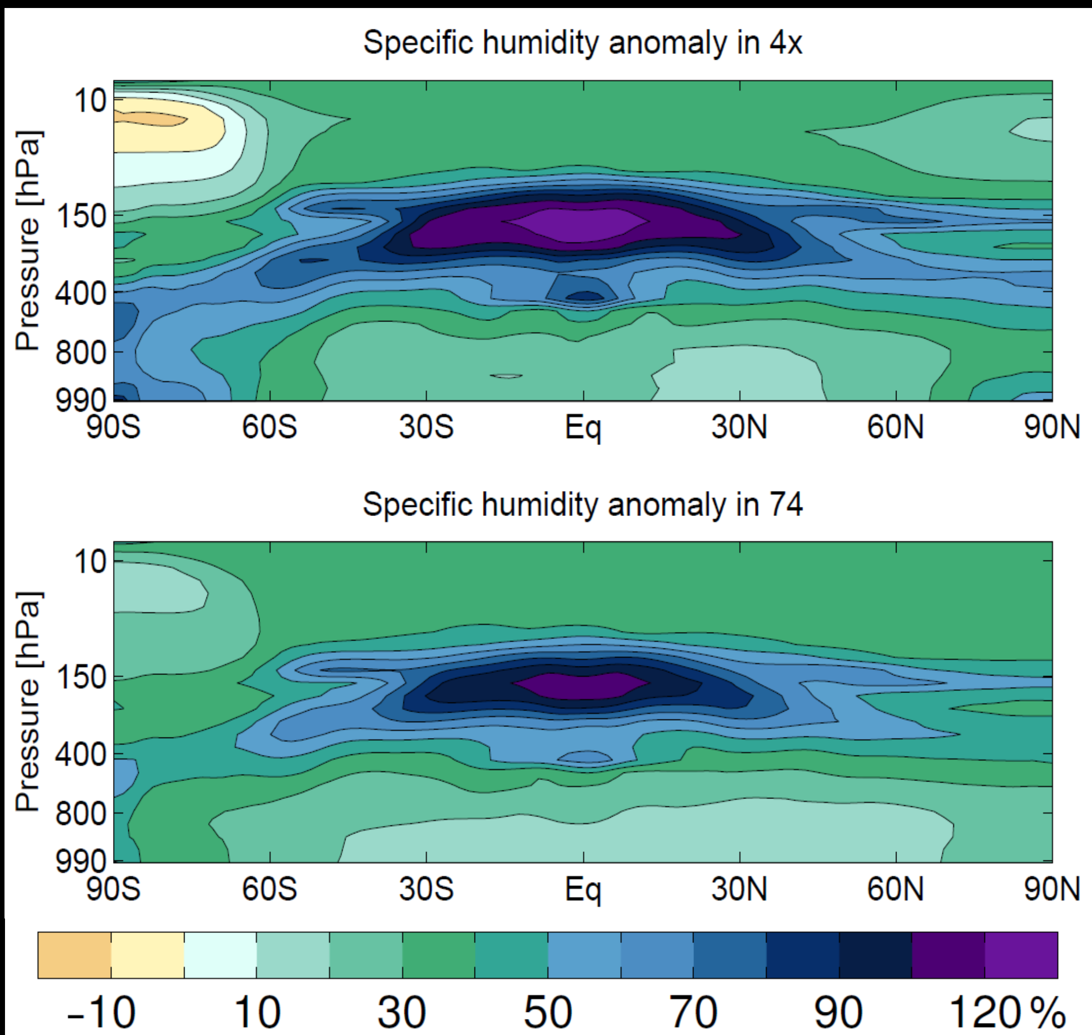


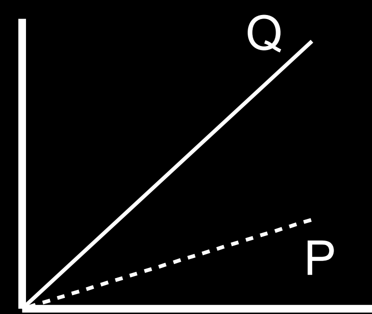
Energy available for precipitation:



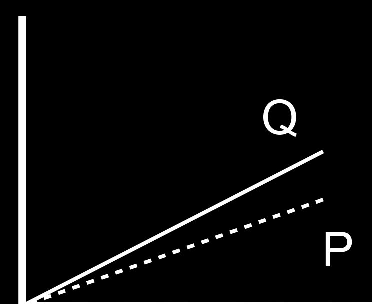
Results b)

- Changes in specific humidity vs. changes in precipitation:





4x

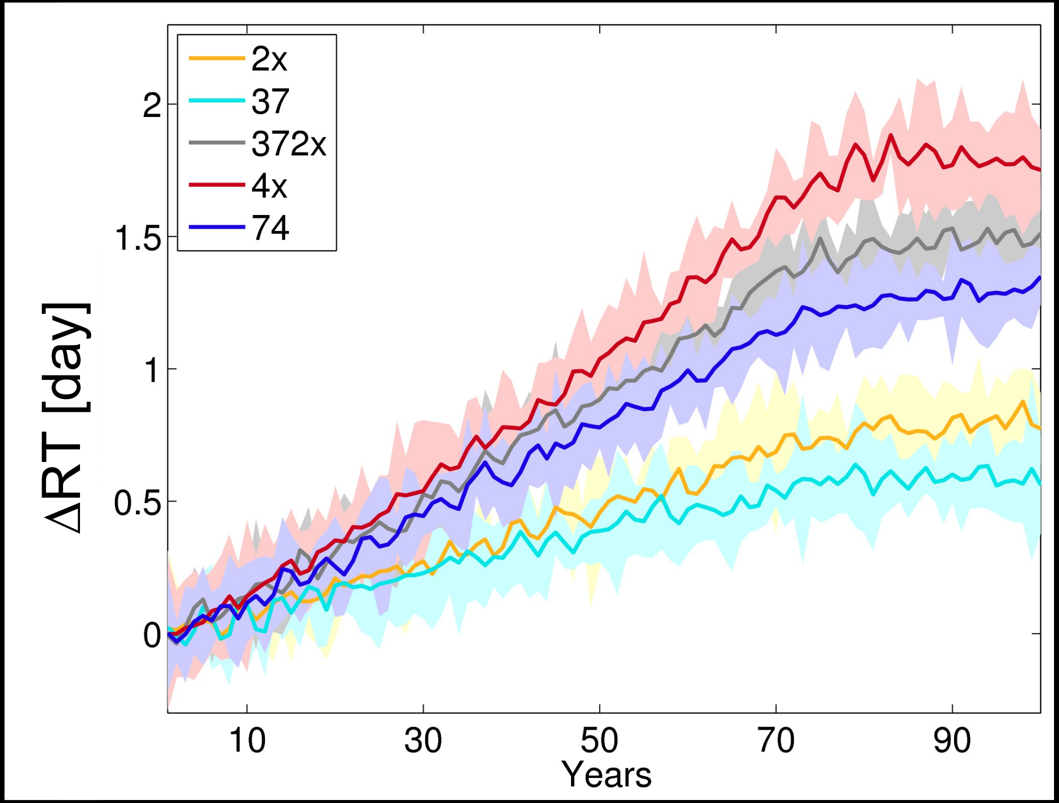


74

Results b)

- *Held & Soden (2006)*: Intensification of hydrological cycle but atmospheric circulation weakens.

$$\text{Residence time} = \frac{\text{Precipitable water}}{\text{Precipitation}}$$



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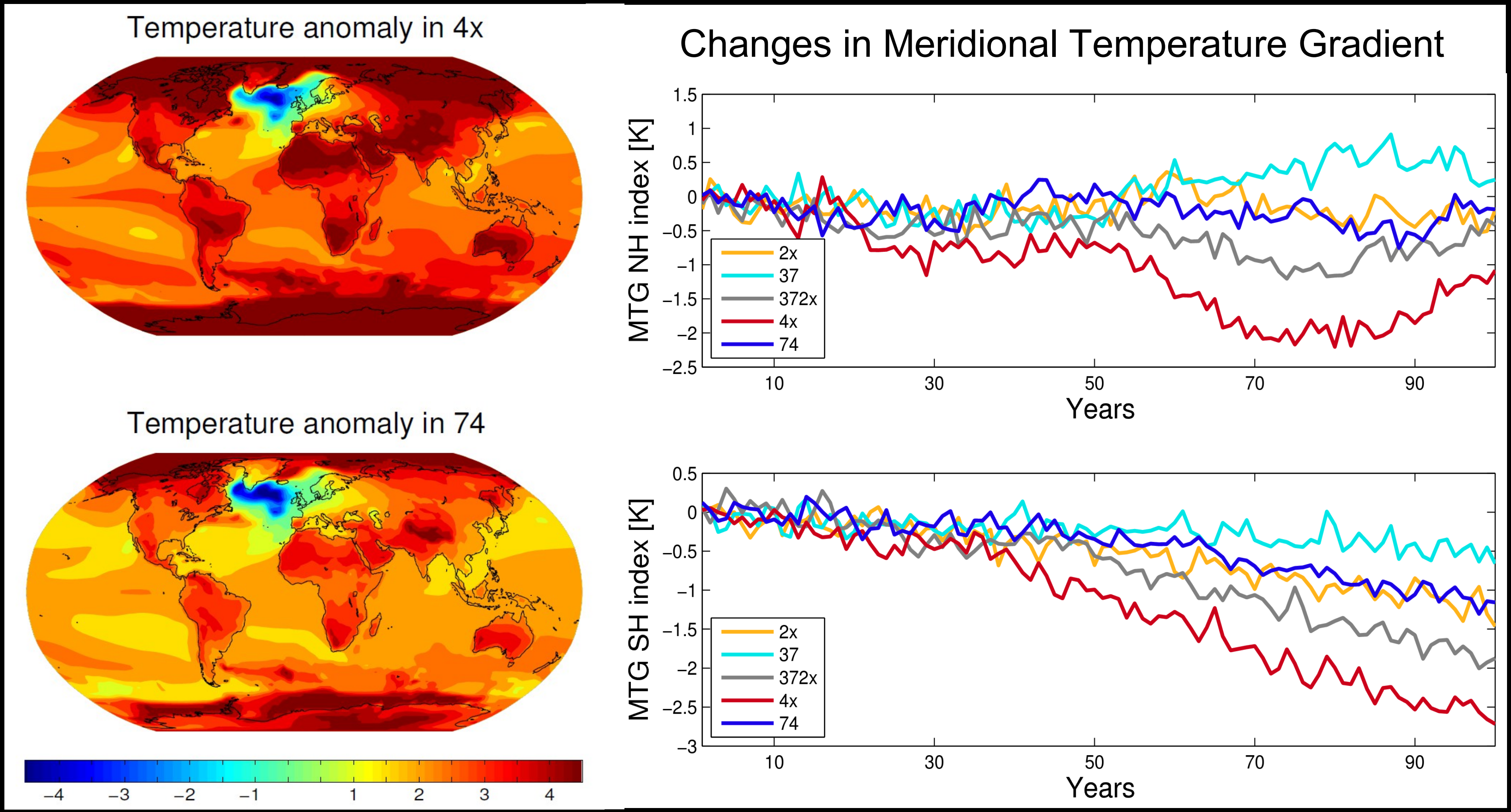
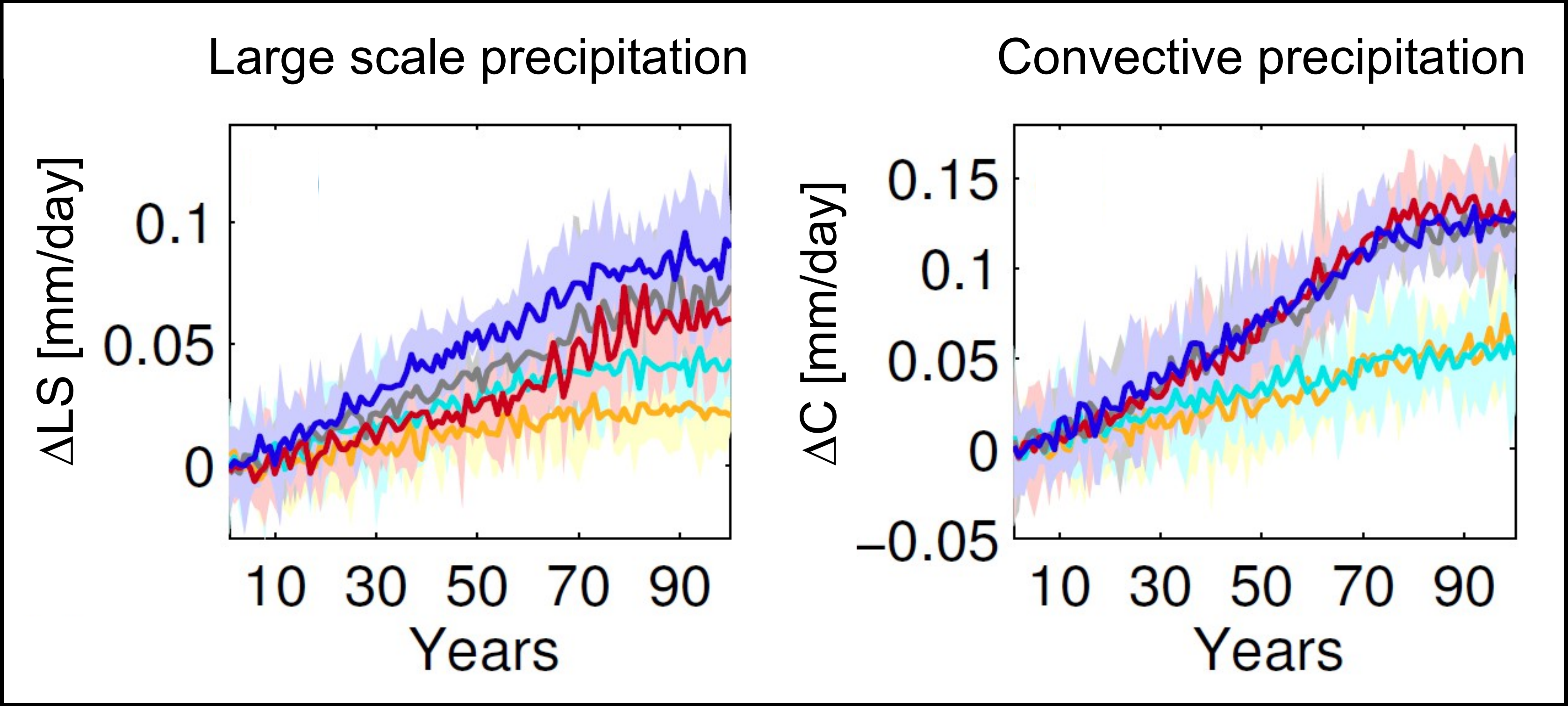
Results b)

- Circulation needs to be stronger in solar simulations



Results b)

- Largest difference in large scale precipitation changes, no forcing-dependance for convective precipitation changes:



Summary

a) Linear additivity assumption is not valid for most variables in the 30 years following a transient forcing increase:

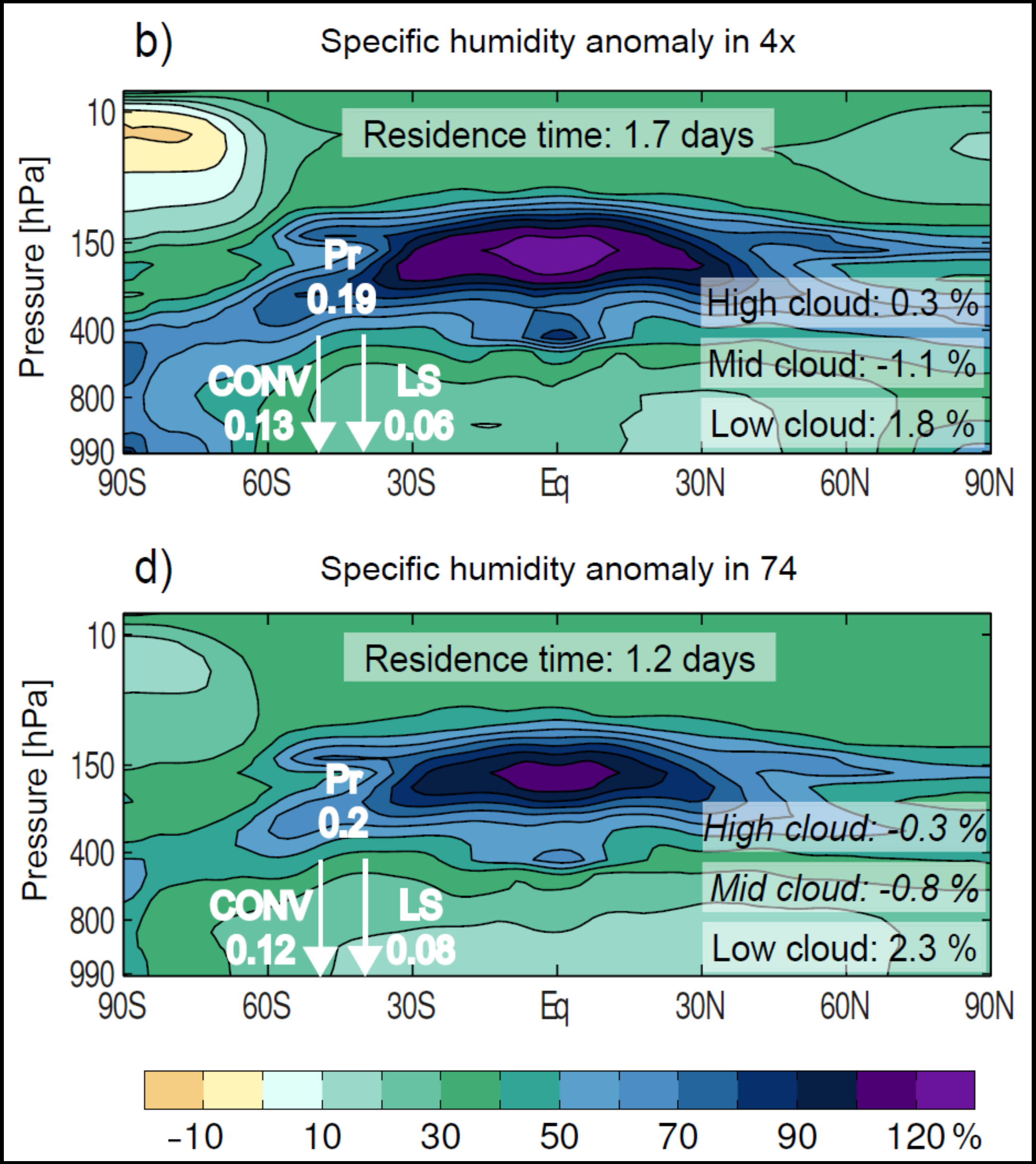
➡ Limitations for pattern scaling, D&A and radiative forcing

b) Weaker precipitation but stronger water vapor increase in CO_2 simulations lead to a weaker atmospheric circulation.

- Results might be model-dependant.

Thank you for your attention

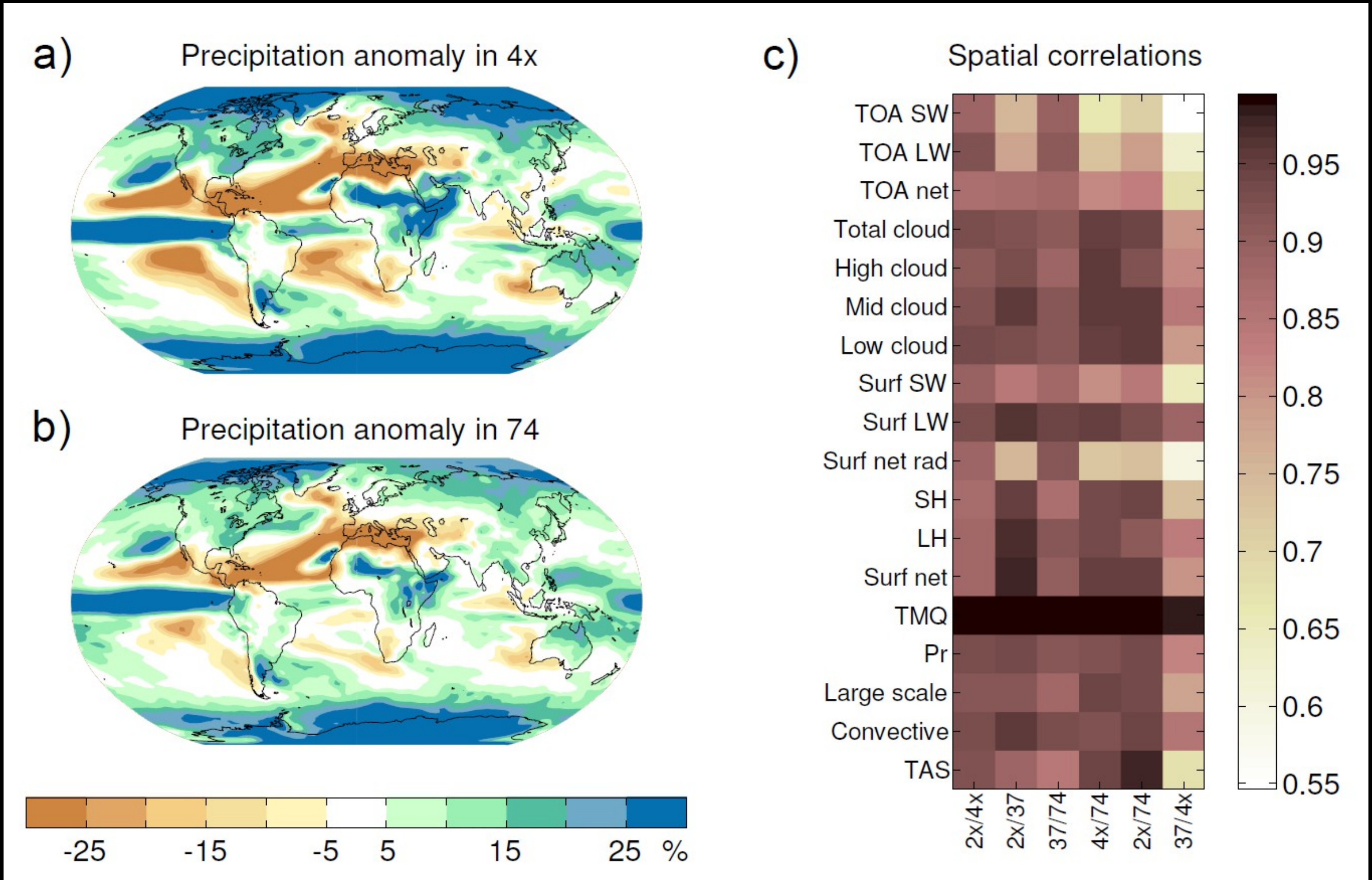
Results



b)
Specific humidity anomaly in 4x
Residence time: 1.7 days
Pr
0.19
CONV
0.13
LS
0.06
High cloud: 0.3 %
Mid cloud: -1.1 %
Low cloud: 1.8 %
Pressure [hPa]
10
150
400
800
990
90S
60S
30S
Eq
30N
60N
90N
d)
Specific humidity anomaly in 74
Residence time: 1.2 days
Pr
0.2
CONV
0.12
LS
0.08
High cloud: -0.3 %
Mid cloud: -0.8 %
Low cloud: 2.3 %
-10
10
30
50
70
90
120 %

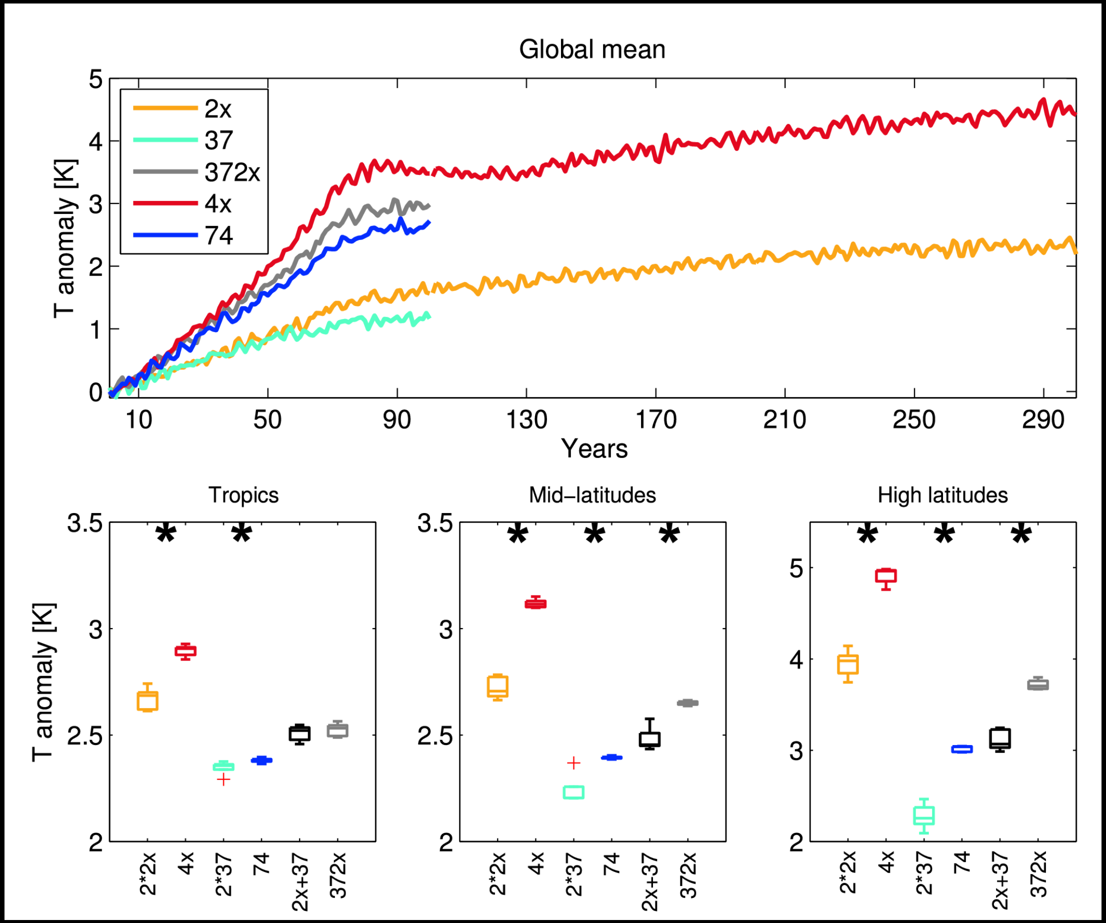
Results

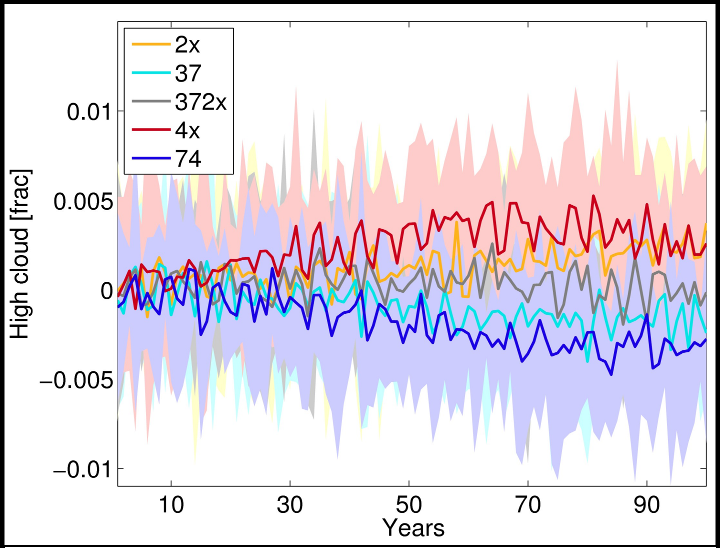
- Spatial correlations are generally high:

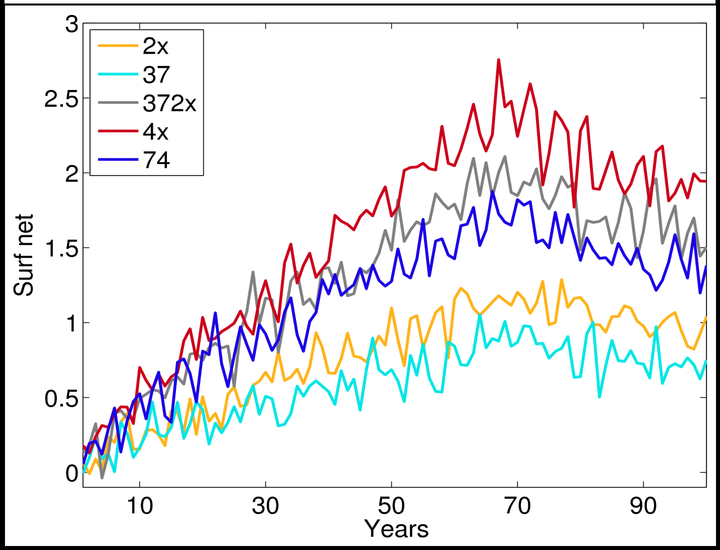


Outlook

- Understand reason for different T response in CO_2 and solar:







Backup

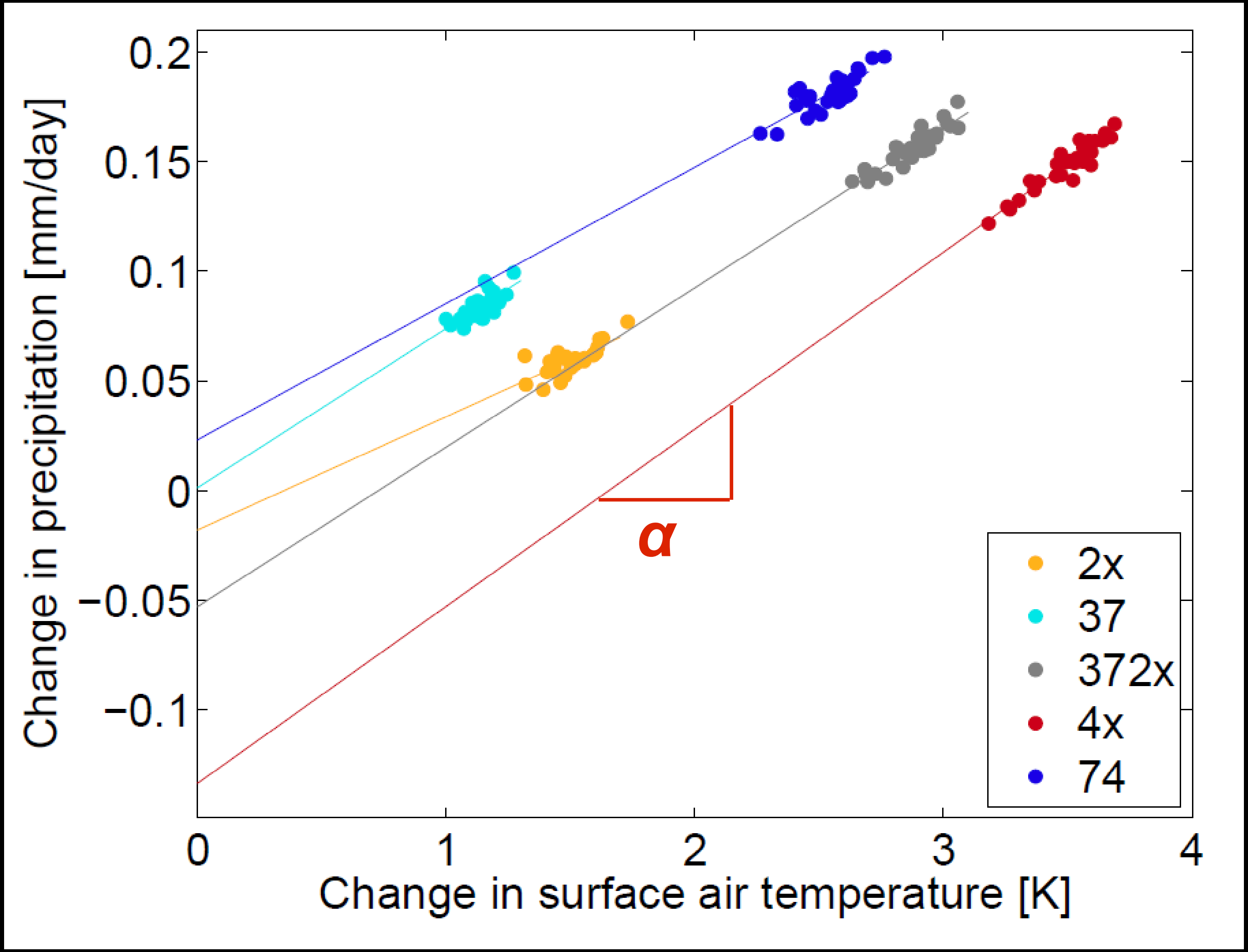
A number of important aspects of the hydrological response to warming are a direct consequence of the increase in lower-tropospheric water vapor. Because the increase in strength of the global hydrological cycle is constrained by the relatively small changes in radiative fluxes, it cannot keep up with the rapid increase in lower tropospheric vapor. The implication is that the exchange of mass between boundary layer and the midtroposphere must decrease, and, since much of this exchange occurs in moist convection in the Tropics, the convective mass flux must decrease. In many popular, and in some scientific, discussions of global warming, it is implicitly assumed that the atmosphere will, in some sense, become more energetic as it warms. By the fundamental measure provided by the average vertical exchange of mass between the boundary layer and the free troposphere, the atmospheric circulation must, in fact, slow down. This large-scale constraint has little direct relevance to the question of how tropical storms will be affected by global warming, since the mass exchange in these storms is a small fraction of the total tropical exchange. In contrast, assuming that the lower-tropospheric relative humidity is unchanged and that the flow is unchanged, the poleward vapor transport and the pattern of evaporation minus precipitation (E P) increases proportionally to the lower-tropospheric vapor, and in this sense wet regions get wetter and dry regions drier. Since the changes in precipitation have considerably more structure than the changes in evaporation, this simple picture helps us understand the zonally averaged pattern of precipitation change. In the extratropics, one can alternatively think of the diffusivity for vapor and for sensible heat as being the same, with similar consequences for the change in the vapor transport. If one assumes that the statistics of the flow are also unchanged, one obtains estimates of the increase in variance of E P (the increased intensity of “droughts and floods”) that are reasonable but overestimate the response of the model variances, perhaps because of the decrease in the strength of the mass exchange. In the Tropics, one confidently expects compensation between the increase in the equatorward latent heat transport and an increase in poleward dry static energy transport; otherwise the net transport in the Tropics would change sign. One also expects a decrease in the poleward sensible heat flux in the extratropics, as seen in many previous GCM studies. Surprisingly we see this decrease only in the equilibrium climate response as estimated with slab ocean models, and not in the transient climate change experiments. Particularly intriguing is the response in the Northern Hemisphere, where there is no reduction in the sensible heat transport despite the reduction in the zonal-mean temperature gradient at low levels associated with polar amplification of the warming. An implication of this result is that one can estimate the differential oceanic heat storage plus transport (the heat entering the ocean, with the global mean removed) directly from the Clausius–Clapeyron dominated response of the latent heat transport. To the extent that we have simple plausible physical arguments that support the model consensus, we believe that one should have nearly as much confidence in these results as one has in the increase in temperature itself.

Held and Soden (2006), conclusion

Background

$$\Delta P = F - \alpha \, \Delta T_s$$

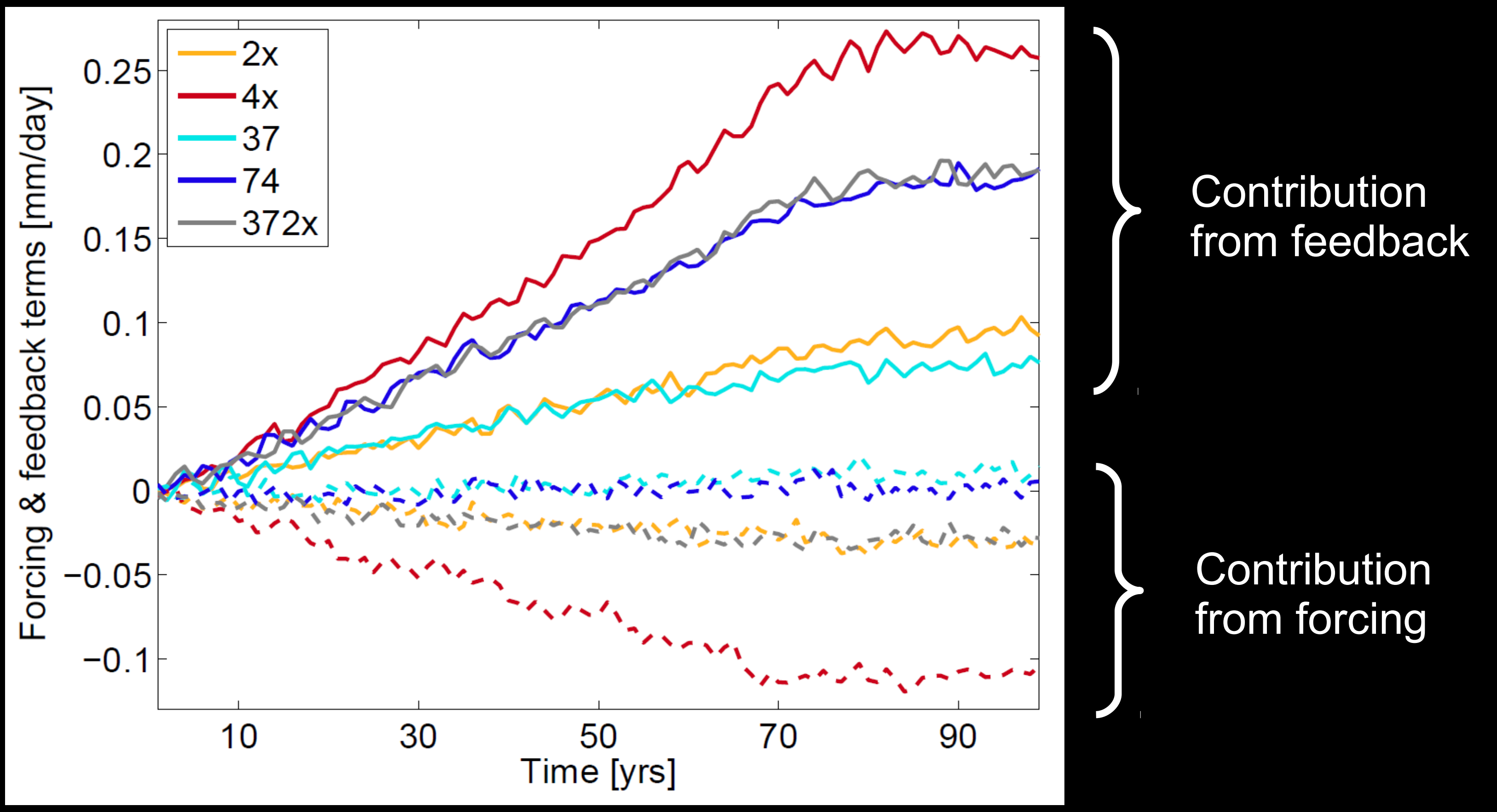
Unknown: feedback parameter ***α***



Motivation

- *Andrews (2009):*

$$\underbrace{\Delta P}_{\text{precipitation change}} = \underbrace{F}_{\text{forcing term}} \underbrace{-\alpha \Delta T_s}_{\text{feedback term}}$$



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