nature geoscience
SUPPLEMENTARY INFORMATION
DOI: 10.1038/NGEO2345

Circulation response to warming shaped by radiative changes of clouds and water vapour

Aiko Voigt[1*] & Tiffany A. Shaw[1,2,3]

[1]Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, NY 10964, USA
[2]Department of Earth and Environmental Sciences, Columbia University, New York, NY 10025, USA
[3]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10025, USA
Correspondence: aiko@ldeo.columbia.edu

1 Model differences in aquaControl and validity of the locking method

The aquaControl simulations of MPI-ESM and IPSL-CM5A reflect the long-standing problem of the double inter-tropical convergence zone [1]. Fig. S1 a shows that MPI-ESM concentrates precipitation into a single ITCZ at the equator whereas IPSL-CM5A simulates a double ITCZ with precipitation peaks at 6° N/S.

Figs. S1 (a, b) further show that locking clouds and water vapor does not distort the climate of aquaControl: the locked simulation T1C1W1 closely resembles aquaControl. Figs. S1 (c, d) illustrate the response to global warming (aqua4K - aquaControl) and the residual between the response and the sum of the contributions from the isolate SST increase, cloud-radiative changes and water-vapor radiative changes. The residual is much smaller than the total response and the model differences therein. This demonstrates the validity of the locking method and the decomposition.

2 Dynamic and thermodynamic components of precipitation response

To illustrate that many aspects of the deep-tropical (within 15° N/S) precipitation response, in particular its meridional pattern, are dominated by circulation changes we decompose the precipitation response into a dynamic and a thermodynamic component. We define the dynamic component following [2]. The thermodynamic component is estimated as the difference between the precipitation response and the dynamic component. The thermodynamic component measures the precipitation response due to the increase in evaporation and the

DOI: 10.1038/NGEO2345

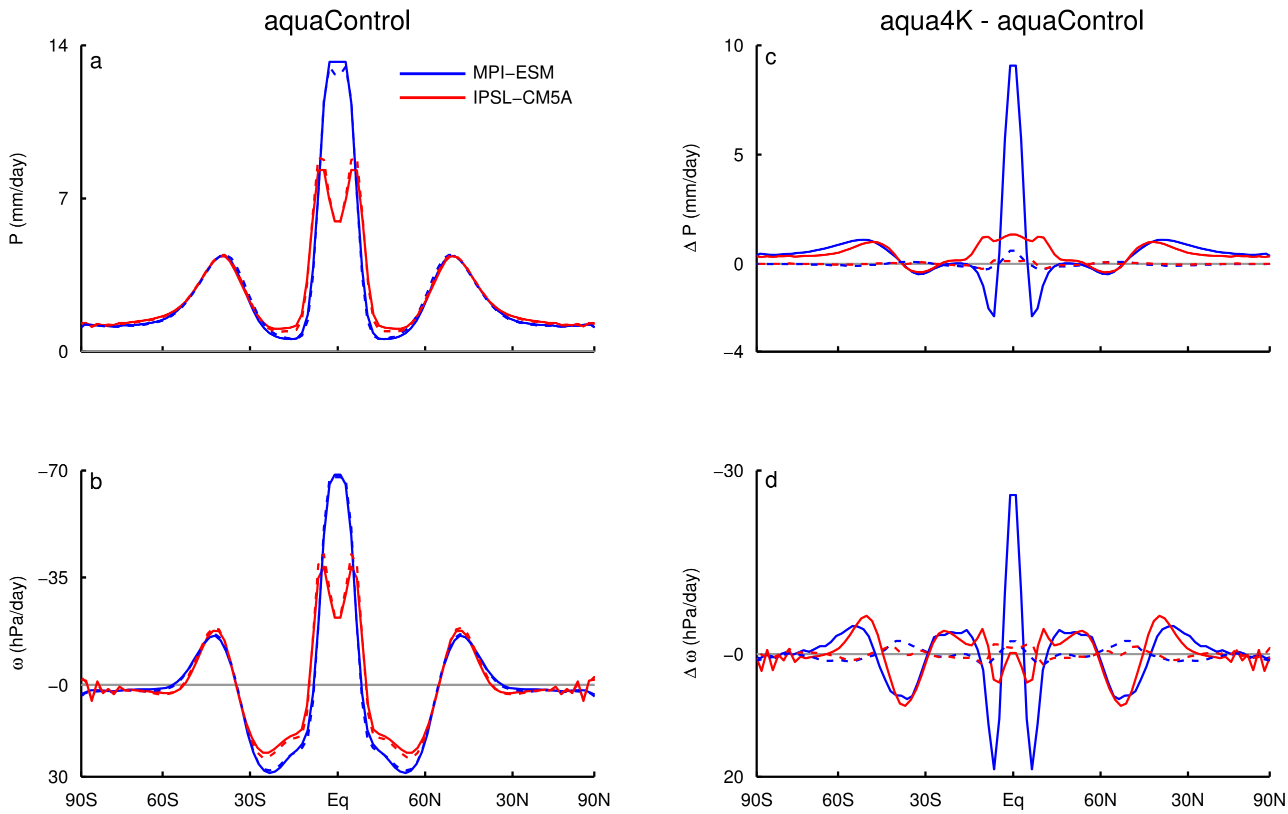

Figure S1 (a,b) Precipitation and 500 hPa pressure velocity in aquaControl. The dashed lines show the simulation T1C1W1, which is the "locked" version of aquaControl (see methods section). T1C1W1 closely resembles aquaControl. (c,d) Response in solid and residual of the locking method in dashed.

Clausius-Clapeyron increase of specific humidity, assuming the circulation did not change. We note that the thermodynamic component is well approximated by

$$\Delta P_{ther} = \Delta E + 4K \cdot 0.065K^{-1} \cdot (P - E)_{aquaControl},$$

where we have assumed a 6.5% increase in specific humidity per degree surface warming to scale the meridional moisture convergence of aquaControl. Fig. S2 clearly shows that the dynamic component dominates the model disagreement in the meridional pattern of the precipitation response. In particular, the precipitation response due to radiative changes of clouds and water vapor is almost entirely due to circulation changes.

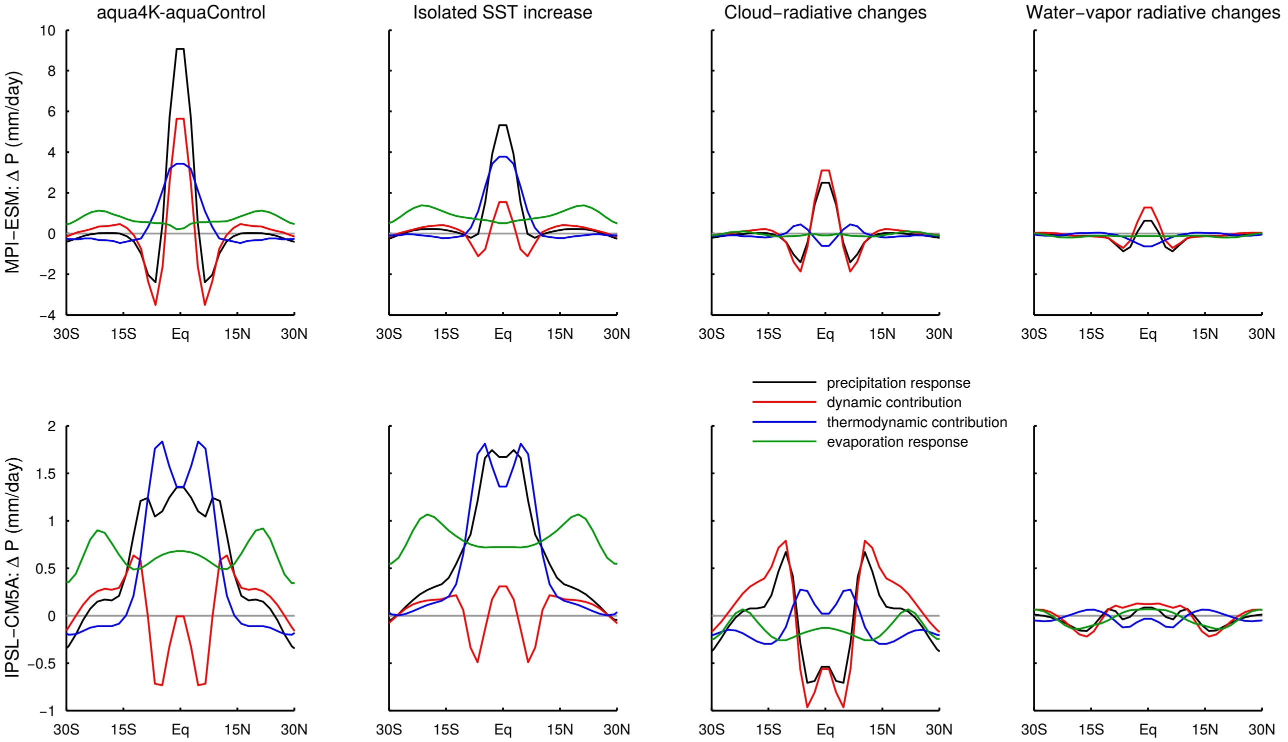

Figure S2 Decomposition of the precipitation response into dynamic and thermodynamic components for MPI-ESM (top) and IPSL-CM5A (bottom). The evaporation response is shown in green.

 DOI: 10.1038/NGEO2345

3 Response of the Hadley circulation and the width of the tropics

We characterize the Hadley circulation via the maximum of the time-mean meridional mass stream function, Ψ_{max}, and the time and zonal-mean upward ($\omega^{\uparrow}$, negative) and downward ($\omega^{\downarrow}$, positive) pressure velocities in the ascending and descending branch of the circulation. The velocities are averaged between 300 and 800 hPa and within 30° N/S. The width of the tropics is defined as the subtropical latitude where the mass stream function crosses zero at 500 hPa. Table S1 list the response of these quantities to global warming (aqua4K minus aquaControl). Changes in the mean upward and downward velocities are expressed as fractional changes with respect to aquaControl. Ψ_{max} is given in units of 10^9 kg/s.

Table S1 Response of the tropical circulation and the width of the tropics.

	Total response	Isolated SST increase	Cloud-radiative changes	Water-vapor radiative changes	Residual
$\Delta\omega^{\uparrow}/\omega^{\uparrow}$:					
MPI-ESM	4.9%	0.2%	5.3%	-1.4%	0.8%
IPSL-CM5A	-24.5%	-13.6%	-14.2%	0.1%	3.2%
$\Delta\omega^{\downarrow}/\omega^{\downarrow}$:					
MPI-ESM	-3.0%	-7.1%	2.0%	0.0%	2.1%
IPSL-CM5A	-5.8%	-4.2%	-3.7%	0.0%	2.1%
$\Delta\Psi_{max}$:					
MPI-ESM	6	0	13	-8	1
IPSL-CM5A	-13	-6	-7	-1	-2
width of tropics (° lat):					
MPI-ESM	1.5	1.4	0.6	-0.3	-0.2
IPSL-CM5A	1.5	0.8	0.9	-0.2	0.0

4 Response of the ITCZ to cloud-radiative changes

4.1 Changes in cloud-radiative heating and upward motion

The imposed cloud-radiative changes heat the deep-tropical atmosphere and require adiabatic cooling through upward motion. Fig. S3 shows the change in atmospheric radiative heating due to cloud-radiative changes, ΔH_{clouds}. Water-vapor is locked in these simulations and changes in atmosphere temperatures are small, so ΔH_{clouds} effectively measures the cloud-radiative forcing.

4.2 Vertically-integrated cloud ice in aquaControl and its response in aqua4K

Vertically-integrated cloud ice peaks at the equator in MPI-ESM but at 6° N/S in IPSL-CM5A in aquaControl (crosses in Fig. S4). The 4 K increase in SSTs leads to meridional displacements of tropical ice clouds that can be seen in changes of vertically-integrated cloud ice. In MPI-ESM, deep-convective clouds contract towards the equator. In IPSL-CM5A, they extend further poleward, which is evident from the increase in cloud ice on the poleward flank of the cloud ice maximum of aquaControl (see Fig. S4).

5 Response of the ITCZ to global warming in the CMIP5 aquaplanet model ensemble

We analyzed the changes in the ITCZ across the CMIP5 aquaplanet model ensemble to study if there is a systematic relationship between the ITCZ in aquaControl (single versus double) and the response of the ITCZ in aqua4K (narrowing versus widening). Nine models provide the necessary data. We used the first realization for each model. Details about CMIP5 are given in [3]; the models are named after their "official" CMIP5 names listed at `http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf`.

Fig. S5 shows the aquaControl precipitation and the response in aqua4K. There is no relationship between the ITCZ location in aquaControl and the ITCZ response. There is one model that simulates a single ITCZ and an ITCZ narrowing (MPI-ESM-LR, and its higher-resolution version MPI-ESM-MR), one model with a single ITCZ and no change in the ITCZ structure (MRI-CGCM3), and one model with a single ITCZ and a widening (FGOALS-g2). Furthermore, there are two double-ITCZ models that simulate a narrowing (CCSM4, FGOALS-s2) and two double-ITCZ models that simulate a widening (IPSL-CM5A-LR, MIROC5).

Changes in the ITCZ structure result from the dynamic component to the precipitation response and are accompanied by changes in vertically-integrated cloud ice in all models (not shown). This suggests that the ITCZ response in all CMIP5 aquaplanet models involves the positive feedback between cloud-radiative changes and upward motion described in paragraph 7 of our manuscript.

DOI: 10.1038/NGEO2345

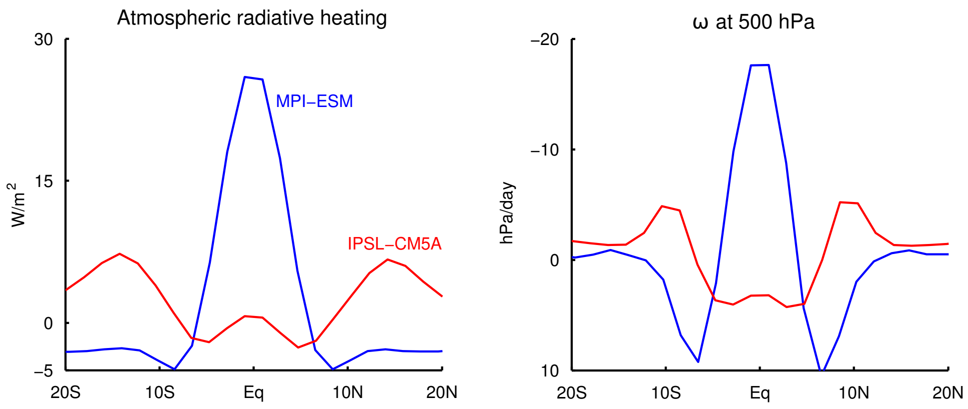

Figure S3 Changes in atmospheric radiative heating due to cloud-radiative changes (a) and response of pressure velocity to this radiative forcing (b).

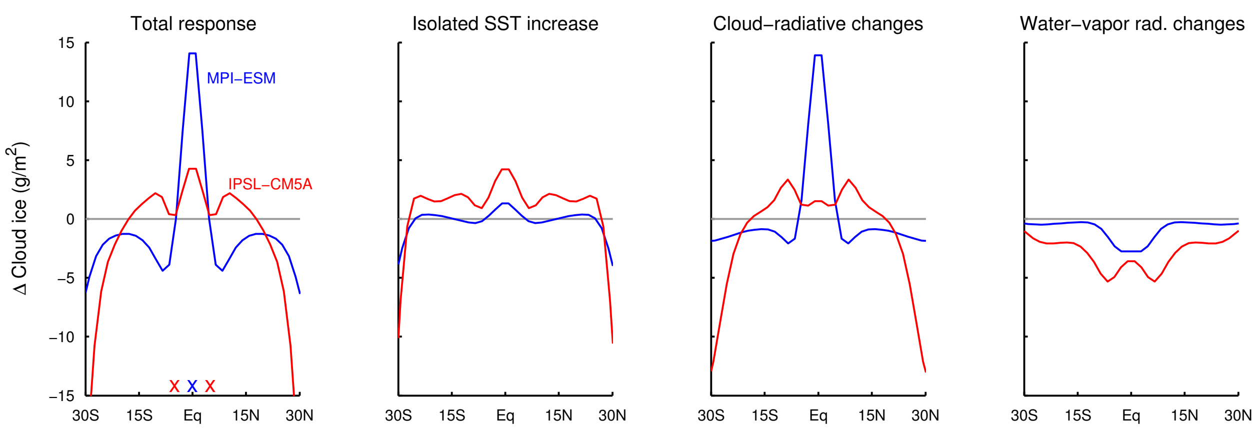

Figure S4 Response of time and zonal-mean vertically-integrated cloud ice and contributions from the isolated SST increase and the radiative changes of clouds and water vapor. The crosses indicate the latitude at which tropical cloud ice peaks in aquaControl.

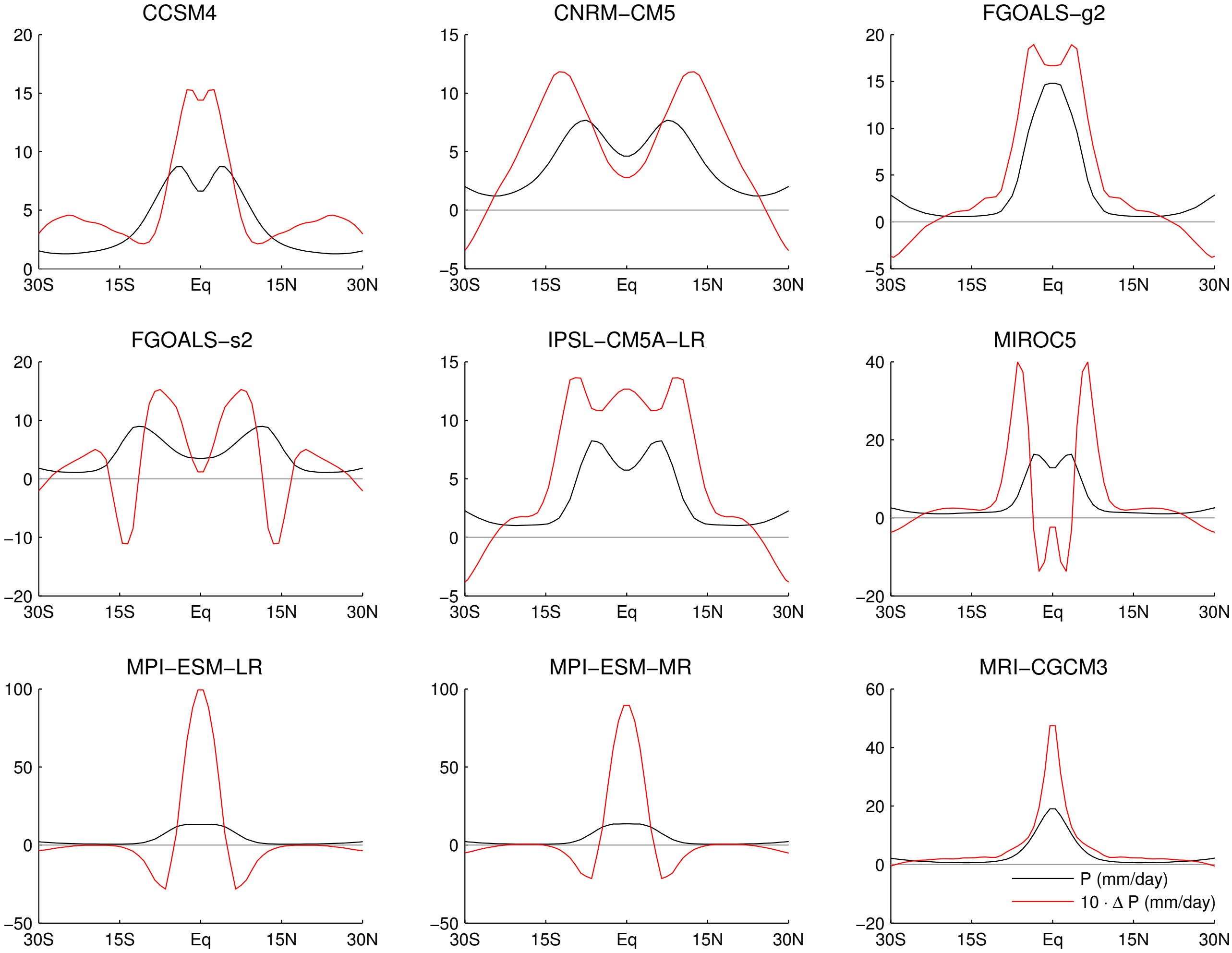

Figure S5 Time and zonal-mean tropical precipitation in aquaControl and its response in aqua4K in the CMIP5 aquaplanet model ensemble.

References

[1] Mechoso, C. *et al.* The seasonal cycle over the tropical Pacific in coupled ocean-atmosphere general-circulation models. *Mon. Weather Rev.* **123**, 2825–2838 (1995).

[2] Bony, S. *et al.* Robust direct effect of carbon dioxide on tropical circulation and regional precipitation. *Nature Geosci.* **6**, 447–451 (2013).

[3] Taylor, K. E., Stouffer, R. J. & Meehl, G. A. An Overview of CMIP5 and the Experiment Design. *Bull. Amer. Meteor. Soc.* **93**, 485–498 (2012).