Supporting Information:
The influence of climate feedbacks on regional hydrological changes under global warming

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Table of Contents

Hadley cell parametrization in the MEBM

Additional details

To simulate a realistic hydrological cycle, we define a Gaussian weighting function w that partitions the transport of latent and dry-static energy within the tropics. We divide F into a component due to the Hadley Cells F_{HC} and a component due to the eddies F_{eddy}, and define w as the fraction of total energy transport that is accomplished by the Hadley Cells at a given latitude:

$$F_{\mathrm{HC}} = wF \text{ and } F_{\mathrm{eddy}} = (1 - w)\,F, \tag{1}$$

and

$$w = \exp\left(\frac{-x^2}{\sigma_x^2}\right), \tag{2}$$

where σ_x is a width parameter, which we set to 0.3 following previous studies. In this formulation, eddies account for essentially all anomalous energy transport poleward of 45°S and 45°N, while the Hadley Cell accounts for most anomalous energy transport between 10°S and 10°N.

In the mean-state climate, poleward atmospheric heat transport by the Hadley Cell F_{HC} is equal to:

$$F_{\mathrm{HC}} = \psi H, \tag{3}$$

where ψ is the mass transport (kg s^{-1}) in each branch of the Hadley Cell and H is the gross moist stability, defined as the difference between h in the upper and lower branches at each latitude. We assume that upper tropospheric moist static energy is uniform in the tropics with a constant value of h_0. Thus, variations in H are due entirely to meridional variations in h giving $H = h_0 - h$ where $h_0 = 1.06 \times h(0)$, or 6% above h at the equator ($x = 0$). However, because we are considering $P - E$ change under warming, the anomalous poleward atmospheric heat transport by the Hadley Cell is represented as:

$$F'_{\mathrm{HC}} = \psi' \overline{H} + \overline{\psi} H' + \psi' H', \tag{4}$$

where ψ' is the anomalous mass transport (kg s^{-1}) in each branch of the Hadley Cell and H' is the anomalous gross moist stability (i.e., the difference between h' in the upper and lower branches at each latitude). H' is estimated in the same way described above. The section below details how the climatological state is approximated using the MEBM.

Climatological state

In the main text, we introduce the Hadley Cell parameterization using the perturbation version of the MEBM. However, the mass transport of the Hadley Cell and thus the pattern of $P - E$ change depends to some extent on the climatological state via Eq. (3) in the main paper. To account for this, we use a climatological version of the MEBM to estimate the climatological state of each GCM. This is done by first calculating the net heating of the atmosphere $Q_{\mathrm{net}}(x)$, which is the difference between the net downward energy flux at the top-of-atmopshere and the surface in preindustrial control simulations. Because the northward column-integrated atmospheric energy transport F is assumed to be related to the meridional gradient in h, the climatological version of the MEBM (with a constant D) is:

$$Q_{\mathrm{net}} = -\frac{p_s}{a^2 g} D \frac{d}{dx}\left[(1 - x^2)\frac{dh}{dx}\right]. \tag{5}$$

The MEBM climatological values of T and q (assuming relative humidity is fixed at 80%) and the value of D can be found by minimizing the difference between the zonal-mean near-surface air temperature and Q_{net} from each GCM and the MEBM using Eq. S5. In other words, the MEBM is tuned to each GCM climatology by finding the value of D that minimizes the difference between the zonal-mean near-surface temperature and Q_{net}. We then calculate ψ, H, and $P - E$ similar to what is described in the main text except the poleward heat flux and moisture flux by the Hadley Cells take the form of:

$$F_{\mathrm{HC}} = \psi H, \tag{6}$$

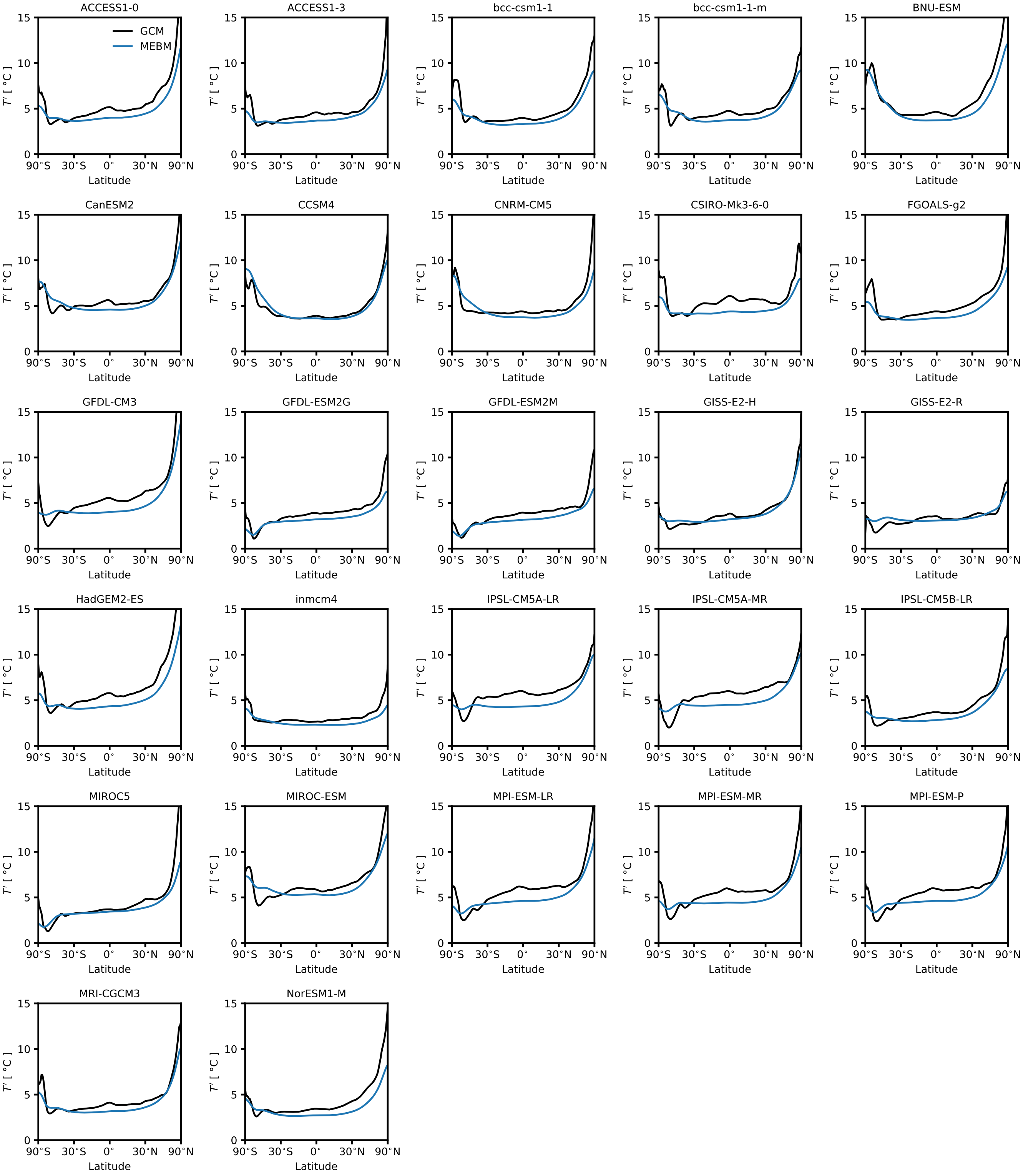
and

$$F_{L,\mathrm{HC}} = -\psi L_v q, \tag{7}$$

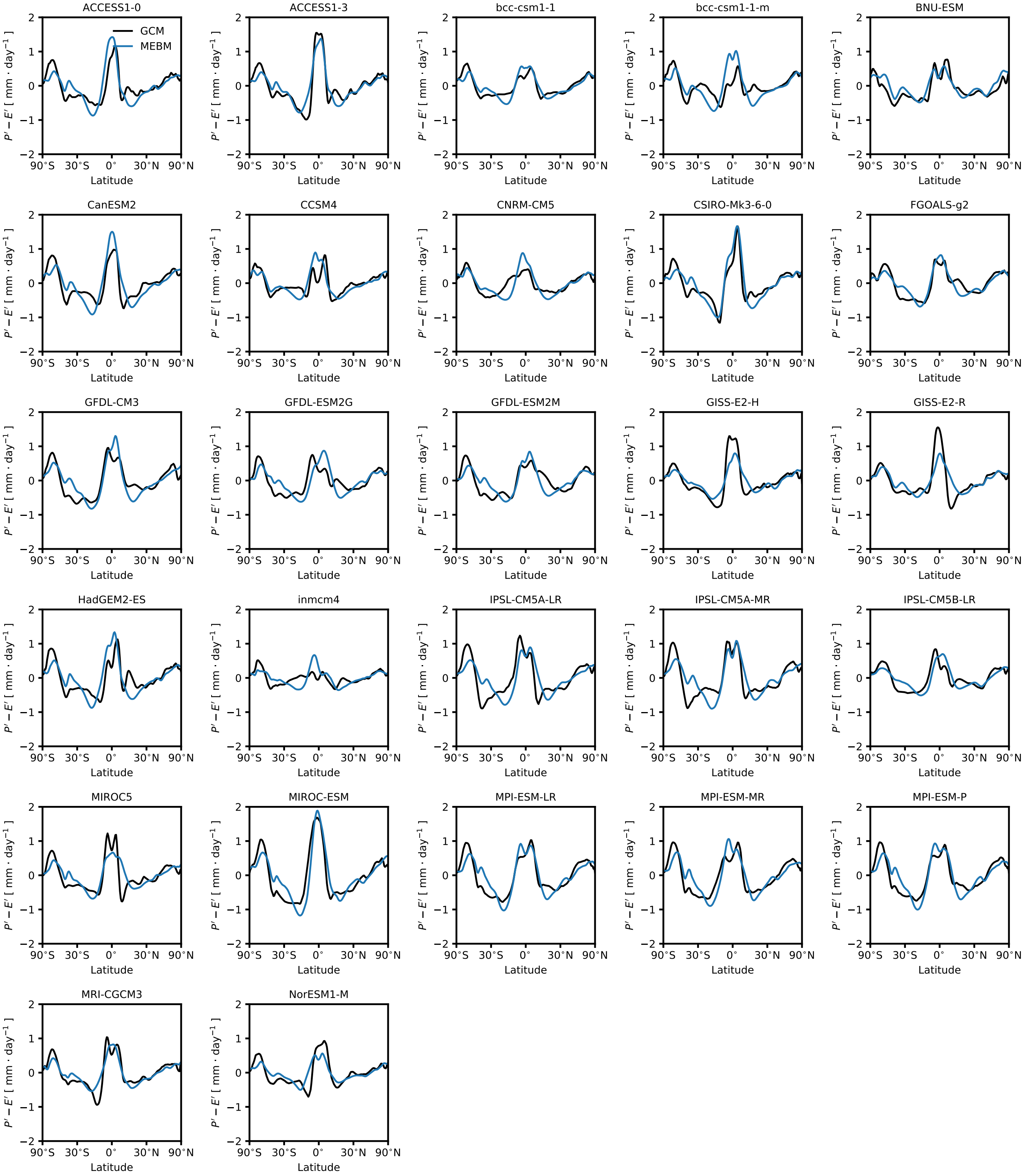
respectively.

	Model Name
1.	ACCESS1-0
2.	ACCESS1-3
3.	bcc-csm1-1
4.	bcc-csm1-1-m
5.	BNU-ESM
6.	CanESM2
7.	CCSM4
8.	CNRM-CM5
9.	CSIRO-Mk3-6-0
10.	FGOALS-g2
11.	GFDL-CM3
12.	GFDL-ESM2G
13.	GFDL-ESM2M
14.	GISS-E2-H
15.	GISS-E2-R
16.	HadGEM2-ES
17.	inmcm4
18.	IPSL-CM5A-LR
19.	IPSL-CM5A-MR
20.	IPSL-CM5B-LR
21.	MIROC5
22.	MIROC-ESM
23.	MPI-ESM-LR
24.	MPI-ESM-MR
25.	MPI-ESM-P
26.	MRI-CGCM3
27.	NorESM1-M

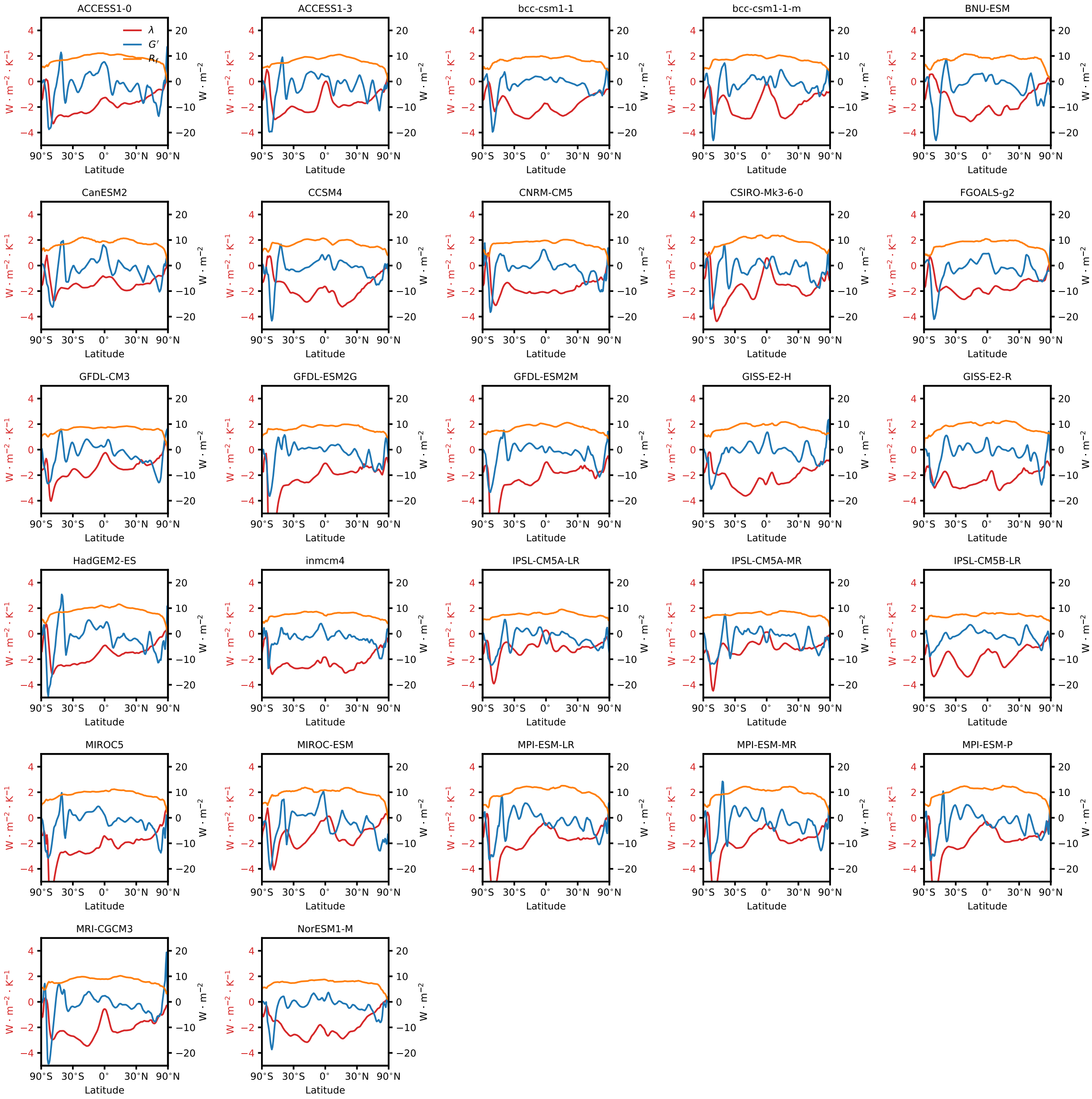
Supplemental Table 1: List of the CMIP5 coupled GCMs used for piControl and 4xCO_2 simulation. Each simulation is from the r1i1p1 ensemble.



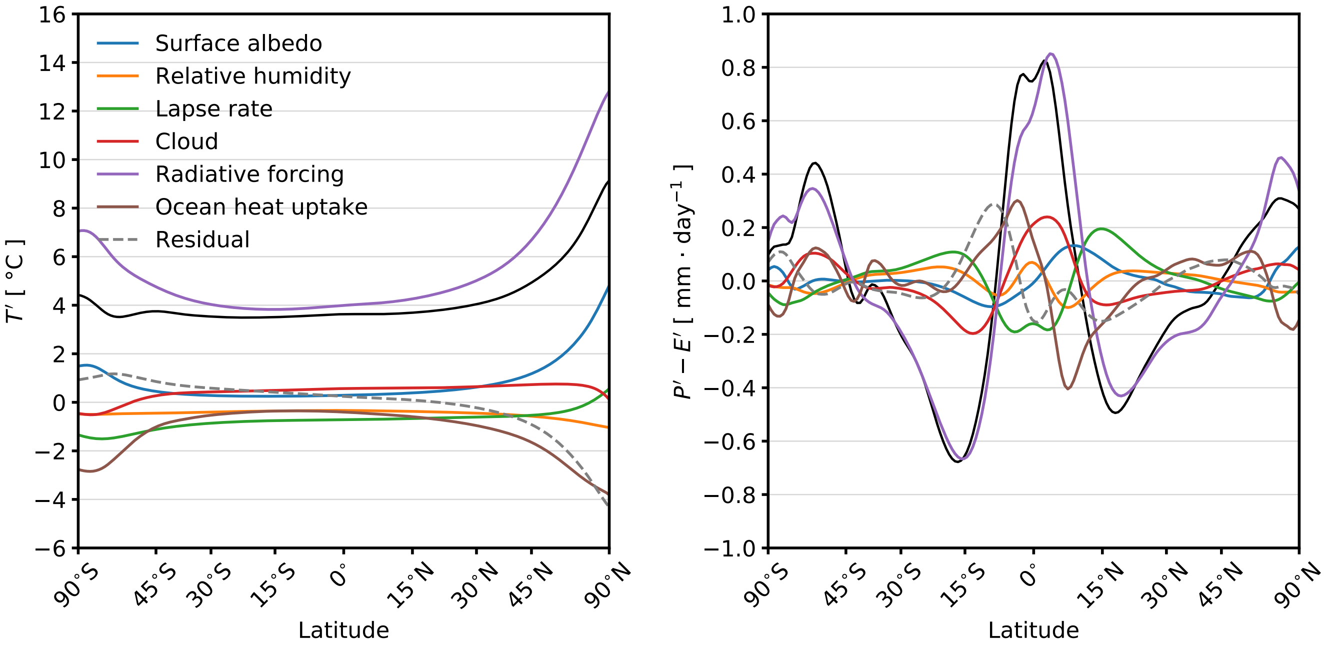
Supplemental Figure 1: **Response of the zonal-mean near-surface air temperature to global warming in a moist energy balance model.** The zonal-mean T change for 27 CMIP5 GCMs 120 – 150 years after an abrupt quadrupling of CO_2. The black line denotes the GCM and the blue line denotes the MEBM.



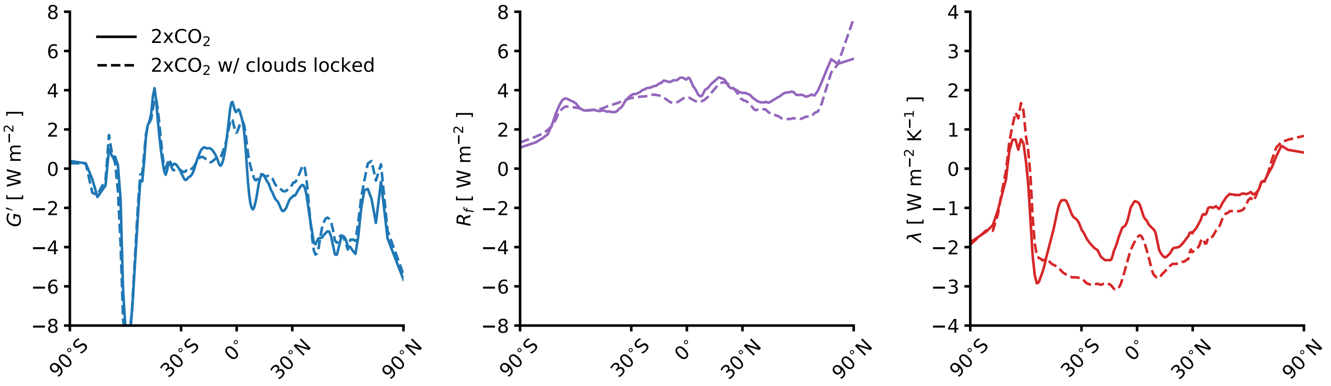
Supplemental Figure 2: **Response of the zonal-mean hydrological cycle to global warming in a moist energy balance model.** The zonal-mean $P-E$ change for 27 CMIP5 GCMs 120 – 150 years after an abrupt quadrupling of $\mathrm{CO_2}$. The black line denotes the GCM and the blue line denotes the MEBM.



Supplemental Figure 3: **Inputs for the moist energy balance model.** Zonal-mean profiles of (red) the net radiative feedback (λ), (blue) ocean heat uptake (G'), (orange) radiative forcing (R_f) for 27 CMIP5 GCMs 120 – 150 years after an abrupt quadrupling of CO_2.



Supplemental Figure 4: **Decomposition of regional hydrological changes for each component.** Contribution of the surface-albedo feedback, relative-humidity feedback, lapse-rate feedback, shortwave and longwave cloud feedbacks, radiative forcing, and ocean heat uptake to changes in zonal-mean T' and zonal-mean $P' - E'$. The black line denotes the MEBM solution and the grey line is the residual of the sum of all colored lines and the black line. The residual is a combination of nonlinear interactions between each component and the Planck feedback, which is not calculated here due to stability issues when removing it in the MEBM.



Supplemental Figure 5: **GCM feedback locking.** Zonal-mean profiles of ocean heat uptake (G'), radiative forcing (R_f), and the net radiative feedback (λ) from the CESM1(CAM5) abrupt2xCO2 experiments with (solid) and without (dashed) cloud radiative effects.