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SUPPLEMENTARY INFORMATION
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An energetic perspective on the regional response of precipitation to climate change

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1 Supplementary Methods

The dry static energy flux divergence may be written as a sum of mean and eddy components

$$H = \nabla . \int \bar{\mathbf{u}}\bar{s} + \nabla . \int \overline{\mathbf{u}'s'} \qquad \text{(S1)}$$

where $\mathbf{u} = (u, v)$ denotes horizontal velocity, ∇ horizontal gradient, $s = c_pT + gz$ dry static energy, overbars climatological means and primes departure from climatological means. The mean dry static energy flux divergence (first term in (Eq. S1)) was calculated using monthly model outputs and a slightly different formulation (obtainable by using the continuity equation and neglecting surface pressure variations),

$$H_m = \int \left(\bar{\mathbf{u}}.\nabla\bar{s} + \bar{\omega}\frac{\partial\bar{s}}{\partial p} \right) \qquad \text{(S2)}$$

where ω is the pressure vertical velocity. The vertical integrals in pressure are difficult to calculate accurately because of the limited vertical resolution of the reported data, especially near the surface. The vertical integrals were taken from zero to the daily surface pressure for daily fields, and from zero to the climatological mean surface pressure for monthly fields. Following ref. 15, missing values near the surface were replaced by interpolation from zonal neighbors if available or by linear extrapolation from upper levels.

Direct calculation of the total dry static energy flux divergence (including the eddy contribution) is problematic because a limited number of pressure levels are available for daily data in most of the models used, and because daily geopotential heights and vertical velocities are not available. Therefore, we calculated changes in the total dry static energy flux divergence as a residual using (1). Because this could potentially introduce errors (if, for example, changes in energy storage in the atmosphere were not negligible as assumed), we confirmed that (1) is satisfied to a reasonable accuracy in one climate model that reported daily output on the same set of pressure levels as monthly output (GFDL-CM2.0). For this test, we calculated the mean contribution as before using (Eq. S2), but because daily vertical velocities were not available, we calculated the eddy contribution from the second term on the right hand side of (Eq. S1). The geopotential height field, needed to calculate the dry static energy, was computed for daily fields using the hydrostatic approximation and the ideal gas law (with virtual temperature). The climatological global mean value of the dry static energy at 500hPa was first subtracted from the dry static energy fields in order to minimize the impact of inaccuracies in mass continuity in the reported daily winds. Fig. S4 shows that (1) is well satisfied for zonal averages, and is adequately satisfied in general, with most of the error over high topography and over some regions of the Southern Ocean.

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2 Supplementary Figures

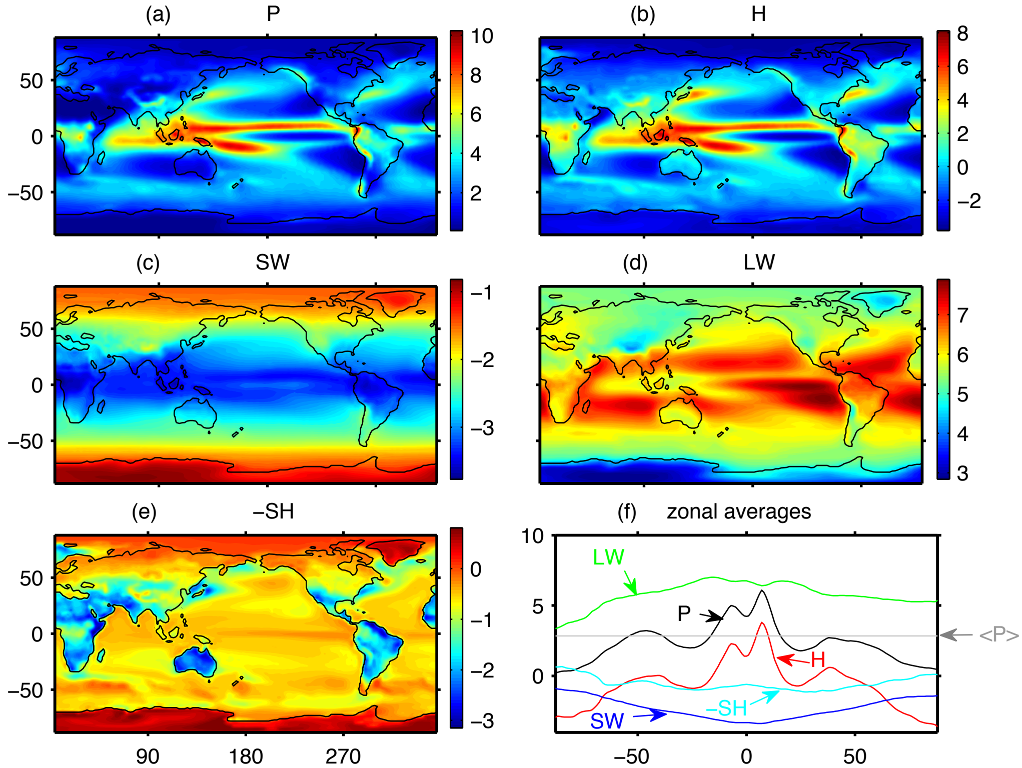

Fig. S1. Twentieth century climatological values of the various contributions to the energy budget (note the different colour scales). All the terms in the energy budget are shown in equivalent precipitation units (mm day^{-1}, see Methods for details about the conversion). Shown are multimodel-mean (a) precipitation (P), (b) dry static energy flux divergence (H), (c) shortwave radiative loss (SW), (d) longwave radiative loss (LW), and (e) net downward surface sensible heat flux (-SH). Zonal averages and the global average precipitation (light gray line) are shown in (f).

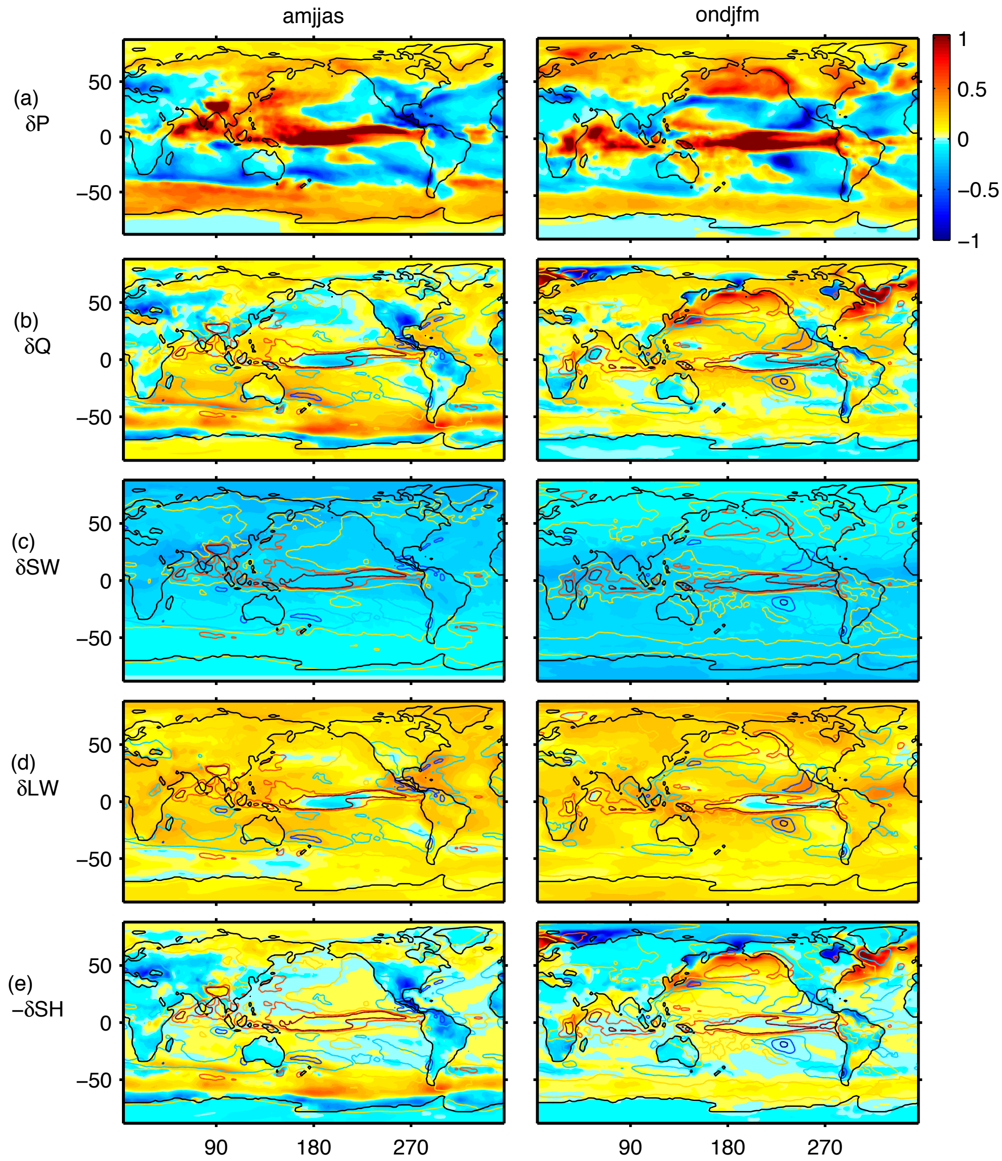

Fig. S2. Multimodel-mean changes in precipitation (δP) and in atmospheric diabatic cooling ($\delta Q = \delta SW + \delta LW - \delta SH$), separately for the six months April to September (left) and October to March (right). As in Fig. S1, all values are in mm day^{-1}. Contours of precipitation change are shown in (b-e) for ease of comparison (contour interval 0.4 mm day^{-1}, from -1 to 1 mm day^{-1}).

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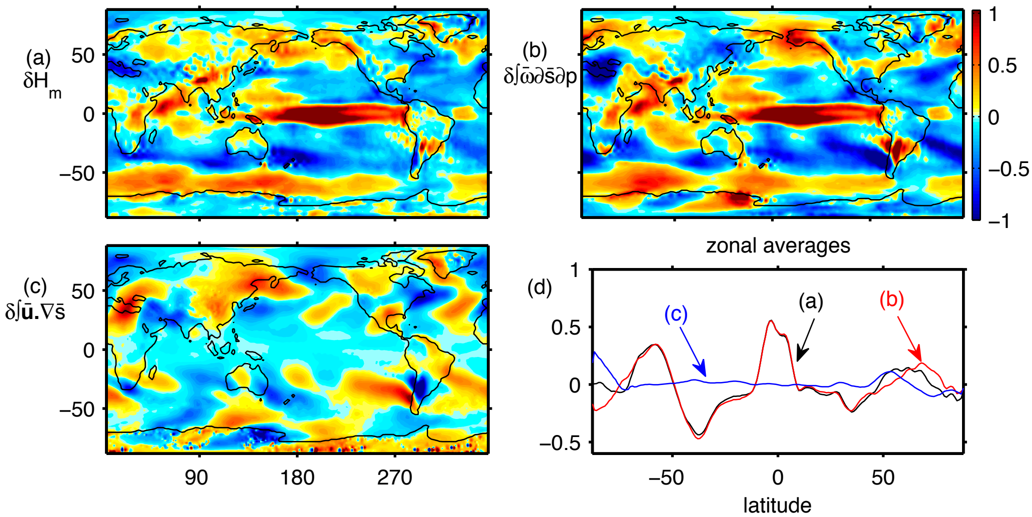

Fig. S3. Annual and multimodel-mean changes in dry static energy flux divergence by the mean circulation (a) and contributions from vertical (b) and horizontal (c) advection (as in Fig. S1, all values are in mm day^{-1}). Zonally-averaged quantities are shown (d).

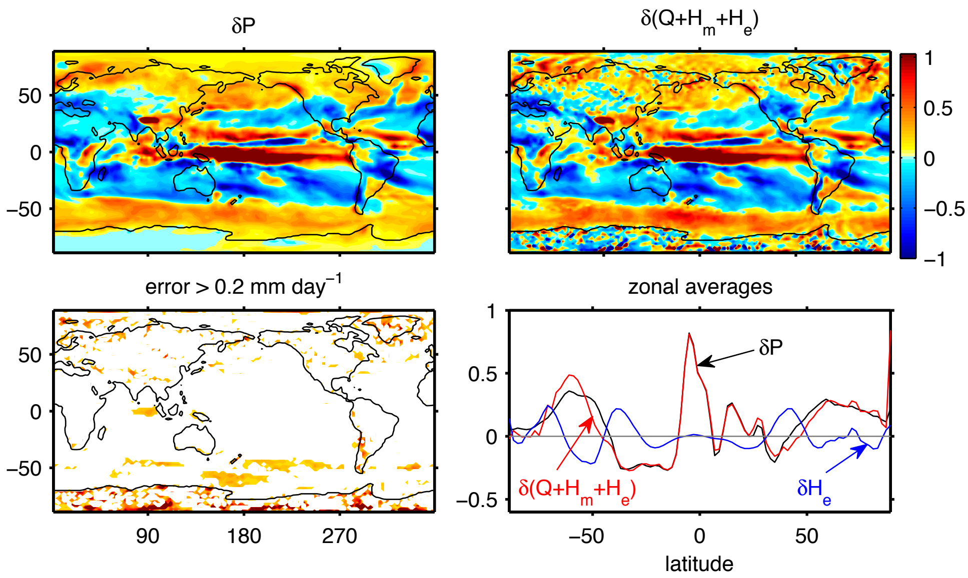

Fig. S4. Perturbation energy budget in one model (GFDL-CM2.0). Shown are the change in annual-mean precipitation δP, the change in the diabatic cooling plus the sum of the mean and eddy dry static energy flux divergence ($\delta Q + \delta H_m + \delta H_e$) estimated from daily outputs, and the difference between the two where it is greater than 0.2 mm day^{-1} (as in Fig. S1, all values are given in mm day^{-1}). Equation (1) is satisfied to a reasonable accuracy in regions away from high topography. The largest errors in the zonal mean (bottom right panel) occur over the Southern Ocean region.