Possible Dependence of Climate on Atmospheric Mass:

A Convection-Circulation-Cloud Coupled Feedback

Supplementary information

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Complementary figures for the simulations in section 6a: Seasonal cycle

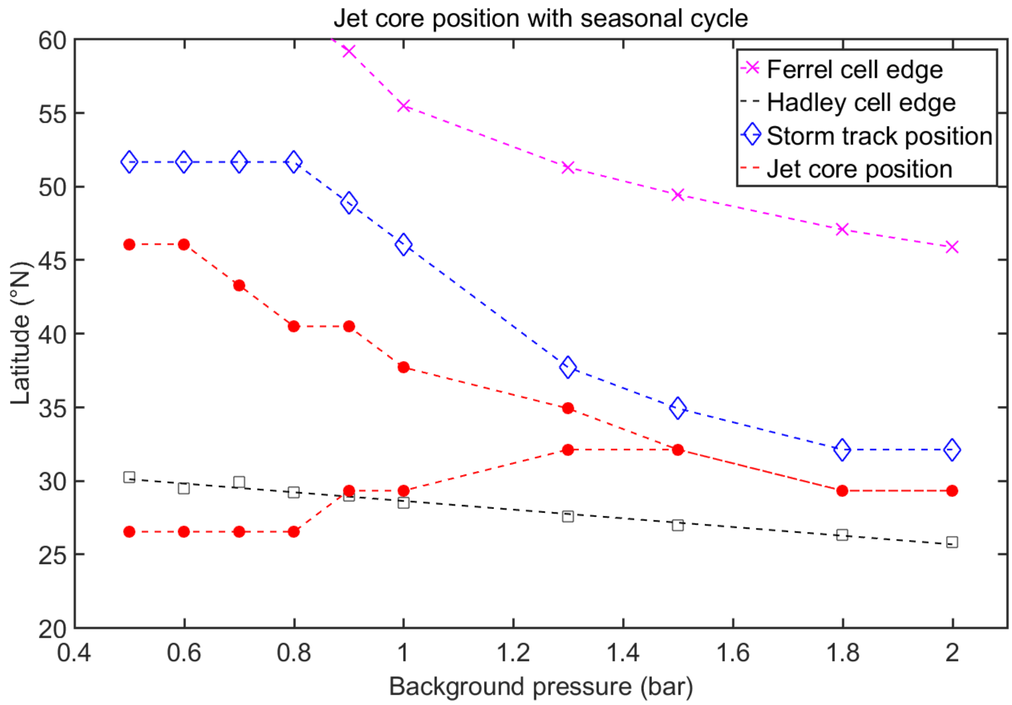

Fig. S1: Same with Fig. 7, but for the group of simulations with the seasonal cycle included.

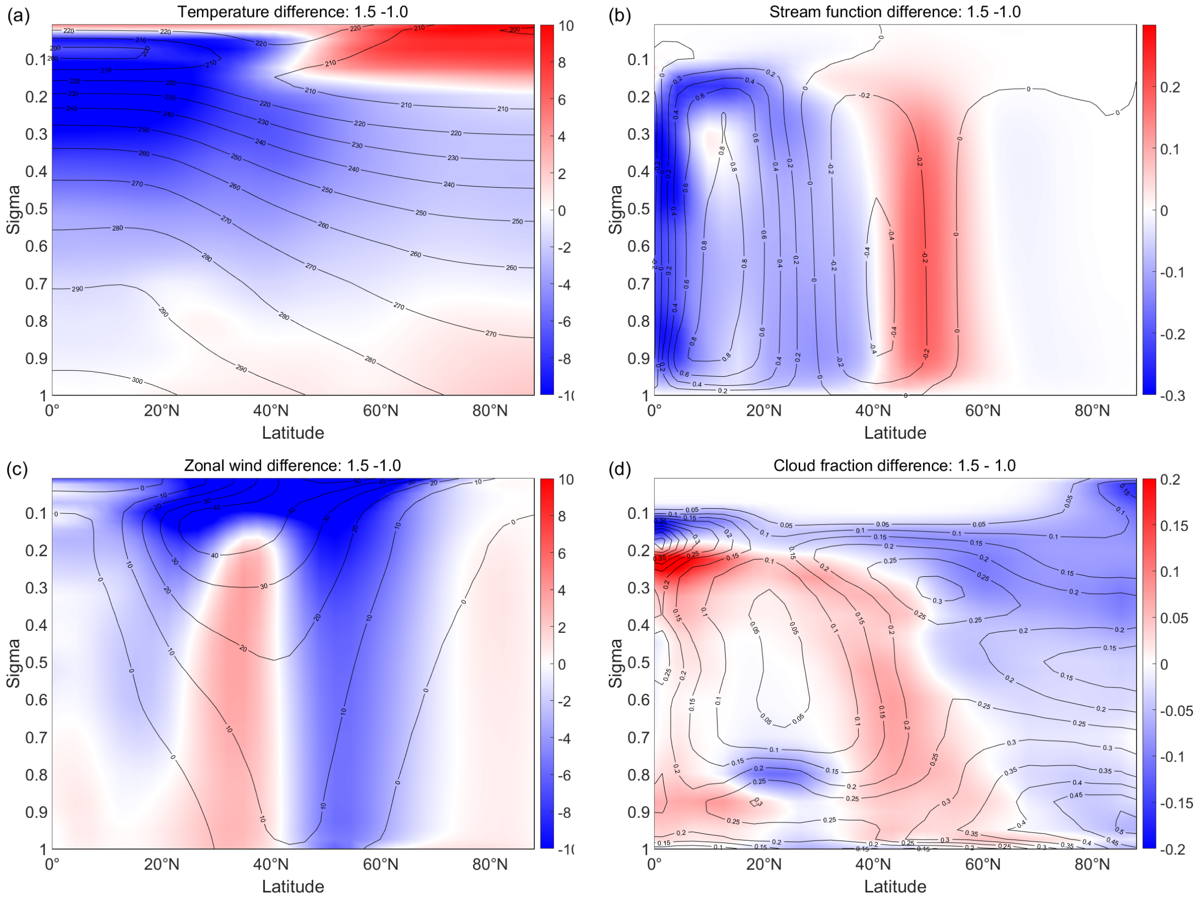

Fig. S2: The annual-mean zonally-averaged (a) temperature (K), (b) mass streamfunction (10^{11} kg/s), (c) zonal wind (m/s), and (d) cloud fraction (unitless). The black contours are for the 1.0 bar case, and the color patches are the difference between the 1.5 bar and 1.0 bar cases.

Complementary figures for the simulations in section 6b: Cloud parameter

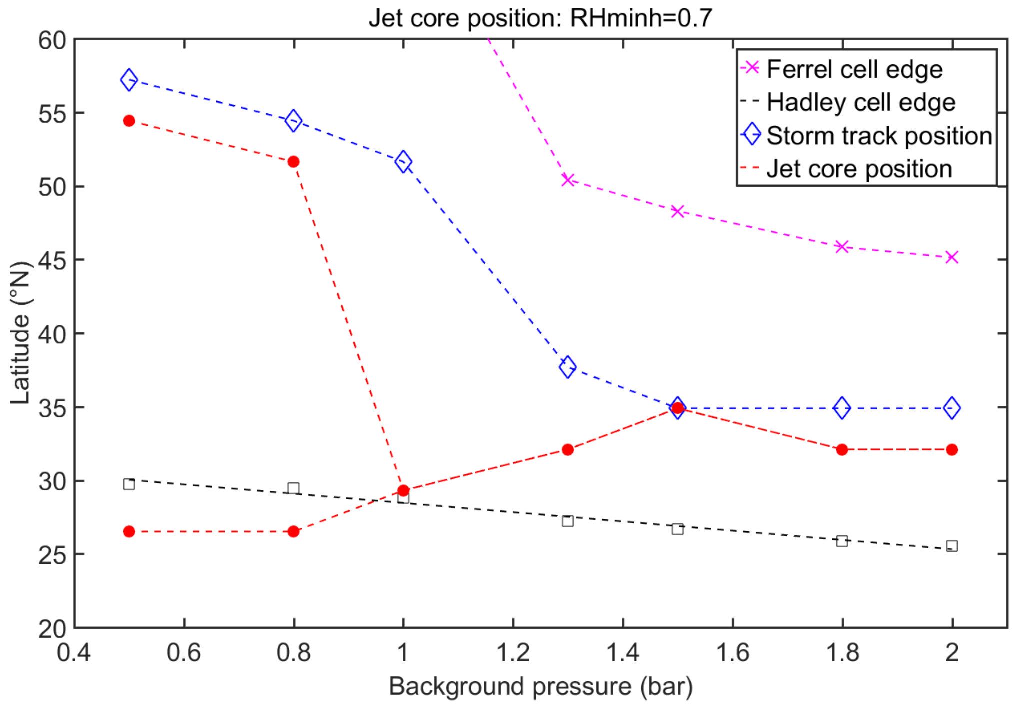

Fig. S3: Same with Fig. 7, but for the group of simulations with RHminh=0.7.

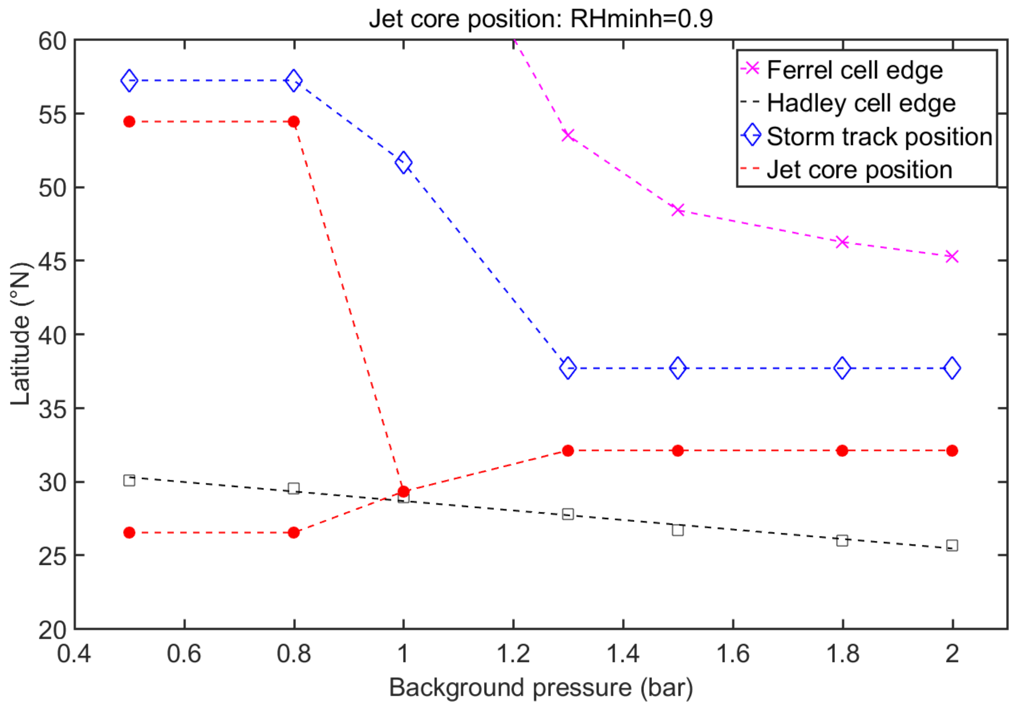

Fig. S4: Same with Fig. 7, but for the group of simulations with RHminh=0.9.

Complementary figures for CAM4 simulations:

To evaluate the robustness of our results with GCMs or physical parameterizations (mainly convective and cloud parameterizations), we repeat the default group simulations with CAM4.0. CAM4.0 is an updated version of CAM3.0, and there are many differences between them (Neale et al. 2010, Collins et al. 2004). We list the differences in the dynamical cores, the convective parameterizations, and the cloud parameterizations in the end.

The nonmonotonic dependence of global mean surface temperature on SP still exist in CAM4.0 simulations (Fig. S5), given there are significant differences between the background state of the control case (1.0 bar case) in the CAM4.0 aquaplanet simulation and that in CAM3.0 (comparing Fig. S6 and Fig. 3-4). As SP increases form 1.0 bar to 1.5 bar, the responses of temperature, westerly jet, and cloud fraction are qualitatively similar to those in CAM3.0 (Fig. S6, Fig. 3-4). The responses of the meridional circulations show larger discrepancies. In CAM4.0, as SP increases, the most significant response of the Hadley cell and the Ferrell cell is becoming more and more bottom heavy. The narrowing of the Hadley cell and strengthening of the Ferrell cell is the secondary responses. Nevertheless, the simulation results suggest that the feedback mechanism presented in the main text functions similarly in CAM4.0.

Some differences between CAM3.0 and CAM4.0:

Dynamical core:

The simulations with CAM3.0 are based on the Eulerian dynamical core, while the simulations with CAM4.0 are based on the finite volume dynamical core.

Parameterization of deep convection:

The parameterizations of deep convection in CAM3.0 and CAM4.0 are both based on Zhang and McFarlane (1995). However, the convective momentum transport is added in the convective parameterization in CAM4.0 (Richter and Rasch 2008). The sub-grid scale convective momentum transport is parameterized as:

$$\left(\frac{\partial V}{\partial t}\right)_{cu} = -\frac{1}{\rho}\frac{\partial}{\partial z}(M_u V_u + M_d V_d - M_c V),$$

$$-\frac{\partial}{\partial z}(M_u V_u) = E_u V - E_u D_u + P_G^u,$$

$$-\frac{\partial}{\partial z}(M_d V_d) = E_d V + P_G^d,$$

where V is the grid mean horizontal velocity, E is the entrainment rate, D is the detrainment rate, M is the mass flux. Subscript u means updrafts, and d means downdrafts. P_G^u and P_G^d are the updraft and downdraft pressure gradient sink terms:

$$P_G^u = -C_u M_u \frac{\partial V}{\partial z},$$

$$P_G^d = -C_d M_d \frac{\partial V}{\partial z}.$$

$C_u = C_d = 0.4$ are tunable parameters (Gregory et al. 1997).

Parameterization of cloud fraction:

In CAM3.0, three types of cloud are diagnosed in parameterization: low-level stratus, convective cloud, and layered cloud. The stratus cloud fraction is parameterized following Klein and Hartmann (1993):

$$C_{st} = min\{1., max[0., (\theta_{0.7} - \theta_s) \times 0.057 - 0.5573]\},$$

where $\theta_{0.7}$ and θ_s are the potential temperature at 0.7 sigma level and at the surface level, respectively. Convective cloud fraction is parameterized based on the mass fluxes of shallow and deep convection (Xu and Krueger 1991):

$$C_{shallow} = k_{1,shallow} ln\left(1.0 + k_2 M_{c,shallow}\right),$$

$$C_{deep} = k_{1,deep} ln\left(1.0 + k_2 M_{c,deep}\right).$$

The layered cloud fraction is parameterized as:

$$C_c = \left(\frac{RH - RH_{min}}{1 - RH_{min}}\right)^2,$$

where RH_{min} is set as:

$$RH_{min} = \begin{cases} RH_{min}^{low} & p > 750mb \\ RH_{min}^{low} + \left(RH_{min}^{high} - RH_{min}^{low}\right)\dfrac{p - 750mb}{p_{mid} - 750mb} & p_{mid} < p < 750mb \\ RH_{min}^{high} & p < p_{mid} \end{cases}$$

The total cloud fraction is subject to the maximum overlap assumption, so that

$$C_{total} = max(C_{st}, C_c, C_{cir}).$$

In CAM4.0, the stratus cloud fraction is parameterized in the same way as CAM3.0. The convective cloud fraction is treated with modifications:

$$C_{shallow} = max\left(0.0, min\left(k_{1,shallow} ln\left(1.0 + k_2 M_{c,shallow}\right), 0.3\right)\right),$$

$$C_{deep} = max\left(0.0, min\left(k_{1,deep} ln\left(1.0 + k_2 M_{c,deep}\right), 0.6\right)\right),$$

$$C_{cir} = min\left(0.8, C_{shallow} + C_{deep}\right),$$

where C_{cir} is the combined convective cloud fraction. The parameterization of the layered cloud is similar to that in CAM3.0, but with a modification if grid water vapor is less than 3 g/kg (Vavrus and Waliser ,2008):

$$C_c^{low} = C_c^{low} max\left(0.15, min(1, Cq_v 0.003)\right).$$

Note that the parameters in the convective cloud parameterization and layer cloud parameterization are different in CAM3.0 and CAM4.0. The total cloud fraction in CAM4.0 is also calculated differently from that in CAM3.0, with the formula of:

$$C_{total} = min(max(C_c, C_{st}) + C_{cir}, 1.)$$

	CAM3-T42	CAM4-fv-2deg	Description
RH_{min}^{low}	0.90	0.91	minimum RH threshold for low stable clouds
RH_{min}^{high}	0.80	0.80	minimum RH threshold for high stable clouds
$k_{1,shallow}$	0.07	0.04	parameter for shallow convection cloud fraction
$k_{1,deep}$	0.14	0.10	parameter for deep convection cloud fraction
p_{mid}	750.e2	750.e2	top of area defined to be mid-level cloud

Table S1. Parameters of cloud parameterizations in CAM3.0 and CAM4.0.

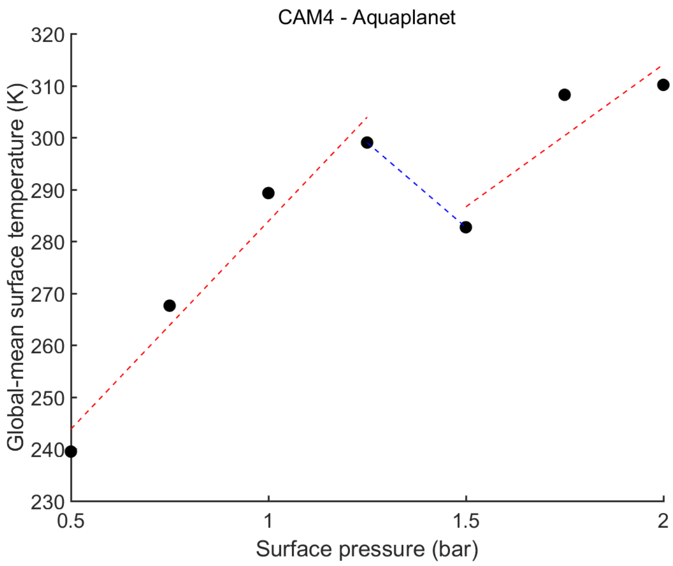

Fig. S5 Global mean surface temperatures (Ts) as a function of SP for the CAM4.0 simulations.

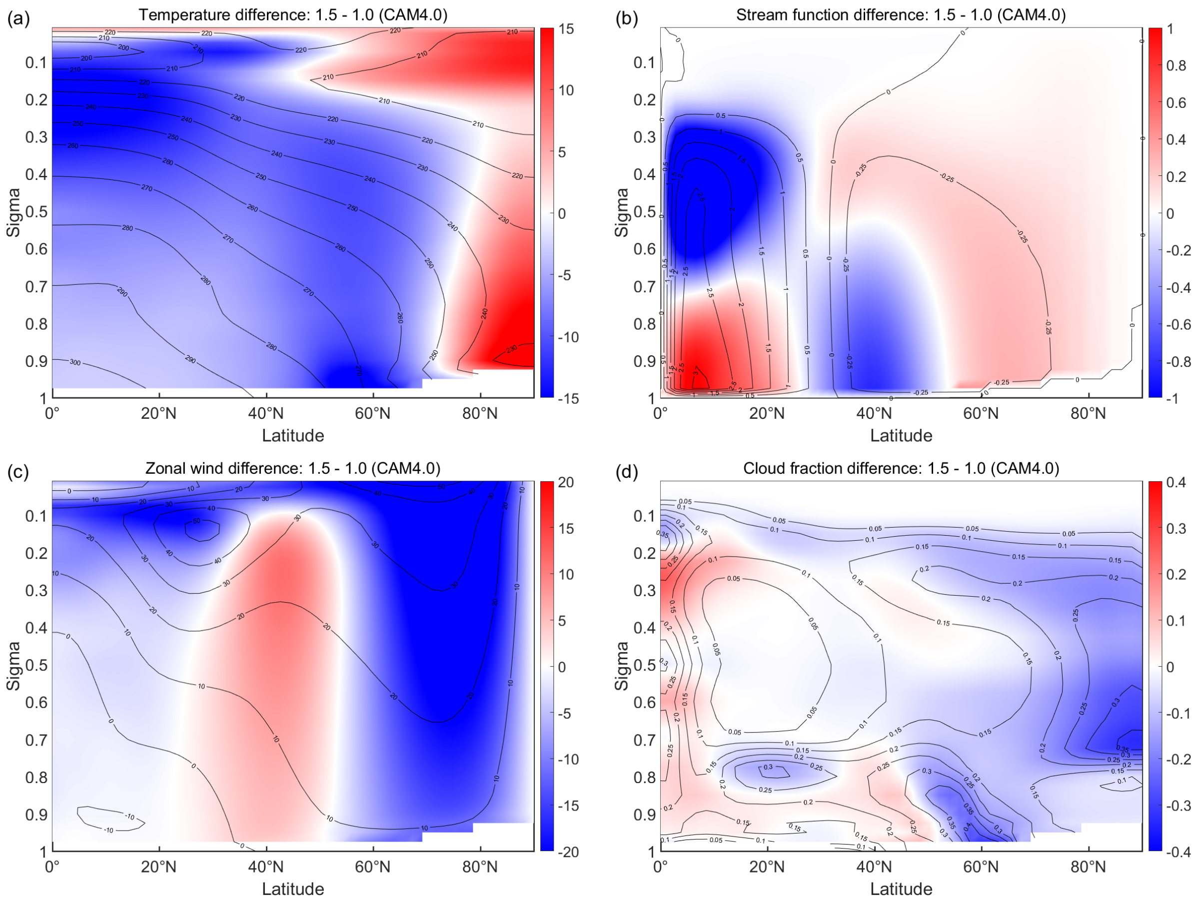

Fig. S6: Same with Fig. S2, but for the CAM4.0 simulations (without seasonal cycle).

Reference:

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Gregory D, Kershaw R, Inness P M, 1997: Parametrization of momentum transport by convection. II: Tests in single-column and general circulation models. Quarterly Journal of the Royal Meteorological Society, 123(541): 1153-1183.

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Richter J H, Rasch P J, 2008: Effects of convective momentum transport on the atmospheric circulation in the Community Atmosphere Model, version 3. Journal of Climate, 21(7): 1487-1499.

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