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On the link between Hadley circulation changes and radiative feedback processes

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[1] Previous studies have demonstrated that meridional displacements of precipitation in the tropics and changes in the Hadley circulation accompany interhemispherically asymmetric surface temperature changes. In this study, an attempt is made to provide a different perspective by linking this dynamical response to radiative feedback processes. An idealized experiment is conducted in which solar irradiance is reduced in the northern hemisphere extratropics. Radiative feedback analysis indicates that the interhemispheric asymmetry of water vapor and lapse rate feedbacks play a key role in maintaining the simulated cross-equatorial heat transport and Hadley circulation change. On the other hand, cloud feedback plays a relatively minor role because of a large cancellation between shortwave and longwave components. While the experiment is idealized, the implications of the results apply widely from paleoclimate to future climate changes. **Citation:** Yoshimori, M., and A. J. Broccoli (2009), On the link between Hadley circulation changes and radiative feedback processes, *Geophys. Res. Lett.*, *36*, L20703, doi:10.1029/2009GL040488.

1. Introduction

[2] In a variety of contexts, from paleo-proxy records to idealized numerical experiments, it has been reported that meridional displacements of precipitation in the deep tropics and changes in the Hadley circulation accompany interhemispherically asymmetric surface air temperature (SAT) changes [*Broccoli et al.*, 2006; *Yoshimori and Broccoli*, 2008, hereafter YB08, and references therein]. Locally, this may reflect a dynamical constraint between sea surface temperature gradients and low-level winds [*Lindzen and Nigam*, 1987], and a linear relationship between tropical SAT gradients and Hadley circulation changes on seasonal timescales was shown by *Otto-Bliesner and Clement* [2005]. *Broccoli et al.* [2006] demonstrated that similar precipitation and Hadley circulation changes can be induced even when an interhemispherically asymmetric forcing is applied to a model only in the extratropics. The Hadley circulation transports energy meridionally in low latitudes, and thus it can reasonably be expected to change in response to net radiation changes at the top of the atmosphere (TOA), and vice versa. YB08 investigated the equilibrium response of the Hadley circulation to various modern radiative forcing agents, including CO_2, solar irradiance, ozone, and aerosols. They found that the Hadley circulation and cross-equatorial heat transport changes are even more tightly linked to the interhemispheric contrast of imposed radiative forcing (RF) than to the contrast in SAT, and are insensitive to the details of the forcing constituents and distributions. As net radiation changes result from both the applied forcing and feedback processes, it is expected that the investigation of the latter would also provide useful insight into the response of the tropical circulation to asymmetric forcing. In the current study, radiative feedback processes are investigated in the context of their link to changes in the meridional heat transport via the Hadley circulation.

2. Model and Experiment

[3] The model used in this study as well as by YB08 is a coupled atmosphere-slab ocean GCM developed at the NOAA Geophysical Fluid Dynamics Laboratory. The atmosphere has a resolution of $2.0° \times 2.5°$ with 24 vertical levels. The model also includes dynamic and thermodynamic sea ice and land surface model components. For a detailed description of the model, readers are referred to YB08 and the references therein. The preindustrial equilibrium simulation by YB08 serves as a control case in the current study. In the previous experiments reported by YB08, the presence of forcings in the tropics makes it complicated to separate the effect of remote and local forcings on tropical responses, and to interpret the relation between forcing and feedback processes. Therefore, we conducted an idealized experiment in which the total solar irradiance is reduced from 30–60°N with a peak at 45°N in a shape of a sine function (Figure 1a). The magnitude of the forcing is chosen such that the instantaneous RF evaluated at the tropopause yields an interhemispheric contrast of about 0.5 PW (0.55 PW at the TOA). The strength and location of the forcing were determined to crudely mimic such forcings as sulfate and black carbon aerosols used by YB08 (see their Figures 3a, 3b and 14c, 14d).

[4] In order to find the relative role of radiative feedback processes, we performed a partial radiative perturbation (PRP) analysis [*Wetherald and Manabe*, 1988; *Colman and McAvaney*, 1997]. The PRP analysis evaluates the radiative fluxes at the TOA due to parameters such as surface albedo and clouds. Both control and perturbed climate states are used as base climates (i.e., a two-sided PRP analysis) in which the climate variables associated with the feedback processes of interest are substituted. Since the stratospheric adjustment in the forcing may be ignored in the case of solar forcing [*Hansen et al.*, 2005] and the

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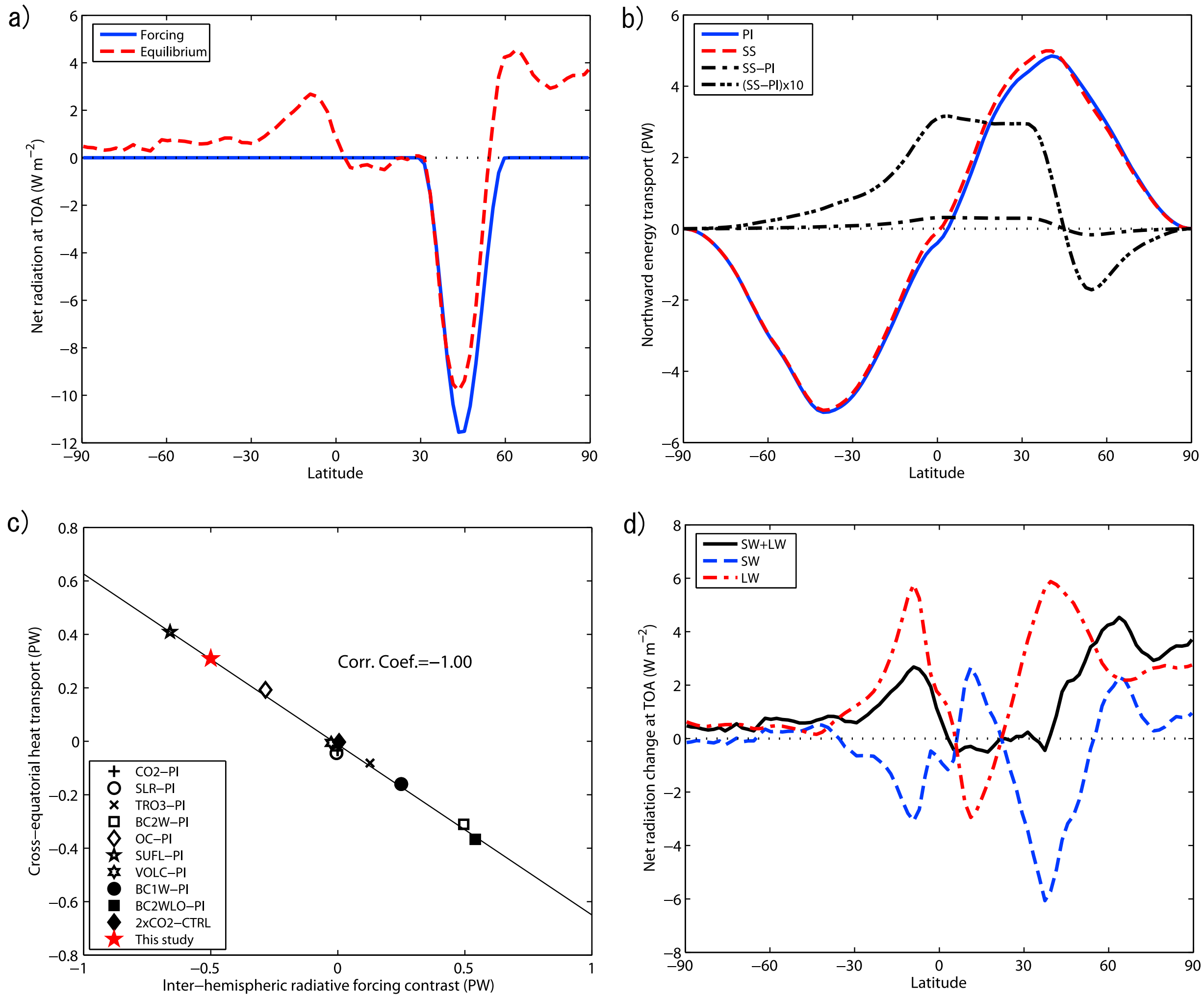

Figure 1. Radiation and energy transport: (a) net radiation at the TOA in forcing and climate equilibrium with respect to the control simulation and (b) northward energy transport in the control and the idealized experiment. "PI" and "SS" denote control and perturbed experiments, respectively. The difference between the two is also plotted with original values and 10 times magnified values for display purposes; (c) relation between interhemispheric contrast in radiative forcing at the tropopause and cross-equatorial heat transport. New data from "This study" is added to Figure 14d of YB08; and (d) net radiation change at the TOA by feedbacks. SW and LW denote shortwave and longwave components, respectively.

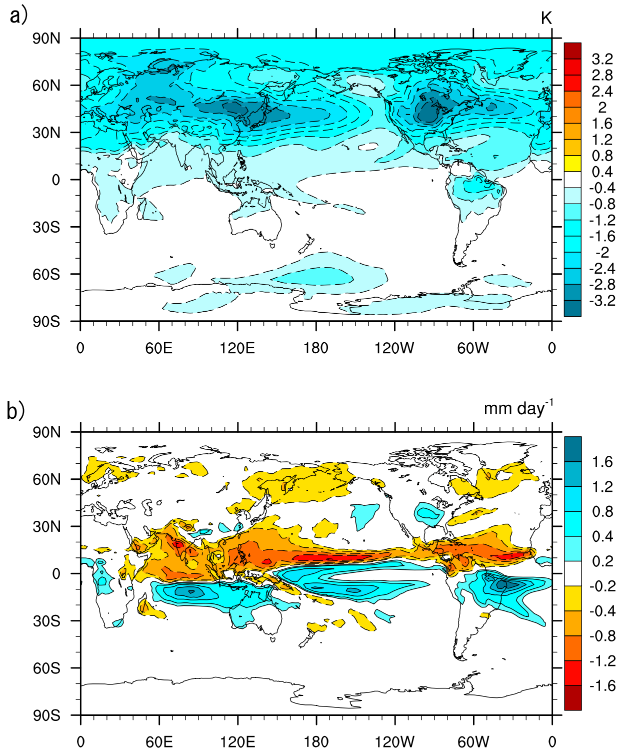

Figure 2. Annual mean changes: (a) surface air temperature (K) and (b) precipitation (mm/day). Negative values are contoured with dashed lines.

definition of the tropopause level is somewhat arbitrary, we discuss TOA fluxes hereafter. Otherwise the detailed procedure follows YB08.

3. Result

[5] Figures 2a and 2b show changes in SAT and precipitation with respect to the control simulation. As expected, a strong cooling of more than 3 K occurs in latitudes where the negative forcing is applied. Cooling in the southern hemisphere (SH) is generally small. This means that the cooling initiated in the northern hemisphere (NH) does not spread efficiently to the SH and the negative thermal anomaly is effectively damped to space in the SH low latitudes. This is consistent with the small change in the meridional heat transport in the SH middle and high latitudes (Figure 1b). Precipitation decreases in the NH tropics and increases in the SH tropics. These precipitation changes occur over a large extent of longitudes and are accompanied by the annual mean change in the Hadley circulation (Figure 3b), very similar to patterns found in many previous studies (e.g., YB08). It is worth mentioning that the forcing is strongest in the NH summer, but the change in the Hadley circulation is strongest in the NH winter.

[6] At the equator, the northward heat transport change is about 0.3 PW, which is about 60% of the interhemispheric contrast of the imposed RF at the tropopause. This is quantitatively consistent with the regression coefficient obtained by YB08 (Figure 1c). The cross-equatorial heat transport change of 0.3 PW is maintained by the increased net radiation of about 0.3 PW in the SH low latitudes, and together with 0.25 PW increase in the NH high latitudes balances the TOA forcing of −0.55 PW (Figure 1d).

[7] To understand the importance of radiative feedbacks in determining the changes in energy balance, consider the case in which the model would behave as a blackbody without the ability to transport energy. The imposed negative RF would be balanced by a reduction in outgoing longwave radiation, so there would be no equilibrium change in net radiation. But instead the change in net radiation is large and negative in the region in which the RF was imposed (Figure 1a) and amplified by positive albedo, water vapor, lapse rate and cloud feedbacks (Figure 4a). Note that the positive values in Figure 4 indicate energy out of the atmosphere and hence amplification of the cooling. This requires a positive contribution to equilibrium global radiation balance from other regions, with anomalous energy convergence in the 30–60°N latitude band. This can be seen in the energy transport anomalies in Figure 1b. The NH tropics do not provide a positive contribution, as there is very strong water vapor feedback and a positive cloud feedback (primarily longwave; see Figure 4b). These probably arise from the southward displacement of subtropical dry zones as the Intertropical Convergence Zone (ITCZ) shifts into the SH. The positive contributions to the global energy balance come from 45–90°N, where there is moderately strong negative cloud feedback, and the SH tropics, where there is strong lapse rate feedback that counteracts the water vapor feedback there. Thus feedbacks are instrumental in creating the need for energy to be imported into the cooled latitude belt and in maintaining a positive energy balance in the energy exporting regions.

[8] The relatively strong and weak negative lapse rate feedbacks in the SH and NH low latitudes are readily confirmed in zonal mean thermal structure (Figure 3a). The cooling in the SH low latitudes is anomalously strong in the upper troposphere where the thermal anomaly is spread from the NH low latitudes through the climatological Hadley circulation because a thermal gradient cannot be maintained there in the absence of Coriolis and frictional forces. The asymmetric strength of water vapor feedback between SH and NH low latitudes is consistent with change in relative humidity and specific humidity (Figures 3b and 3c) where there is an intensified rising branch of the Hadley circulation with a small surface temperature change in the SH. Note that these features are also seen in the sulfate and black carbon aerosol experiments of YB08 in which large displacements of the ITCZ and changes in the Hadley circulation were also simulated.

[9] As discussed, the change in the Hadley circulation is modulated by individual feedback processes. On the other hand, the changes in the Hadley circulation also influence the individual feedback processes. Anomalous upward motion in the SH low latitudes increases specific and relative humidity (Figures 3b and 3c), high-level clouds (Figure 3d), and condensational heating (Figure 3e). Anomalous sinking motion in the NH low latitudes leads to opposite responses there. The changes in humidity reinforce the meridional asymmetry in water vapor feedback between the NH and SH, and thus the thermodynamic effects of this asymmetry would lead to an intensification of the circula-

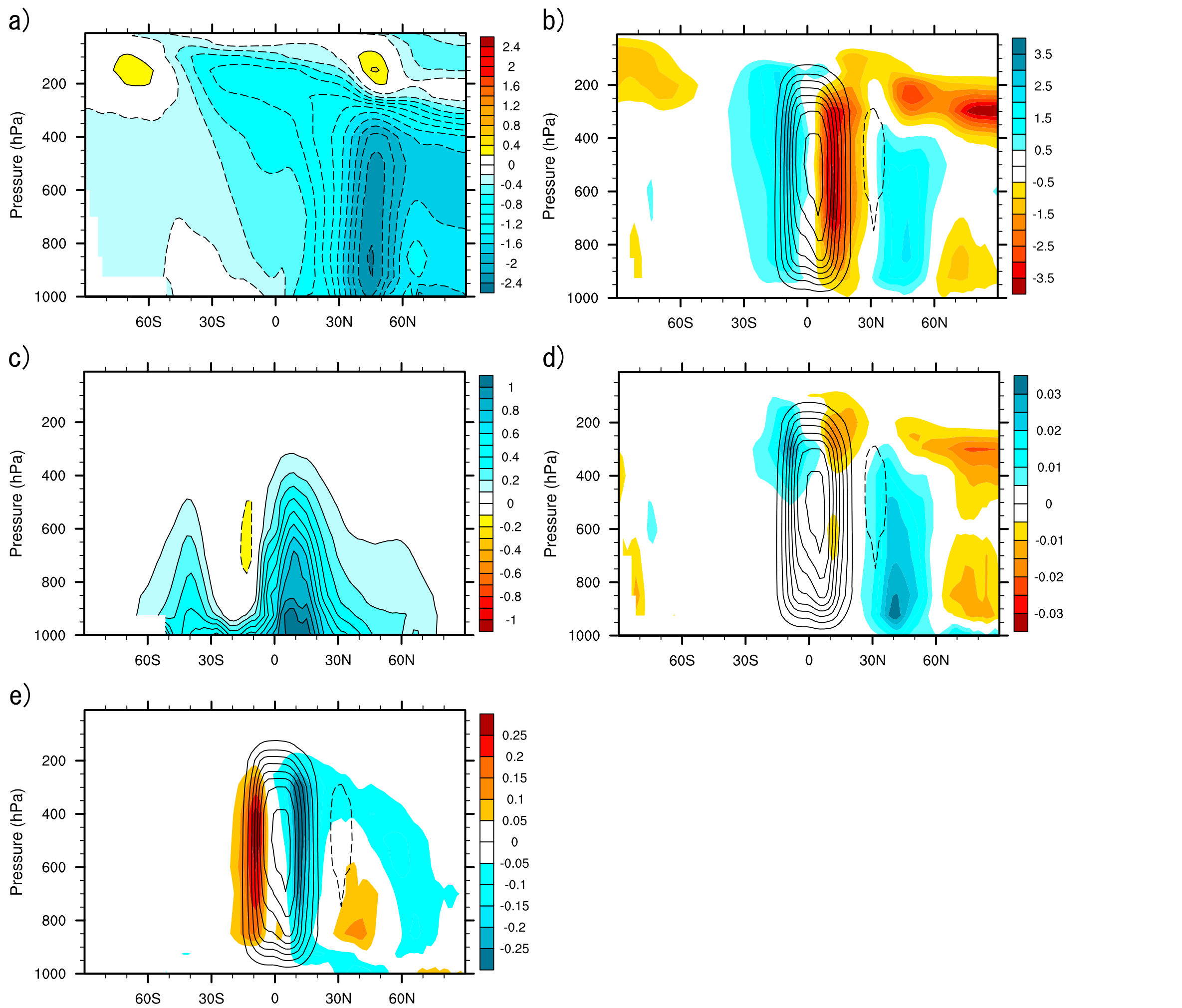

Figure 3. Zonal and annual mean changes: (a) air temperature (K), (b) relative humidity (shading, %) and stream function (contours, interval 4×10^9 kg/s), (c) normalized specific humidity (g/kg/K), (d) same as in Figure 3b except cloud amount (shading, %), and (e) same as in Figure 3b except condensational heating rate (shading, K/day). Note that positive values for stream function indicate clockwise circulation. Values in Figure 3c are divided by zonal mean SAT changes, and thus actual changes in specific humidity show opposite signs. Negative values are contoured with dashed lines.

tion anomaly. Similarly, the changes in high-level clouds would also increase the meridional asymmetry of the positive cloud feedback with a similar effect. Changes in condensational heating would decrease the lapse rate in the SH low latitudes while increasing the lapse rate in the NH, an asymmetry that would tend to counteract the changes in the Hadley circulation.

4. Summary and Discussion

[10] We have demonstrated that interhemispheric asymmetries in the strength of water vapor and lapse rate feedbacks play a key role in the energy balance changes in an experiment with idealized extratropical forcing. Cloud feedback plays a role in cooling the band from 0–50°N, primarily accomplished via longwave from 0–25°N and shortwave from 25–50°N. Although it is important to stress that feedback processes cannot be said to cause the changes in the Hadley circulation in this experiment, they enable such changes to be maintained and amplified. Thus it is essential that models incorporate realistic radiative feedback processes to study the dynamical response of the Hadley circulation. For example, there is a large cancellation of shortwave and longwave components in cloud feedback over many latitudes (Figure 4b), and any imbalance of these two components would likely result in changes in the response of the Hadley circulation. Given the uncertain nature of cloud feedback processes, the response may thus depend on model parameterizations. Indeed, *Kang et al.* [2008] demonstrated that meridional displacements of the ITCZ are sensitive to the convection scheme in an aquaplanet configuration of the same atmospheric GCM. Thus it would be desirable to repeat this analysis with other climate models to determine the extent to which these results are model-dependent. Such intercomparison is beyond the scope of this study.

[11] While *Chiang and Bitz* [2005] were not able to verify a relationship between interhemispheric differences in temperature anomalies and tropical precipitation using modern instrumental records, asymmetric forcing of tropical circulation may become important in the future if aerosol forcing, which has a large interhemispheric contrast,

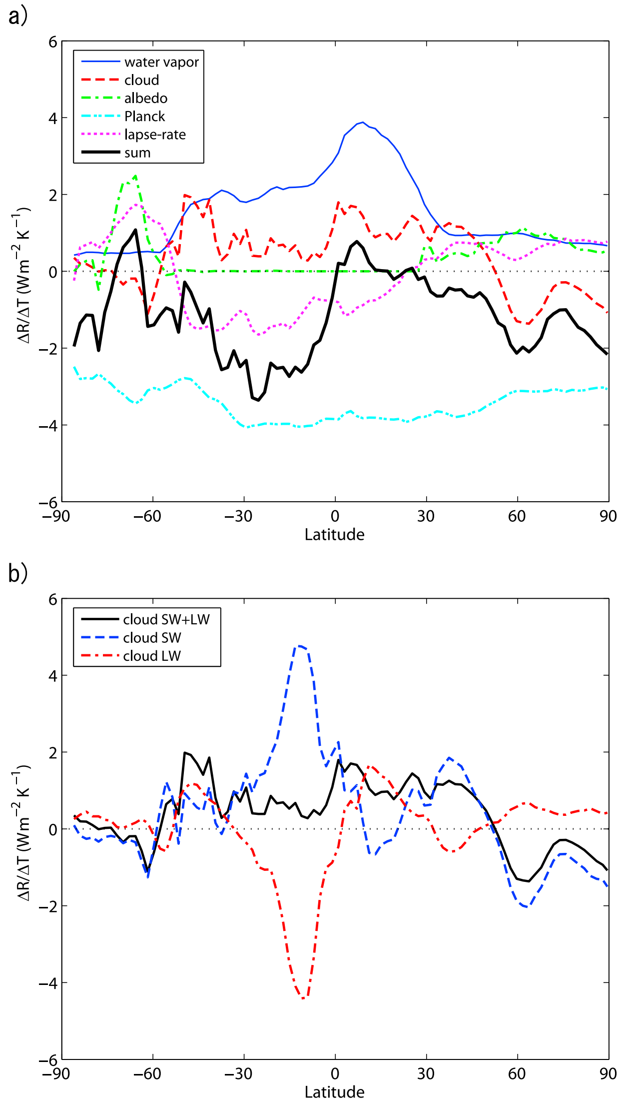

Figure 4. Feedback strength normalized by zonal mean SAT changes: (a) decomposition into individual feedback process and (b) cloud feedback. Note that the values are not plotted where the SAT change is close to zero. The feedback strength is displayed after being divided by the zonal mean, rather than by the global mean (as usually done), SAT change, considering that feedback processes are more tightly linked to local temperature changes. As the zonal mean SAT change is negative in all latitudes, simulated radiative perturbations have opposite signs to the feedback strength.

increases. In paleoclimate, the results provide some insight for tropical precipitation response and the propagation of thermal anomalies such as those introduced by large ice sheets during glacial periods. The importance of feedback processes may be especially relevant on these time scales, as slow feedbacks involving the growth and decay of continental ice sheets or changes in vegetation could enhance the response of the Hadley circulation to asymmetric forcing. Further investigation of this topic is warranted using more comprehensive models that include, for example, ocean dynamics and vegetation feedbacks.

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