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Response of the ITCZ to Northern Hemisphere cooling

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[1] Climate simulations, using models with different levels of complexity, indicate that the north-south position of the intertropical convergence zone (ITCZ) responds to changes in interhemispheric temperature contrast. Paleoclimate data on a variety of timescales suggest a similar behavior, with southward displacements of the ITCZ and associated changes in tropical atmospheric circulation during cold periods in the Northern Hemisphere. To identify a mechanism by which ITCZ displacements can be forced from the extratropics, we use a climate model with idealized geography and a simple slab ocean. We cool the northern extratropics and warm the southern extratropics to represent the asymmetric temperature changes associated with glacial-interglacial and millennial-scale climate variability. A southward shift in the ITCZ occurs, along with changes in the trade winds and an asymmetric response of the Hadley circulation. Changes in atmospheric heat exchange between the tropics and midlatitudes are the likely cause of this response, suggesting that this mechanism may play an important role in ITCZ displacements on timescales from decadal to glacial-interglacial. **Citation:** Broccoli, A. J., K. A. Dahl, and R. J. Stouffer (2006), Response of the ITCZ to Northern Hemisphere cooling, *Geophys. Res. Lett.*, *33*, L01702, doi:10.1029/2005GL024546.

1. Introduction

[2] The importance of tropical influences on the climate of the extratropics is well-recognized in the context of interannual variability, and the tropics have been postulated as a driving force behind changes in extratropical climate on longer time scales as well. In contrast, extratropical forcing is not typically regarded as an important source of tropical climate variability on interannual time scales. Although changes in the circulation of the North Atlantic Ocean have been linked to global climate changes on paleoclimatic time scales, specific physical mechanisms by which the tropical climate may be influenced by events in the extratropics have not been fully explored.

[3] Evidence for one such mechanism arose during the early development of atmosphere-slab ocean climate models, when one of the authors (RJS) noticed a dependence of the latitude of the intertropical convergence zone (ITCZ) on the interhemispheric temperature contrast. The southward bias of the tropical rainfall maximum in one simulation [*Manabe and Stouffer*, 1980] results from an austral warm bias caused by the underestimation of cloud cover in the southern extratropics. The ITCZ was displaced toward the warmer hemisphere, in a manner consistent with its observed seasonal migration between its northernmost latitude in boreal summer and its southernmost latitude in boreal winter.

2. Glacial and Freshwater Forcing Experiments

[4] We provide further evidence for the influence of extratropical forcing on ITCZ position from two pairs of climate simulations using closely related models. Both model configurations employ a three-dimensional atmospheric model (R30 resolution; 2.25° by 3.75° latitude-longitude transform grid) coupled to ocean models of different complexities. The first pair of simulations, in which the atmospheric model is coupled to a slab ocean of 50-m depth with predicted sea ice, consists of a simulation of the last glacial maximum (S-LGM), forced by prescribing continental ice, atmospheric CO_2 concentration, sea level, and orbital parameters from 21 ka, and its corresponding control run (S-CTRL) [*Broccoli*, 2000]. A more comprehensive coupled model [*Delworth et al.*, 2002] that includes a dynamical ocean component is used in the second pair of simulations, which consists of a control run (C-CTRL) and a simulation in which 1 Sv of fresh water was added to the Atlantic Ocean from 50–70°N (C-FW). The model and experimental design are otherwise identical to *Dahl et al.* [2005] except that the forcing was increased by a factor of 10 to yield a more robust response. Fresh water input to the North Atlantic, either in the form of glacial melt water or iceberg discharges, has been proposed as a mechanism of millennial-scale climate variability, and C-FW studies this mechanism through the use of an idealized forcing.

[5] In S-LGM and C-FW, extratropical temperature changes are asymmetric about the equator (Figure 1). Most of the expansion of continental ice sheets during the last glacial occurred in the Northern Hemisphere, producing an interhemispheric asymmetry in radiative forcing. Thus the largest cooling in S-LGM occurs in the boreal extratropics.

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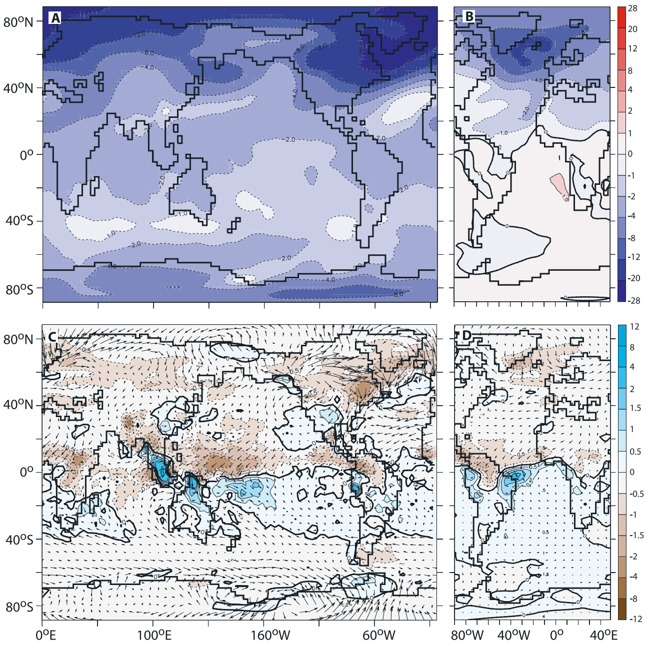

Figure 1. Difference in annual mean surface air temperature (K) (a) between S-LGM and S-CTRL, and (b) between C-FW and C-CTRL. Difference in annual mean precipitation rate (colors, mm d^{-1}) and surface winds (vectors) (c) between S-LGM and S-CTRL, and (d) between C-FW and C-CTRL.

In C-FW, there is a substantial regional cooling centered on the subpolar North Atlantic, where the prescribed input of fresh water disrupts the northward transport of heat associated with the meridional overturning circulation.

[6] In the tropics, a southward shift in the tropical rainfall maximum associated with the ITCZ is simulated in S-LGM globally and in C-FW in the Atlantic sector (Figure 1). This shift is consistent with the hypothesis that the ITCZ should move toward the relatively warmer hemisphere in response to a differential cooling. In association with this shift, the northern trade winds are enhanced and northerly surface wind anomalies dominate the near-equatorial latitudes. The results from S-LGM are consistent with those of *Chiang et al.* [2003], in which a southward displacement of the ITCZ in a simulation of the ice age climate was attributed to ice sheet-induced cooling of the North Atlantic.

[7] Similar changes in climate have been inferred from the paleoclimate record in response to glacial-interglacial and millennial-scale climate variability. Accumulation rates in ice cores from the high Andes indicate that precipitation decreased at Huascaran (9°S) and increased at Sajama (18°S) during the LGM, which has been interpreted as a southward shift of South American precipitation [*Thompson et al.*, 2000]. *Wang et al.* [2004] analyzed 210 kyr of speleothem and travertine deposits and found that northeast Brazil was anomalously wet during periods when the Northern Hemisphere was cold, consistent with a southward displacement of the tropical rainfall maximum. *Koutavas and Lynch-Stieglitz* [2004] find that the marine ITCZ in the eastern Pacific is displaced southward when the Northern Hemisphere is cool. Rapid changes in tropical vegetation in northern South America during the last deglaciation lagged high-latitude North Atlantic climate by several decades [*Hughen et al.*, 2004], and changes in riverine discharge into the Caribbean Sea accompanied temperature changes in the high-latitude North Atlantic [*Peterson et al.*, 2000; *Haug et al.*, 2001]. Both of these records may be indicative of changes in precipitation associated with ITCZ displacements. *Black et al.* [1999] show that a proxy for the strength of the northeast trade winds in the southeastern Caribbean is negatively correlated with sea surface temperature (SST) anomalies in the high latitude North Atlantic on decadal timescales. Viewed collectively, these studies provide paleoclimatic evidence of the commonality of ITCZ response to Northern Hemisphere cooling on timescales from glacial-interglacial through decadal.

3. Idealized Simulations

[8] An additional pair of simulations was designed to determine how extratropical forcing induces the southward displacement of the ITCZ that occurs in the LGM and fresh water forcing experiments. This pair of simulations is made with the same atmosphere-slab ocean model used for S-LGM, but with idealized modern-day boundary conditions to simplify the interaction between continental configuration and climate. In the control run (I-CTRL), two flat continents, symmetric about the equator, occupy approximately the same surface area as the actual continents. An idealized heat flux adjustment, zonally uniform and symmetric about the equator, is added to the slab ocean to mimic the effects of ocean heat transport and make the meridional distribution of temperature quasirealistic. The resulting climate resembles a more zonally symmetric version of the actual climate, with tropical SSTs averaging ~30°C and the winter sea ice margin at ~70° latitude. The ITCZ migrates from the southern tropics in boreal winter to the northern tropics in boreal summer. An interhemispheric asymmetry in heating is introduced in a second run with the same idealized geography (I-ASYM) by adding an incremental heat flux of -10 W m^{-2} to the slab ocean north of 40°N and a heat flux of +10 W m^{-2} south of 40°S. The forcing is antisymmetric so that it neither adds nor subtracts heat from the global climate system.

[9] In response to this forcing, dramatic changes in tropical circulation occur in I-ASYM, with a southward shift of the ITCZ of ~6° latitude. Antisymmetric precipita-

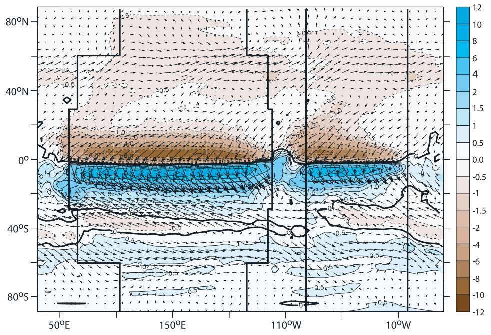

Figure 2. Differences in annually averaged precipitation rate (colors, in mm d^{-1}) and surface winds (vectors) between I-ASYM and I-CTRL.

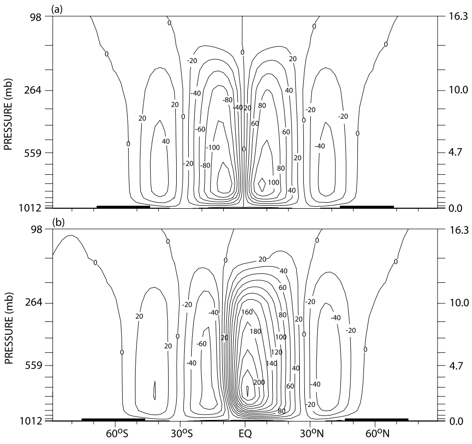

Figure 3. Latitude-height cross section of annually averaged meridional stream function (10^9 kg s^{-1}) from I-CTRL (top) and I-ASYM (bottom).

tion anomalies straddle the equator, and cross-equatorial wind anomalies are present, directed from north to south (Figure 2). The northern trade winds are enhanced while the southern trades are weakened. These features are most evident over the oceans, as monsoonal effects produce more complicated patterns over the low-latitude continents. Changes in precipitation and meridional wind in I-ASYM are qualitatively similar to those that appear globally in S-LGM and in the Atlantic sector in C-FW. This similarity is consistent with the hypothesis that the interhemispheric asymmetry in cooling in these experiments would lead to a southward displacement of the mean position of the ITCZ. The response in I-ASYM is much larger because of the exaggerated asymmetry of the forcing used in that run.

[10] An equally dramatic response is evident in the annually averaged mean meridional circulation. The symmetric Hadley cell structure of I-CTRL becomes much more asymmetric. The northern cell expands and intensifies at the expense of its southern counterpart, and the rising branch of the Hadley circulation shifts southward (Figure 3). Seasonal analyses (not shown) indicate that the winter seasons dominate, with the most pronounced intensification of the northern cell and the weakening of the southern cell during boreal and austral winter, respectively.

[11] By construction, there is no direct communication between the grid points of the slab ocean, thus any response of tropical climate to extratropical forcing must be transmitted through the model atmosphere. In response to the imposed extratropical cooling in I-ASYM, the total atmospheric energy flux to the northern extratropics increases as the pole-to-equator temperature gradient strengthens. The converse occurs in the Southern Hemisphere, where the atmospheric energy flux to the extratropics decreases (Figure 4). Thus the northern extratropics demand more heat from the tropics, while the southern extratropics demand less.

[12] Transient eddies are the dominant mechanism of atmospheric energy transport in the real climate system poleward of ~30° latitude, while the Hadley circulation dominates in the deep tropics [*Peixoto and Oort*, 1992]. Thus the latter would be expected to play an important role in altering the interhemispheric heat exchange. In I-ASYM, the increased demand of the northern extratropics and the decreased demand of the southern extratropics is reconciled by a reorientation of the Hadley circulation such that heat is transported across the equator. Evidence that the tropical energy balance is satisfied primarily through this mechanism is found in the relatively weak meridional dependence of the anomalous northward energy flux in I-ASYM, which implies that no important net sources or sinks of energy are present in low latitudes. The change in the delivery of heat that occurs in response to this reorientation is qualitatively consistent with theory [*Lindzen and Hou*, 1988] and simulations with a low-order model [*Taylor*, 1980].

4. Discussion

[13] The mechanism described in the previous section can be regarded as an "atmospheric bridge" (to borrow a phrase from *Lau and Nath* [1996]) that allows temperature changes at high latitudes to affect ITCZ position. Changes in tropical SST are essential to this mechanism, as the asymmetric thermal forcing induces extratropical SST anomalies which then propagate equatorward and lead to a southward shift of the SST maximum. This shift is intimately involved in the ITCZ displacement, consistent with the findings of *Goswami et al.* [1984].

[14] In a study in which ITCZ displacements were induced by prescribing changes in sea ice extent, *Chiang and Bitz* [2005] suggest that wind-evaporation-SST (WES) feedbacks are important in the equatorward progression of SST anomalies initiated in the extratropics. Without additional experiments, we cannot clearly determine if WES feedbacks are an essential part of our atmospheric bridge, or if anomalous meridional heat transports associated with changes in transient eddy activity would be sufficient even in the absence of these feedbacks.

[15] From a modeling standpoint, ITCZ displacements in response to asymmetric extratropical forcing have appeared most robustly in atmosphere-slab ocean models, including a number of simulations of the climate of the last glacial

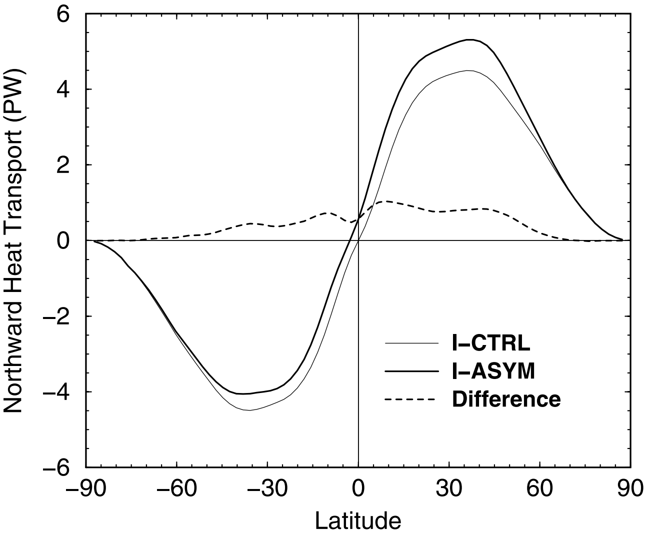

Figure 4. Annually averaged total northward energy flux by the atmosphere (PW) for I-CTRL (thin solid), I-ASYM (thick solid), and I-ASYM minus I-CTRL (dashed).

maximum [*Chiang and Bitz*, 2005, Figure 12] as well as the I-ASYM and S-LGM simulations described herein. Although the C-FW experiment and the work of *Zhang and Delworth* [2005] indicate similar behavior in coupled models, additional studies with coupled atmosphere-ocean models are needed to fully understand the mechanisms capable of transmitting climate signals from high latitudes to the tropics. Other mechanisms, such as those involving subduction of subtropical waters [*Gu and Philander*, 1997] or coastal Kelvin wave propagation [e.g., *Yang*, 1999] may also be capable of transmitting a high-latitude signal to the deep tropics in a relatively rapid manner.

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