Coupled ocean-atmosphere response to Indian Ocean warmth

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[1] The coupled ocean-atmosphere response to Indian Ocean warmth is studied. It is shown with atmospheric models that Indian Ocean warmth forces a positive polarity phase of the North Atlantic Oscillation (NAO), confirming results of previous studies. Coupled model experiments show that this NAO response forces a local air-sea feedback over the North Atlantic Ocean, which intensifies the NAO response. This enhancement is realized through a positive feedback between the NAO atmospheric circulation anomaly and a tripolar North Atlantic SST pattern, consistent with other studies on North Atlantic air-sea interactions. It is concluded that the North Atlantic and European climate response to Indian Ocean warming may be considerably greater than hitherto judged from the analyses of atmospheric model experiments alone. **Citation:** Li, S., M. P. Hoerling, and S. Peng (2006), Coupled ocean-atmosphere response to Indian Ocean warmth, *Geophys. Res. Lett.*, *33*, L07713, doi:10.1029/2005GL025558.

1. Introduction

[2] The North Atlantic Oscillation (NAO) is known to be sensitive to interactions with underlying sea surface temperatures (SSTs). Its associated coupled air-sea interaction over the North Atlantic basin has been extensively studied [e.g., *Rodwell et al.*, 1999; *Mehta et al.*, 2000; *Robertson et al.*, 2000; *Sutton et al.*, 2001; *Peng et al.*, 2003]. The NAO, in its positive polarity, is responsible for a tripolar pattern of SST anomalies with warm waters off the east coast of the United States and cool waters across the sub-polar and subtropical North Atlantic [*Cayan*, 1992a, 1992b]. These are driven largely by anomalous surface heat fluxes associated with the surface wind anomalies that accompany the NAO. There are also indications that Ekman transport associated with the anomalous wind stress contributes to the tripolar pattern [*Peng et al.*, 2006], and strengthens the coupled air-sea interactions [*Haarsma et al.*, 2005]. Diagnosis indicates these SST anomalies initiate a positive feedback, contributing to the NAO atmospheric state on seasonal and longer time scales. The tripole is therefore not a mere passive element in the air-sea interaction [*Rodwell et al.*, 1999; *Sutton et al.*, 2001; *Peng et al.*, 2003].

[3] Far-field SST anomalies over the tropical Indian Ocean are also believed to be important for North Atlantic atmospheric circulation [*Hoerling et al.*, 2001; *Lin et al.*, 2002; *Bader and Latif*, 2003; *Schneider et al.*, 2003; *Hoerling et al.*, 2004; *Hurrell et al.*, 2004]. Warm states of the Indian Ocean have been shown to force a wintertime extratropical response that projects strongly upon the positive phase of the NAO. Such sensitivity supports the theory that a progressive warming of the Indian Ocean, as has been witnessed in recent decades and attributed to greenhouse gas forcing [*Hurrell et al.*, 2004], forces a simultaneous occurrence of a linear trend in indices of the NAO [*Hoerling et al.*, 2004].

[4] It is evident that a complete picture of North Atlantic/European climate response to Indian Ocean warming must also account for the North Atlantic sea surface response and its feedback. Does this additional air-sea feedback modify the climate response to far-field Indian Ocean forcing? To what extent can the observed trend in North Atlantic SSTs since 1950, resembling the tripole pattern [e.g., *Hoerling et al.*, 2001] itself, be understood as the indirect response to Indian Ocean forcing?

[5] Our study seeks answers to these specific questions by conducting a large ensemble of coupled and uncoupled climate simulations subjected to a specified Indian Ocean warmth. The experimental design is described in Section 2. The results of Section 3 confirm the findings of prior model studies for an NAO-like response to Indian Ocean warmth. A new result is that an NAO-like atmospheric response is substantially enhanced by incorporating the SST response of the extratropical oceans to specified Indian Ocean warmth. A summary is given in Section 4.

2. Model and Experiments

[6] The coupled model consists of an atmospheric general circulation model and a slab mixed-layer ocean that includes effects of both the surface heat flux and Ekman ocean heat transport. We subsequently refer to it as AGCM_EML. The uncoupled atmospheric model is an earlier version of National Centers of Environmental Prediction (NCEP)'s seasonal forecast model (SFM) [*Kanamitsu et al.*, 2002], with T42 spectral truncation and 28 sigma levels. We subsequently refer to it as AGCM. The slab ocean uses a constant 75-meter mixed-layer depth, and its temperature anomaly is predicted by the effects of surface heat flux and Ekman heat transport. The coupling domain is from 10°N poleward to the climatological maximum ice-boundary in the north. A more detailed description of the coupling physics is given by *Peng et al.* [2006].

[7] Parallel control and Indian Ocean SST anomaly simulations were performed for both the coupled and uncoupled models. A 100-member AGCM_EML control ensemble using climatological seasonally-evolving SST south of 10°N was adapted from *Peng et al.* [2006]. The model was integrated for eight months (September–April) from 100 different atmospheric initial conditions from the NCEP-NCAR (National Centers for Atmospheric Research) reanalysis of 00Z, Sept.1–5, 1980–1999 [*Kalnay et al.*, 1996]. A 60-member AGCM_EML ensemble using a

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Table 1. Summary of Experiments

	AGCM	AGCM_EML
Control run	60	100
Indian Ocean warmth	60	60
Extratropical SST	60	

specified Indian Ocean warmth added to the climatological SST was performed starting from the initial fields of Sept. 1–3 1980–99. Similar to *Hoerling et al.* [2004], the imposed forcing has a maximum amplitude of +1°C along the equatorial Indian Ocean and spans the zonal width of Indian Ocean basin, with amplitude that reduces to zero at 20S, and near zero at 10N at the edge of the mixed layer model, and idealizes the observed SST trend in the tropical Indian Ocean in the latter half of the 20th century. A parallel 60-member uncoupled AGCM ensemble using climatological seasonally evolving SST globally was conducted, in addition to a 60-member AGCM ensemble using the specified Indian Ocean warmth. Finally, one set of 60 AGCM runs forced with the extratropical SST response to the prescribed Indian Ocean warmth was conducted. All these experiments are summarized in Table 1. The mean response during February–April is the focus of our analyses, at which time the mixed layer ocean response has fully developed.

3. Results

[8] Figure 1 compares the (left) uncoupled and (right) coupled model Northern Hemisphere responses to Indian Ocean warmth. A mid-latitudinal belt of positive height anomalies in the uncoupled experiments extends across the Pacific and Atlantic Oceans, consistent with the response patterns of different AGCMs studied by *Hoerling et al.* [2004]. There is a regional projection onto the positive NAO phase. Whereas a similar pattern of response occurs in the coupled experiment (the pattern correlation is 0.8 with the uncoupled response), the amplitude of North Atlantic anomalies is considerably greater. Also, the coupled model response projects more strongly upon both 1000-hPa and 500-hPa centers-of-action for the NAO pattern.

[9] These two differences in coupled responses are further quantified in Figure 2, which shows the estimated probability distribution function (PDF) of an NAO index of monthly 500-hPa height response. The NAO index is defined as the difference of 500-hPa height anomalies averaged over a southern (30°N–50°N, 80°W–20°E) minus a northern (60°N–80°N, 80°W–20°W) domain, as by *Hurrell et al.* [2004]. For the AGCM (AGCM_EML) control baselines, the PDFs are constructed from the 60 (100) separate years of simulated unforced variability. For the forced experiments, the PDFs are constructed from the 60 separate years of simulations. A shift of the PDF toward positive index values of the NAO is seen in both forced experiments, however the shift is enhanced when the Indian ocean-forced response pattern is permitted to interact with and couple to the underlying North Atlantic sea surface. In fact, 80% of the ensemble members drawn from the coupled runs yield a positive NAO response. The change in shape of the PDF is intriguing, but would require a much larger ensemble size to establish statistical significance.

[10] The ensemble mean change in the NAO forced by the Indian Ocean warmth in the coupled experiments is somewhat weaker than the observed NAO trend of the past 50-years. The ensemble mean NAO index response derived from Figure 1d is +50 meters, which compares to a +72 meter linear trend observed during 1950–1999. It is evident, however, that individual coupled simulations yield stronger responses (see Figure 2), suggesting the apparent role of pure internal atmospheric variability.

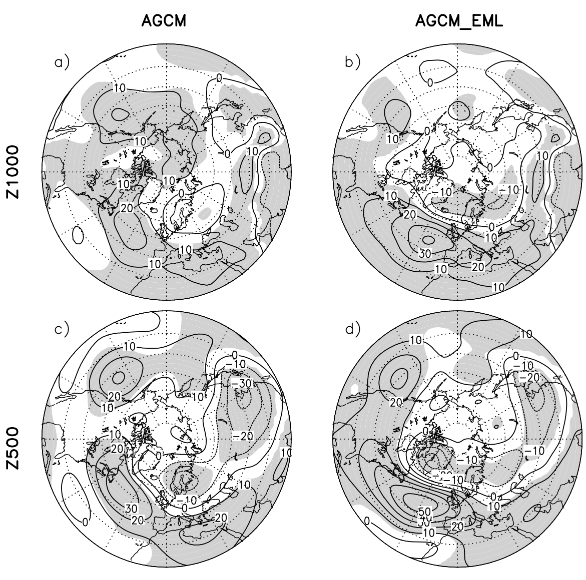

Figure 1. February–April geopotential height response to the tropical Indian Ocean +1°C warmth in (a, c) the uncoupled AGCM and (b, d) the coupled AGCM_EML. Figures 1a and 1b are for 1000-hPa, and Figures 1c and 1d are for 500-hPa. Units are in meters. Shading represents significance at the level of 95% by a t-test.

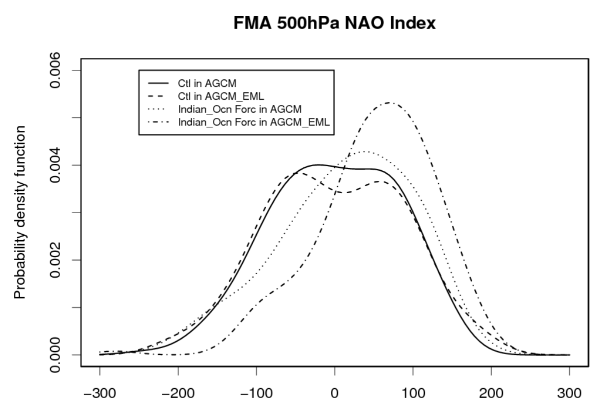

Figure 2. Estimated Probability Distribution Functions (PDFs) of the February–April 500-hPa NAO index for: the ensemble of AGCM control runs (solid line), the ensemble of AGCM_EML control runs (dashed line), the ensemble of the Indian Ocean-forced AGCM runs (dotted line), and the ensemble of the Indian Ocean forced AGCM_EML runs (dotted-dashed line). The NAO index is defined as the difference of 500-hPa height anomalies averaged over a southern (30°N–50°N, 80°W–20°E) minus a northern (60°N–80°N, 80°W–20°W) domain.

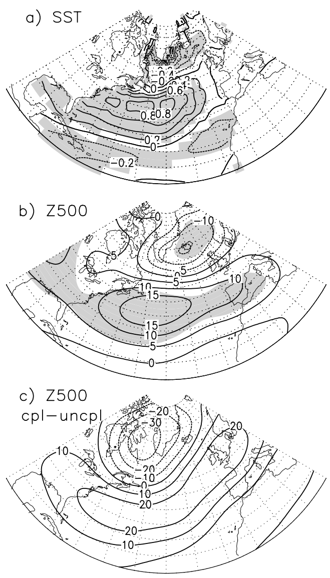

Figure 3. (a) Coupled SST response to the Indian Ocean +1°C warmth. Units are in °C. (b) AGCM Z500 response to the SSTA displayed in Figure 3a. Units are in meters. (c) Z500 response difference between the coupled (Figure 1d) and uncoupled response (Figure 1c). Units are in meters. Shading in Figures 3a and 3b represents significance at the level of 95% by a t-test.

[11] Figure 3a displays the North Atlantic SST response to the tropical Indian Ocean warmth, likely induced through a positive reinforcement between the anomalous surface heat flux and Ekman transport as depicted by *Peng et al.* [2006]. The significant tripolar SST anomalies have up to 0.8°C amplitude, and project onto the characteristic SST pattern associated with observed wintertime NAO variability [see *Peng et al.*, 2003, Figure 1]. In our experiments, the SST tripole is solely the consequence of Indian Ocean forcing, occurring through interaction with the NAO atmospheric response to such forcing.

[12] To further demonstrate that the difference between the coupled and uncoupled atmospheric responses is indeed due to extratropical air-sea feedback, one additional ensemble of AGCM experiment with 60 members are conducted. The experiments are similar to the previous uncoupled AGCM experiments, except that the coupled extratropical SST response (Figure 3a) is used as the only specified boundary forcing, while climatological SSTs are used throughout the tropics. The 500-hPa height response shown in Figure 3b is consistent with the positive polarity of the NAO, and resembles the difference between the coupled and uncoupled 500-hPa height responses (Figure 3c). This confirms the enhanced NAO-like response in the AGCM_EML indeed originates from the feedback of the underlying oceans, playing a substantial role in the enhanced NAO response in the coupled system.

4. Summary

[13] A large amplitude atmospheric pattern, resembling the positive polarity of the North Atlantic Oscillation, is shown to be the coupled ocean-atmospheric response to Indian Ocean warmth. This response is further shown to result from two in-phase ocean-forced signals. In our model, half of the NAO response amplitude originates from pure atmospheric dynamics involving teleconnection processes that link the remote tropical Indian Ocean with the North Atlantic, as discussed in earlier atmospheric modeling studies of *Hurrell et al.* [2004] and *Hoerling et al.* [2004]. The remaining half of the NAO response amplitude originates from local North Atlantic air-sea coupled feedback. Our results from uncoupled AGCM simulations, forced with specified Indian Ocean warmth and North Atlantic tripolar anomalies, confirms earlier AGCM findings on the efficiency of each boundary forcing for producing NAO-like variability [e.g., *Sutton and Hodson*, 2003; *Hoerling et al.*, 2004; *Rodwell et al.*, 1999; *Bader and Latif*, 2003]. The results also suggest that previous efforts to attribute the origin of North Atlantic climate change to Indian Ocean warmth [*Bader and Latif*, 2003; *Hoerling et al.*, 2004] likely underestimate the power of such an influence, since they were all based on uncoupled AGCM approaches.

[14] Nonetheless, when the effect of extratropical air-sea coupling is included, the change in the NAO forced by prescribed Indian Ocean warmth is still about one-third weaker than the observed NAO trend. We show that part of this discrepancy can be attributed to the contributions of pure internal atmospheric variability to the single-realization observed trend. We also note that other physical processes have been shown to contribute to NAO-like atmospheric variability, and these are not included in our simulations. In particular, the increase of greenhouse gases and the decrease in northern hemispheric stratospheric ozone may have contributed to the observed trend [e.g., *Gillett et al.*, 2002; *Kindem and Christiansen*, 2001].

[15] Several further questions remain. In particular, it is important to understand the effect of Indian Ocean forcing and coupling on the intrinsic NAO timescales. Also, the simulated responses based on a single model suite need to be confirmed with independent coupled model experiments. It would be especially useful to repeat the experiments of *Hoerling et al.* [2004] with an ocean model coupled to various AGCMs.

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