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Role of Indian Ocean warming in the development of Philippine Sea anticyclone during ENSO

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[1] The anomalous, low-level anticyclone near the Philippines and suppressed convection over the western Pacific associated with the mature warm phase of El Niño–Southern Oscillation (ENSO) have been suggested as important elements in the interaction between ENSO and the East Asian monsoon. We examined the causes of these anomalies in the circulation and convection using a newly developed, linear baroclinic model that includes interactive moist processes of the cumulus convection and surface heat fluxes. A conventional version of the linear model forced by prescribed heating indicates that the diabatic cooling due to suppressed convection over the maritime continent generates the Philippine Sea anticyclone. From a series of the moist linear model experiments, we found that the modest warming of the Indian Ocean, in addition to the strong warming in the central–eastern Pacific and weak cooling in the western Pacific, is significant to suppress the convection over the maritime continent. Observed data also show a coincidence of the development between the Philippine Sea anticyclone, Indian Ocean warming, and the ascending motion over the Indian Ocean, supporting the model results. The above results indicate that the atmosphere-ocean system in the Indian Ocean may be one of important factors to improve predictability of the East Asian climate during ENSO. *INDEX TERMS:* 3314 Meteorology and Atmospheric Dynamics: Convective processes; 3319 Meteorology and Atmospheric Dynamics: General circulation; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology

1. Introduction

[2] It is well known that the El Niño-Southern Oscillation (ENSO) phenomenon has a global impact on the atmospheric general circulation. During the mature phase of ENSO, which is often locked in boreal winter, convective activity tends to be enhanced over the central equatorial Pacific while suppressed over the western Pacific near Philippines. Associated with the latter, it has been reported that anticyclonic anomalies appear in the low-level circulation over the east of Philippines [*Harrison and Larkin*, 1996; *Wang et al.*, 2000]. This Philippine Sea anticyclone has been suggested not only to link ENSO with milder winter over East Asia but also to play an important role in the ENSO dynamics [*Wang et al.*, 1999]. In this study, we attempt to investigate sources which generate and maintain the convection and circulation anomalies over the western Pacific and East Asia, using a linear dynamical model.

[3] Linear baroclinic models have been used as a tool to diagnose the atmosphere response to forcing [cf. *Hoskins and Karoly*, 1981; *Ting and Lau*, 1993]. The forcing, anomalous diabatic heating in many cases has been prescribed in most of the linear model [e.g. *Jin and Hoskins*, 1995]. However, convective activity which causes the anomalous diabatic heating is itself driven by the atmospheric circulation, in particular within the tropics. We therefore incorporate interacting moist processes of the convection and surface heat fluxes into the linear baroclinic model in order to examine the anomalous climate over East Asia associated with sea surface temperature (SST) anomalies during ENSO. In the following sections, a brief description of the model is given, then results of the model diagnoses are presented.

2. Linear Baroclinic Models

[4] The model used here consists of primitive equations linearized about the winter (DJF) climatology obtained from the NCEP/NCAR reanalysis for 1958–1997. It has a horizontal resolution of T21 and vertical 20 levels on a σ surface, and employs a ∇^4 (harmonic) horizontal (vertical) diffusion, Rayleigh friction, and Newtonian damping. The latter two terms have a time scale of $(1\ \mathrm{dy})^{-1}$ for $\sigma \geq 0.9$ and $\sigma \leq 0.03$ while $(30\ \mathrm{dy})^{-1}$ elsewhere. Details of the model formulation are given in *Watanabe and Kimoto* [2000, 2001]. To obtain the linear atmospheric response to forcing, we adopt a time integration method in this study. An extension of the linear model which includes an interacting convection is symbolically explained as follows.

[5] A linearized form of the primitive equations is written as

$$d_t \mathsf{X} + \mathsf{L}\mathsf{X} = \mathsf{F} \quad , \tag{1}$$

where X is a vector containing perturbations $()'$ for prognostic variables of vorticity, divergence, temperature, and surface pressure, i.e., $\mathsf{X} \equiv \mathsf{X}\,(\zeta', D', T', \ln Ps')$, while F and L denote a prescribed forcing and linear dynamical operator, respectively. When we consider the forcing solely due to anomalous cumulus convection, equation (1) can be solved with a given diabatic heating as F (referred to as the dry linear model). With the dissipation terms adopted, the tropical response approaches steady state approximately after day 10, so that we can obtain a near steady response using the time integration method. When the anomalous convective heating is internally generated in response to SST anomaly, F will be a function of both X and an SST anomaly T_s'. Then it can be decomposed into two components, $\mathsf{F}_i(\mathsf{X})$ and $\mathsf{F}_e(T_s')$ ('*i*' and '*e*' stand for internal and external, respectively), so that equation (1) is rewritten as

$$d_t \mathsf{X} + (\mathsf{L} - \mathsf{F}_i)\mathsf{X} = \mathsf{F}_e \quad . \tag{2}$$

[6] Note that X in equation (2) now includes perturbation in the specific humidity q'. The heat source and moisture sink induced by anomalous convection are represented by F_i. In the linear model represented by equation (2) (referred to as the moist linear model), a forcing F_e is composed by terms in linearized surface bulk fluxes that depend on T_s' and the basic state but not on the perturbation X.

[7] The convection in the moist linear model, as denoted by F_i, is actually calculated by a linearized Betts-Miller scheme

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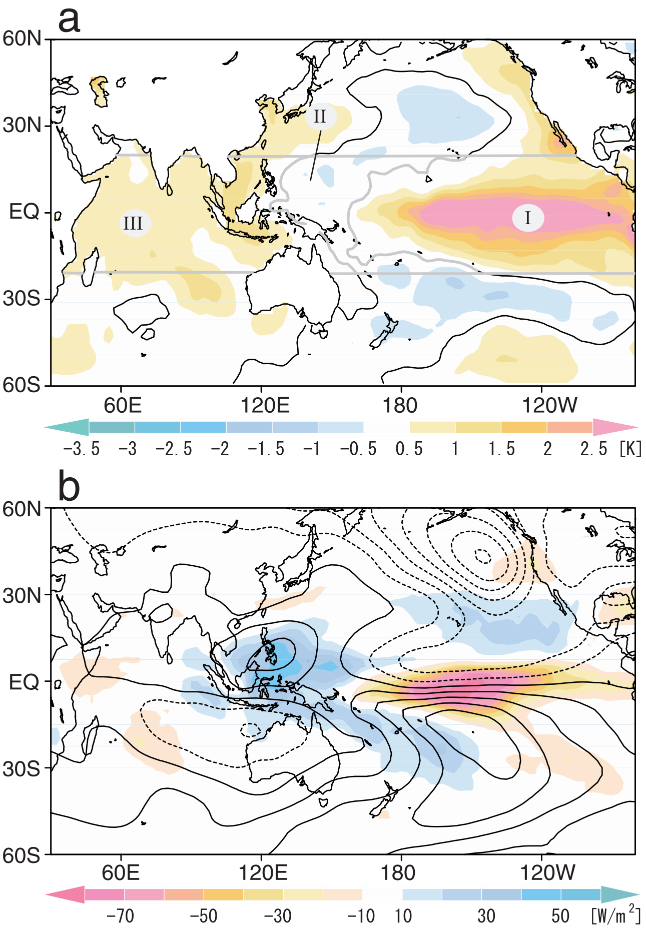

Figure 1. Composite anomalies of observed (a) SST (K, color), (b) OLR (W m^{-2}, color) and ψ_{850} (m^2 s^{-1}, contour) with respect to the Niño 3 SST index. The zero contour is only drawn in (a) while the contour interval in (b) is 2×10^6 m^2 s^{-1}. Gray boundaries in (a) define three regions of El Niño SST anomalies to force a linear model. Note that the color for OLR composite is reversed.

[*Neelin and Yu*, 1994; *Seager and Zebiak*, 1994] with some modifications (see *Watanabe and Jin*, 2002 for details). Both for the dry and moist linear models, the time integration is continued up to 30 days, while the responses at day 15 are only shown in the subsequent section. While the time integration fails to capture steady response when unstable baroclinic modes dominate, the boundary layer damping of (1dy)$^{-1}$ is enough in neutralizing those modes [cf. *Hall and Sardeshmukh*, 1998], that ensures the steady state response can be obtained in this method.

3. Results of Linear Model Experiments

[8] Anomalous features of convection and circulation during ENSO are first documented. In Figure 1 we showed a composite of winter SST, NOAA—derived outgoing longwave radiation (OLR), and 850 hPa stream function (ψ_{850}) in the NCEP/NCAR reanalysis with respect to El Niño/La Niña events, i.e. difference between 5 (2) El Niños and 6 (3) La Niñas for SST and ψ_{850} (OLR). The SST composite (Figure 1a) shows a well-known structure of the large (~3 K) warming in the eastern equatorial Pacific and cooling in the midlatitude of both hemispheres. Other cold and warm anomaly centers are found in the east of Philippines (around 150°E and 10°N) and in the entire Indian Ocean, with the latter having a relatively uniform pattern of less than 1 K. The anomalous convection, inferred from the OLR composite, reveals a strongly enhanced activity over the central equatorial Pacific with suppressed activity over the surrounding regions in particular over the maritime continent (Figure 1b). The concurrent low-level circulation between 30°S and 30°N has a pattern roughly asymmetric about the equator and furthermore about the 150°E longitude (Figure 1b). Note that the Philippine Sea anticyclone, which is visible in Figure 1b, is one of the conspicuous signals in the low-level circulation and is somewhat stronger than its counterpart in the Southern Hemisphere.

[9] To examine whether the enhanced convection near the dateline can generate the anticyclonic anomalies near Philippines, the dry linear model expressed by equation (1) was integrated with a heating estimated from the negative OLR anomalies over the central Pacific [cf. *Reed and Recker*, 1971]. The low-level response, however, does not indicate the anticyclonic signal over Philippines (not shown). On the other hand, the anomalous anticyclone is successfully reproduced when the anomalous heating is extended to the whole tropics of 20°S–20°N (Figure 2a). Note that the absence of cyclonic anomalies over the North Pacific is largely due to lack of the transient eddy feedback [cf. *Held et al.*, 1989]. We further confirmed that the diabatic cooling due to suppressed convection over the maritime continent is of crucial importance for the development of the Philippine Sea anticyclone and the Southern Hemisphere counterpart. This indicates that a pair of the western Pacific anticyclones can be interpreted as a direct Rossby response to anomalous cooling resulted from the in situ suppressed convection. An important question then becomes: how and why the convection is suppressed? Referring to the SST anomaly pattern during ENSO, there may be at least three possibilities, namely, the weakened convection occurs due to (1) SST warming in the eastern equatorial Pacific, (2) in situ negative SST anomalies, and/or (3) SST anomalies outside of the Pacific.

[10] As for the first hypothesis, one may simply expect that the ascending motion over the central Pacific accompanies a descent over the western Pacific through change in the Walker circulation. Alternatively, a low-level, equatorward horizontal flow associated with the Rossby waves (a pair of cyclonic anomalies over the central Pacific, see Figure 1b) excited to the west of the heating is compensated by a downward motion due to the Sverdrup balance, thus the convection may be suppressed over the western Pacific. However, the moist model driven only by the eastern Pacific SST anomalies (region I in Figure 1a) captures neither the suppressed convection nor the anticyclone over Philippines (Figure 2b), indicating that the above hypothesis does not work effectively. When weak negative SST anomalies in region II were incorporated, the diabatic cooling over the off-equatorial central Pacific extends toward the west and anticyclonic anomalies appear near the Philippines (Figure 2c). However, the magnitude is weak (less than half that of the observation) and no convective cooling over the maritime continent is generated. The moist model driven by the ENSO SST anomalies in the entire Pacific-Indian Ocean basins (regions I–III) reproduced realistic features of ψ_{850} and convective cooling over the western Pacific (Figure 2d). It implies that the modest warming of the Indian Ocean has a considerable impact on the anomalous climate over the western Pacific.

[11] A mechanism of how the Indian Ocean warming weakens the western Pacific convection is explained in terms of change in the Walker circulation, as illustrated by the steady response in the vertical *p*-velocity at 500 hPa (ω_{500}) over the equatorial band of 10°S–10°N (Figure 3). It is shown that the ω_{500} response with and without the Indian Ocean SST anomalies corresponds to an ascent and descent over the Indian Ocean, respectively. Since the El Niño SST anomalies in the Pacific have induced a large ascent, the convection between the two ascending branchs, i.e. the western

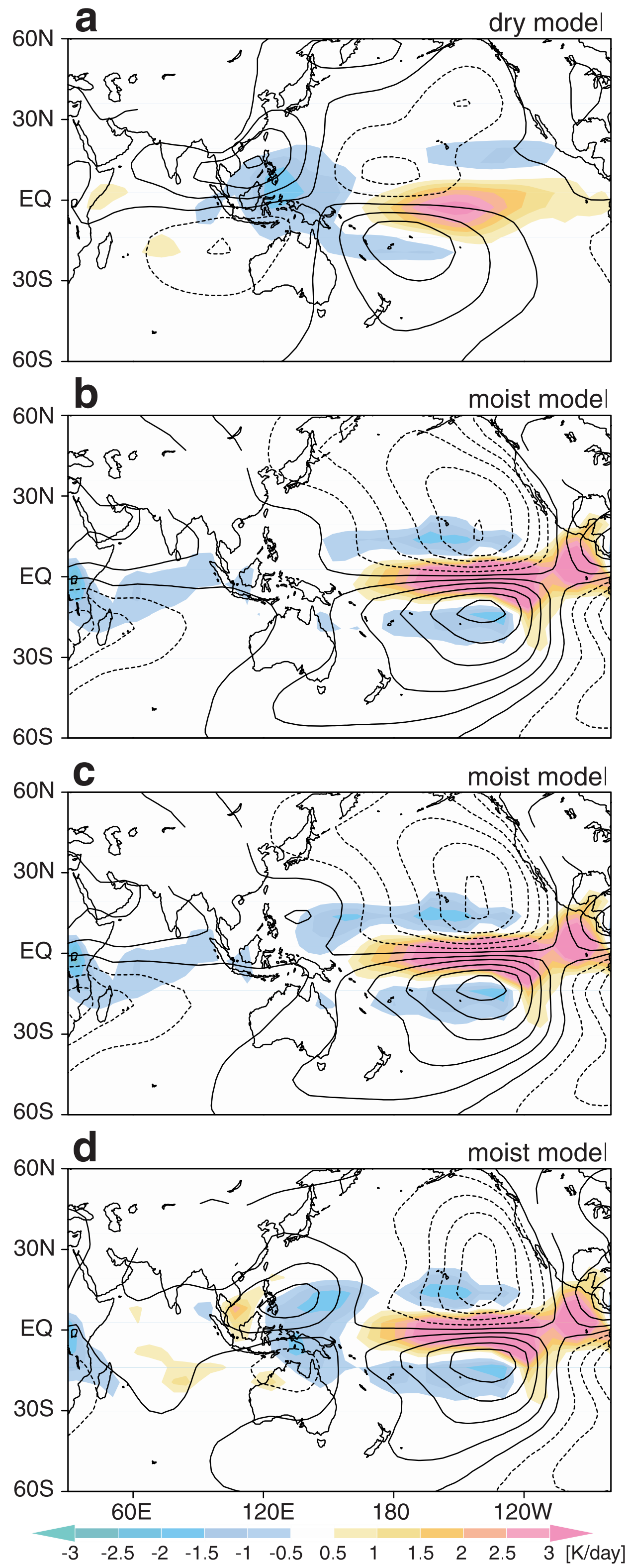

Figure 2. ψ_{850} response ($m^2\ s^{-1}$, contour) in (a) dry linear model with prescribed heating (K day^{-1}, color) estimated from the observed OLR composite, (b) moist linear model with prescribed SST anomalies in the central-eastern equatorial Pacific (region I in Figure 1a), (c) as in (b) but with SST anomalies in the whole tropical Pacific (region I and II), and (d) as in (b) but with SST anomalies in the tropical Pacific and Indian Ocean (region I–III). The contour interval is $2 \times 10^6\ m^2\ s^{-1}$. Note that the heating in (b)–(d) (color) is internally computed in the model.

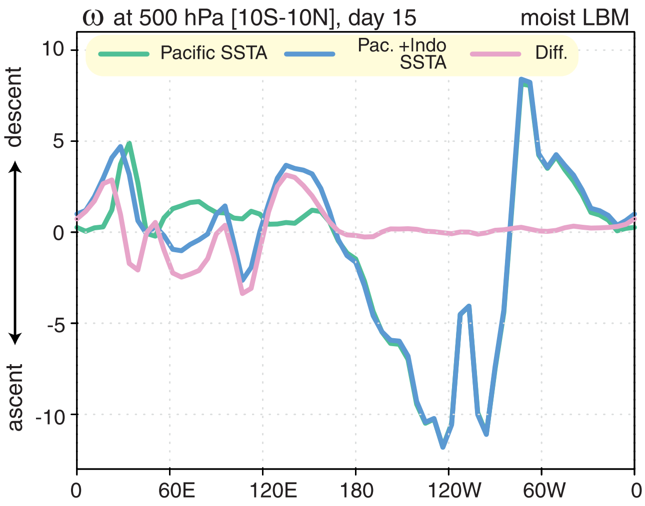

Figure 3. Equatorial ω_{500} response (average for 10°S–10°N) in the moist linear model corresponding to Figures 2b and 2d (green and blue curves, respectively) and the difference between them (red curve). Unit is 10^{-4} hPa s^{-1}.

Pacific, is strongly suppressed in the case with Indian Ocean SST anomalies, as revealed by a large subsidence in Figure 3.

4. Observational Evidence

[12] In order to verify the hypothesis obtained in the moist linear model experiments, a lagged composite for El Niño has been made for several observed indices, namely, Niño 3 SST and SST in the Indian Ocean (40°–100°E, 20°S–20°N), ψ_{850} over the Philippines (100°–140°E, 0°–20°N), and ω_{500} over the equatorial Indian Ocean (40°–80°E, 10°S–10°N) (areas are shown in Figure 4a).

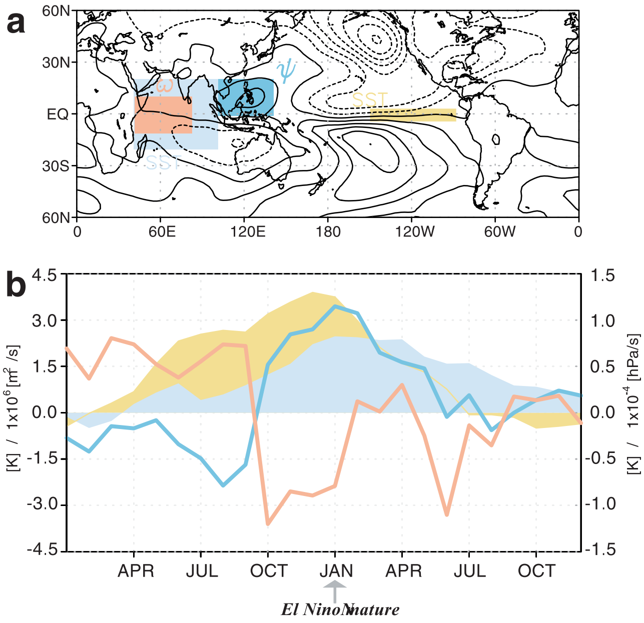

Figure 4. (a) Box areas to define indices associated with El Niño superimposed on the ψ_{850} composite pattern (same as in Figure 1b). (b) Lagged composite time series of Niño 3 SST (orange shade), Indian Ocean SST (blue shade), ψ_{850} over 100°–140°E, 0°–20°N (blue curve), and ω_{500} over 40°–80°E, 10°S–10°N (red curve). The left axis indicates scales for Niño 3 SST and ψ_{850} while the right axis for the Indian Ocean SST and ω_{500}.

As discussed by *Wang et al.* [2000], the Philippine Sea anticyclone is rapidly developed around October, which does not follow a gradual warming of Niño 3 SST (Figure 4). The rapid development is clearly in concert with the reversal of the vertical motion over the Indian Ocean from downward to upward. The timing of phase reversal in ω_{500} seems to be controlled by the magnitude of the Indian Ocean warming, which has smaller magnitude until September. Note that the ψ_{850} anomaly persists until spring while the ω_{500} anomaly does not, suggesting that the long-lasting feature of the anticyclone is due to other mechanisms, perhaps the local air-sea interaction [*Wang et al.*, 2000]. The lagged response of this Indian Ocean SST to El Niño has been examined by previous studies [*Klein et al.*, 1999; *Lau and Nath*, 2000], which suggest the leading role of a radiative warming of the Indian Ocean associated with reduced cloudiness induced by El Niño. The steady response without Indian Ocean warming does show a reduction in the convection over the Indian Ocean (Figures 2b–2c), consistent with their finding. Therefore we may propose a following chain of processes: El Niño → Indian Ocean warming → in situ ascent and modified Walker circulations → weakened convection over the western Pacific and the development of the Philippine Sea anticyclone.

5. Concluding Remarks

[13] We investigated processes responsible for the development of the Philippine Sea anticyclone associated with the suppressed convective activity over the western Pacific during the mature phase of ENSO. From a series of linear baroclinic model experiments, it was shown that the convective cooling over the maritime continent, which is found crucial to excite the anticyclone, is strongly enhanced by the Indian Ocean warming that modifies the Walker circulation. Numerical experiments using an atmospheric general circulation model (AGCM) which employs ENSO SST anomalies with and without Indian Ocean warming will be worth carrying out to further clarify the above argument. This study suggests that one needs to consider the coupled atmosphere-ocean interaction over the Indian Ocean to improve understanding and prediction skill of the East Asian climate during ENSO.

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