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

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 \( \nabla^h \) (harmonic horizontal) diffusion, Rayleigh friction, and Newtonian damping. The latter two terms have a time scale of \( (1 \text{ dy})^{-1} \) for \( \sigma \geq 0.9 \) and \( \sigma \leq 0.03 \) while \( (30 \text{ dy})^{-1} \) 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

\[
\frac{dX}{dt} + LX = F, \tag{1}
\]

where \( X \) is a vector containing perturbations (\( \eta \) for prognostic variables of vorticity, divergence, temperature, and surface pressure, i.e., \( X \equiv X(\zeta, D, T, \ln P) \), 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 \( T_a \). Then it can be decomposed into two components, \( F(X) \) and \( F_a(T_a) \) (\( i' \) and \( e' \) stand for internal and external, respectively), so that equation (1) is rewritten as

\[
\frac{dX}{dt} + (L - F_e)X = F_e. \tag{2}
\]

[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 \( F_e \). 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 \( T_a \) and the basic state but not on the perturbation \( X \).

[7] The convection in the moist linear model, as denoted by \( F_e \), is actually calculated by a linearized Betts-Miller scheme.
model. Note that the color for OLR composite is reversed.

3. Results of Linear Model Experiments

[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 (\( \omega_{500} \)) over the equatorial band of 10°S–10°N (Figure 3). It is shown that the \( \omega_{500} \) 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 branches, i.e. the western...
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), ψ50 over the Philippines (100°–140°E, 0°–20°N), and ω500 over the equatorial Indian Ocean (40°–80°E, 10°S–10°N) (areas are shown in Figure 4a).

Figure 2. ψ500 response (m² 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 × 10⁶ m² s⁻¹. Note that the heating in (b)–(d) (color) is internally computed in the model.

Figure 3. Equatorial ω500 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 10⁻⁵ hPa s⁻¹.

Figure 4. (a) Box areas to define indices associated with El Niño superimposed on the ψ500 composite pattern (same as in Figure 1b). (b) Lagged composite time series of Niño 3 SST (orange shade), Indian Ocean SST (blue shade), ψ500 over 100°–140°E, 0°–20°N (blue curve), and ω500 over 40°–80°E, 10°S–10°N (red curve). The left axis indicates scales for Niño 3 SST and ψ500 while the right axis for the Indian Ocean SST and ω500.
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 $\omega_{500}$ seems to be controlled by the magnitude of the Indian Ocean warming, which has smaller magnitude until September. Note that the $\omega_{500}$ anomaly persists until spring while the $\omega_{500}$ 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 $\rightarrow$ Indian Ocean warming $\rightarrow$ in situ ascent and modified Walker circulations $\rightarrow$ 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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References


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