11-1998

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Scholar Commons Citation
Wang, Chunzai and Weisberg, Robert H., "Climate Variability of the Coupled Tropical-Extratropical Ocean-Atmosphere System" (1998). *Marine Science Faculty Publications*. 382.
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GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 21, PAGES 3979-3982, NOVEMBER 1, 1998

Climate variability of the coupled tropical-extratropical ocean-atmosphere system

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Abstract. Observations show that tropical and extratropical Pacific SST anomalies vary out-of-phase, and that the atmospheric meridional Hadley and zonal Walker Circulations are related to these variations. A tropical-extratropical model is constructed to show oscillations consistent with observations. The positive feedback introduced by the Walker Circulation causes tropical warming so that the air rises and flows toward the subtropics where it sinks. When the sinking air approaches the sea surface, it flows both equatorward and poleward enhancing tropical easterly and extratropical westerly winds, respectively. Enhanced extratropical westerlies increases wind speed and hence evaporation, resulting in extratropical cooling. The Walker and Hadley Circulations thus result in tropical warming and extratropical cooling, respectively. The tropical warming and extratropical cooling increase the meridional SST difference and hence the meridional heat transport which erodes the tropical warming and extratropical cooling. Enhanced tropical easterlies due to the Hadley Circulation cools the tropical ocean through ocean dynamics. These negative feedbacks help the system to switch from warm to cold phases, and vice versa.

Introduction

During the past decades our understanding of interannual climate variability associated with the phenomenon of El Niño-Southern Oscillation (ENSO) has been greatly advanced by focusing on the tropical Pacific Ocean and atmosphere interactions [e.g., *Suarez and Schopf*, 1988; *Philander*, 1990; *McCreary and Anderson*, 1991; *Neelin et al.*, 1998; *Weisberg and Wang*, 1997]. However, how the interactions between the tropics and extratropics affect climate variability has not been well studied. A theory for the interactions between the tropical and extratropical Pacific has been proposed by *Gu and Philander* [1997]. This theory emphasizes the role of oceanic processes in linking the tropics and extratropics; in particular, the effect of an influx of ocean water from higher latitudes on equatorial sea surface temperature (SST). What are atmospheric processes that link the tropics and extratropics?

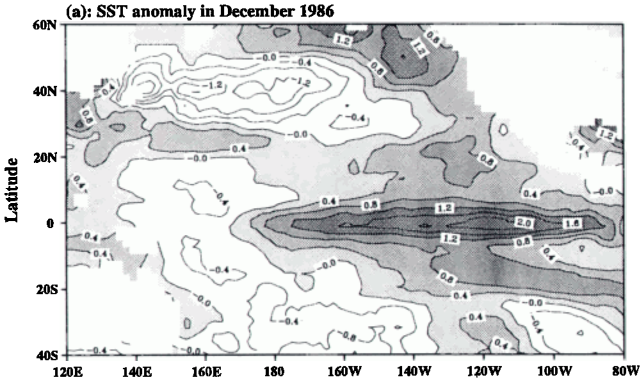
The present paper emphasizes the atmospheric Hadley Circulation as a link between the tropics and extratropics. The Hadley Circulation, the Walker Circulation, oceanic meridional heat transport, and extratropical local ocean-atmosphere coupling are proposed to form a coupled tropical-extratropical ocean-atmosphere system. This coupled system may be responsible for the climate variability of the tropical-extratropical system, as observed in nature.

Paper number GRL-1998900082.
0094-8276/98/GRL-1998900082$05.00

Observations

The NOAA/NCEP SST data are first used to demonstrate the climate variability of the tropical-extratropical system. Fig. 1a shows a contour plot of Pacific SST anomalies in December 1986, at the peak phase of the 1986-87 El Niño event. During that time, the tropical Pacific shows warm SST anomalies in the equatorial eastern Pacific and weaker cold SST anomalies in the off-equatorial western Pacific (*Wang et al.* [1998b] discussed the dynamical consequences of these weak off-equatorial western Pacific cold SST anomalies in the evolution of ENSO). Associated with these tropical Pacific SST anomalies, cold SST anomalies are in the extratropical central Pacific located around 40°N. For longer time scales, Fig. 1b shows the Pacific SST difference between the period 1976-95 and the period 1950-75. The periods are chosen based on the fact that 1976 is a transitional year for climate variability on decadal/interdecadal time scales [e.g., *Zhang et al.*, 1997]. Similar to Fig. 1a, Fig. 1b shows that when the tropical Pacific is warm, the extratropical Pacific is cold.

(a): SST anomaly in December 1986



(b): SST change between periods 1976-95 and 1950-75

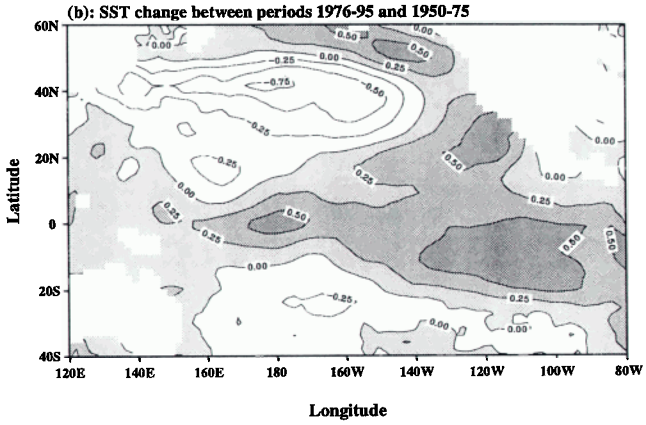


Figure 1. Observations of (a) the Pacific SST anomalies in December 1986 and (b) the Pacific SST difference between the period 1976-95 and the period 1950-75.

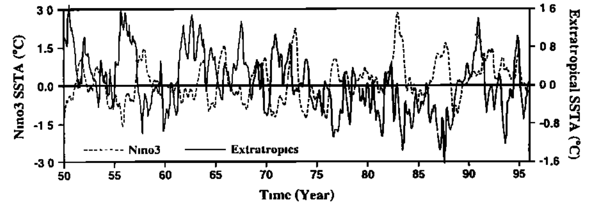


Figure 2. Observed three-month running mean SST anomalies in the Nino3 region (150°W-90°W, 5°S-5°N) and in the extratropical central Pacific (160°E-160°W, 35°N-45°N).

The out-of-phase relationship between tropical and extratropical SST anomalies can also be seen from time series, as shown in Fig. 2. The Nino3 SST anomalies are approximately out-of-phase with the extratropical SST anomalies, with relatively weak SST anomalies in the extratropics. This relationship may be attributed to the tropical-extratropical interactions linked by the Hadley Circulation. Tropical warm (cold) SST anomalies strengthen (weaken) the Hadley Cell and the Ferrel Cell, resulting in strong (weak) surface poleward-moving air in the extratropics and thus strong (weak) extratropical westerly wind (see Fig. 5 of *Latif* [1998]). The strong (weak) extratropical westerly wind increases (decreases) wind speed and hence increases (decreases) evaporation which, in turn, results in more (less) extratropical SST cooling. Therefore, when the tropical Pacific is warm (cold), the extratropical Pacific is cold (warm).

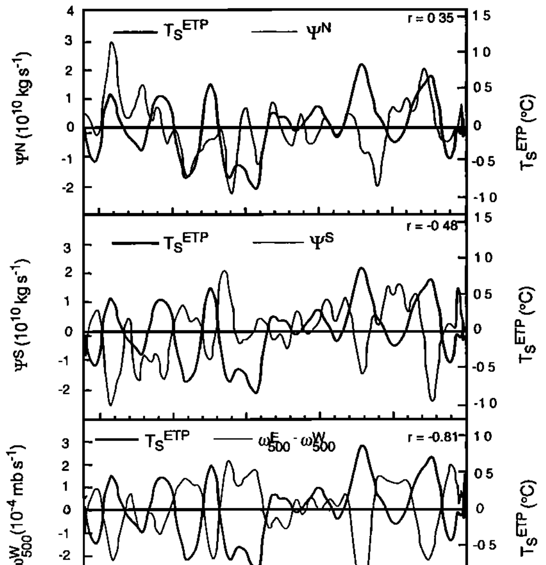


Figure 3. Time series of the anomalies of SST (T_S^{ETP}) in the eastern tropical Pacific (180°-80°W, 20°S-20°N), the maximum streamfunction (ψ^N) in the 0°-30°N belt (top), the minimum streamfunction (ψ^S) in the 0°-30°S belt (middle), and the 500-mb vertical pressure velocity difference ($\omega_{500}^E - \omega_{500}^W$) between the eastern (180°-100°W, 10°S-10°N) and western (100°E-150°E, 10°S-10°N) tropical Pacific (bottom). Maximum positive value of ψ^N and maximum negative value of ψ^S indicate stronger Hadley Cells in the NH and SH, respectively. Positive (negative) values of $\omega_{500}^E - \omega_{500}^W$ indicate intense (weak) Walker Circulation.

Based on observed daily global winds, *Oort and Yienger* [1996] showed significant correlation between the Hadley Cell and ENSO. A zonal mean streamfunction (ψ) was calculated from the wind data, with positive and negative ψ denoting clockwise and anti-clockwise rotations, respectively. Strengthenings of the Hadley Cells in the Northern Hemisphere (NH) and the Southern Hemisphere (SH) are thus represented by larger positive and negative values of ψ, respectively. Relationships among the Hadley Circulation, Walker Circulation, and ENSO can be explored by the anomalous time series of maximum positive ψ in the NH (ψ^N), maximum negative ψ in the SH (ψ^S), 500-mb vertical pressure velocity difference between the eastern and western tropical Pacific ($\omega_{500}^E - \omega_{500}^W$), and SST in the eastern tropical Pacific (T_S^{ETP}). The results are shown in Fig. 3. The warm (cold) T_S^{ETP} during El Niño (La Niña) correspond to positive (negative) ψ^N and negative (positive) ψ^S that indicate strong (weak) Hadley Cells in the NH and SH. One of exceptions to this relationship is in the NH during the 1982-83 El Niño event when ψ^N appears to be negative. A weakening (strengthening) of the Walker Circulation indicated by more negative (positive) values of $\omega_{500}^E - \omega_{500}^W$ is accompanied by warming (cooling) in the eastern tropical Pacific. Fig. 3 also shows that the positive (negative) ψ^N and negative (positive) ψ^S are associated with the negative (positive) values of $\omega_{500}^E - \omega_{500}^W$, suggesting an out-of-phase relationship between the Hadley Circulation and the Walker Circulation.

A Tropical-Extratropical Oscillator

The zonal Walker Circulation introduces a positive feedback for the tropical Pacific Ocean and atmosphere system. Increasing SST in the tropical central/eastern Pacific decreases the east-west SST gradient which weakens the Walker Circulation and hence further increases SST there. This positive feedback thus can result in a tropical Pacific warming. The meridional Hadley Circulation can serve to link the tropical and extratropical oceans. The warm tropical air rises and flows poleward to the subtropics where it sinks. When the sinking air approaches the sea surface, it divides into two branches: one flowing equatorward and the other flowing poleward. The poleward-moving air is deflected to the east by the Coriolis force, enhancing the extratropical westerly wind which increases wind speed and hence evaporation. Increasing evaporation results in extratropical SST cooling, which in turn increases the tropical-extratropical SST difference and then strengthens the Hadley Circulation. The Hadley Circulation thus can act as a positive feedback for extratropical cool SST

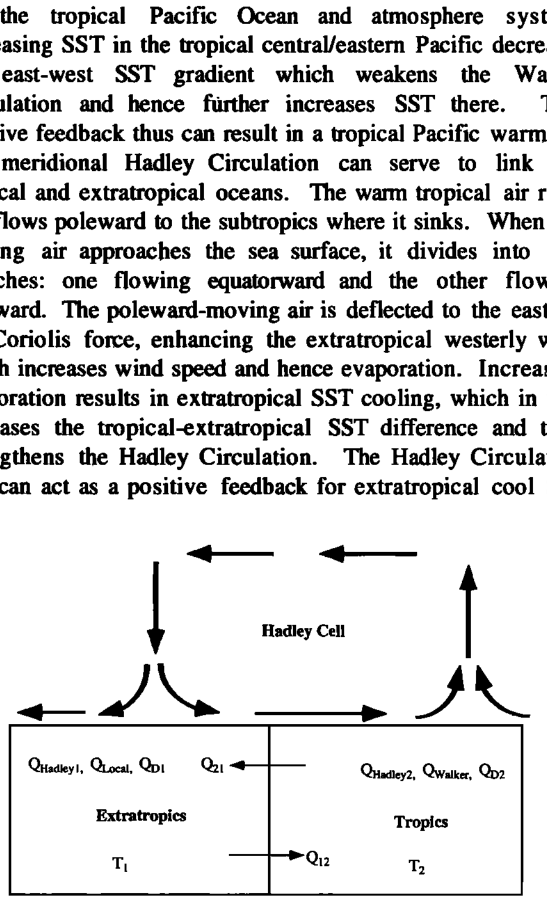


Figure 4. Schematic diagram of the ocean two-box model overlying with the atmospheric meridional Hadley Cell.

through evaporative process. The above two positive feedbacks result in tropical warming and extratropical cooling, respectively. On the other hand, the surface equatorward-moving air associated with the Hadley Circulation is deflected to the west by the Coriolis force, enhancing the tropical easterly wind that cools the tropical SST by ocean dynamics. The stronger Hadley Circulation thus also acts as a negative feedback for the tropical ocean. *Li* [1997] emphasized a contribution of the Hadley Circulation to ENSO. The enhanced tropical-extratropical SST difference resulting from the tropical warming and extratropical cooling (due to the Walker and Hadley Circulations) increases the meridional heat transport. Increasing the meridional heat transport erodes the tropical warming and extratropical cooling, providing an additional negative feedback for the coupled system.

This conceptual model can be described by considering a two-box model ocean coupled with an atmosphere, as shown in Fig. 4. The perturbed SSTs for extratropical and tropical ocean boxes are represented by T_1 and T_2, respectively. The heat budget of these two boxes over time t can be written as

$$\frac{dT_1}{dt} = Q_{21} + Q_{Hadley1} + Q_{Local} + Q_{D1}, \tag{1}$$

$$\frac{dT_2}{dt} = Q_{12} + Q_{Hadley2} + Q_{Walker} + Q_{D2}, \tag{2}$$

where Q_{21} (Q_{12}) is oceanic meridional heat transport from box 2 (1) to box 1 (2); $Q_{Hadley1}$ ($Q_{Hadley2}$) is the effect of the Hadley Circulation on box 1 (2); Q_{Local} is local coupling feedback in the extratropics; Q_{Walker} represents the effect of the Walker Circulation on box 2; Q_{D1} (Q_{D2}) is damping term in box 1 (2).

The oceanic meridional heat transport is simply assumed to be proportional to the temperature difference $T_2 - T_1$. Imagine that T_2 is warm and T_1 is cold, then the ocean removes heat from box 2 and puts heat into box 1. Therefore, Q_{12} and Q_{21} are proportional to $-(T_2 - T_1)$ and $T_2 - T_1$, respectively. The Hadley Circulation is driven by the heating difference between the tropics and extratropics. As discussed early, the Hadley Circulation acts as negative and positive feedbacks for tropical warm and extratropical cool SST anomalies, respectively. Thus, both $Q_{Hadley1}$ and $Q_{Hadley2}$ can be parameterized as being proportional to $-(T_2 - T_1)$.

The local ocean-atmosphere coupling in the extratropics is a difficult problem. One of the major unresolved issues is how the atmosphere responds to SST anomaly. There has been a controversy regarding whether the atmospheric response is cyclonic or anticyclonic to an extratropical warm SST anomaly. General circulation models [e.g., *Ting*, 1991] suggest that a cyclonic response to warm SST anomaly is a reasonable assumption. Note that how the atmosphere responds to an extratropical SST anomaly does not qualitatively affect the behavior of the model here, as discussed later. If the extratropical warm (cold) SST tends to produce low (high) pressure, then the low (high) pressure induces positive (negative) wind stress curl which induces upwelling (downwelling) via Ekman pumping, and causes the cooling (warming) of SST. Thus, local ocean-atmosphere coupling feedback in the extratropics may be negative and Q_{Local} is parameterized by $-T_1$. The intensity of the zonal Walker Circulation depends on the SST difference between the tropical western and eastern Pacific, so Q_{Walker} is proportional to T_2 (tropical western Pacific SST anomaly is not considered). Finally, the damping terms, Q_{D1} and Q_{D2}, are chosen to be the cube of the temperature anomalies that limit anomaly growth.

Using these parameterizations in Eqs. (1) and (2), we obtain

$$\frac{dT_1}{dt} = a(T_2 - T_1) - b(T_2 - T_1) - cT_1 - \varepsilon T_1^3, \tag{3}$$

$$\frac{dT_2}{dt} = -d(T_2 - T_1) - e(T_2 - T_1) + fT_2 - \varepsilon T_2^3, \tag{4}$$

where all constants are positive. For clarity, Eqs. (3) and (4) can be further rearranged to:

$$\frac{dT_1}{dt} = -\alpha T_2 - \beta T_1 - \varepsilon T_1^3, \tag{5}$$

$$\frac{dT_2}{dt} = \gamma T_1 + \delta T_2 - \varepsilon T_2^3, \tag{6}$$

where $\alpha = b - a$, $\beta = a + c - b$, $\gamma = d + e$, $\delta = f - d - e$.

A set of parameters, which is physically reasonable, has been chosen for the purpose of demonstrating the possibility of oscillations for this heuristic model. Both α and γ are related to the Hadley Circulation and ocean heat transport. α is chosen to give a rate of change of extratropical SST of about 1.0°C over a year per 1.0°C change of tropical SST, whereas γ is chosen to give a rate of change of tropical SST of about 2.0°C over a year per 1.0°C change of extratropical SST. These values are consistent with observations in that the SST signal in the tropics is stronger than that in the extratropics. The collective extratropical ocean adjustment rate β is chosen with a damping time scale of 0.83 years. The parameter δ measures the net effect of the Walker Circulation, Hadley Circulation, and ocean heat transport on tropical SST. It is chosen to give a rate of change of tropical SST of about 1.5°C per 1.0°C change of tropical SST. With these model parameters, the model shows an oscillation with a period of about 11.5 years (Fig. 5). The tropical SST anomaly is out-of-phase with the extratropical SST anomaly, with a weaker SST anomaly amplitude in the extratropics. An experiment was also performed to show that the period of coupled oscillations is independent of ε. Therefore, the cubic dampings do not affect model oscillations and their effect is to limit linear instability growth.

Since the fundamental properties of model oscillations are determined by linear processes, we next focus on a linear analysis of the coupled system. Dropping the damping terms in Eqs. (5) and (6), we can obtain solution of the linear system:

$$T_2 = Ae^{Gt}\sin(\omega t + \varphi), \tag{7}$$

$$T_1 = A(\alpha/\gamma)^{1/2}e^{Gt}\sin(\omega t + \varphi + \phi), \tag{8}$$

where A and φ are arbitrary constants, the growth rate G and frequency ω are

$$G = (\delta - \beta)/2 = (b + f - a - c - d - e)/2, \tag{9}$$

$$\begin{aligned}\omega &= [\alpha\gamma - (\delta + \beta)^2/4]^{1/2} \\ &= [(b - a)(d + e) - (a + c + f - b - d - e)^2/4]^{1/2},\end{aligned} \tag{10}$$

and the phase difference ϕ between T_1 and T_2 is

$$\phi = \cos^{-1}\left\{\frac{G - \delta}{[(G - \delta)^2 + \omega^2]^{1/2}}\right\}. \tag{11}$$

The oscillatory solution requires ω being a real number, and linear instability requires a positive of G. Thus, we can obtain two conditions for an oscillatory and unstable solution:

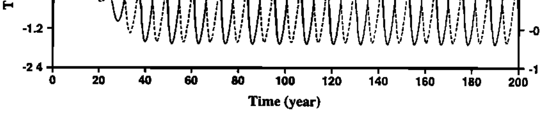


Figure 5. Solution of the tropical-extratropical oscillator model of Eqs. (5) and (6).

$$(b-a)(d+e) > (a+c+f-b-d-e)^2/4, \quad (12)$$

$$b+f > a+c+d+e. \quad (13)$$

The parameters b and f relate to positive feedbacks, and the parameters a, c, d, and e relate to negative feedbacks. For linear instability, the combination of positive feedbacks must be larger than the sum of negative feedbacks.

There are two points that are worthy of note. First, Eq. (12) states that the Hadley Circulation plays an important role in the coupled system. A relatively strong extratropical evaporation feedback introduced by the Hadley Circulation is necessary for the coupled model to oscillate ($b > a$). Second, an oscillatory and unstable solution does not necessarily require a negative extratropical local ocean-atmosphere coupling feedback. If the sign of c is changed (a positive extratropical local coupling feedback), Eqs. (12) and (13) show that an oscillatory and unstable solution is still possible. Thus, the issue of the extratropical local ocean-atmosphere coupling does not qualitatively affect the coupled model here.

The sensitivity of the oscillation period to the model parameters was also studied. The oscillation period increases with increasing parameters a, c, and f, whereas it decreases with increasing parameters d, e, and b (not shown). The model can oscillate over a broad range of model parameters and over a broad range of time scales. Eqs. (7) and (8) show that the relative amplitude between T_1 and T_2 is $[(b-a)/(d+e)]^{1/2}$. For a weaker extratropical SST anomaly amplitude, the combined effects of the Hadley Circulation and oceanic meridional heat transport on the tropics should be larger than those on the extratropics (i.e., $b-a < d+e$). The Walker Circulation and extratropical local coupling feedbacks (f and c) do not affect the relative amplitude between T_1 and T_2.

Discussion

The coupled tropical-extratropical oscillator model proposed herein is different from that of *Gu and Philander* [1997]. In their model, the key for interdecadal oscillations is the delay term which represents the effect of an influx of ocean water from higher latitudes on equatorial SST. The influx following surfaces of constant density, which rises from the tropical thermocline to the ocean surface in the extratropics, affects the equatorial thermocline and then equatorial SST via equatorial upwelling. The whole process is parameterized by a delay term. Without the delay term, their model can not oscillate. In our coupled tropical-extratropical ocean-atmosphere model, the Hadley Circulation along with oceanic meridional heat transport connects the tropics and extratropics. The model oscillation does not require the delay physics. The model oscillates as a natural oscillator of the coupled tropical-extratropical ocean-atmosphere system. The Walker and Hadley Circulations provide positive feedbacks for the tropics and the extratropics, respectively, resulting in an out-of-phase relationship between the tropical and extratropical SST anomalies. Negative feedbacks due to meridional heat transport and the effect of the Hadley Circulation on the tropics bring the system from warm (cold) to cold (warm) phases. Since the coupled system herein involves the heat exchanges between the tropics and extratropics, it may implicitly include the water influx from higher latitudes, as suggested by *Gu and Philander* [1997].

The heuristic tropical-extratropical oscillator model herein gives a periodic solution, whereas the climate variability of the coupled tropical-extratropical system in nature is irregular. Introduction of random forcing to a perfectly periodic oscillatory system can lead to irregular oscillations [e.g., *Gu and Philander*, 1997] and interactions between different time scales [e.g., *Jin et al.*, 1994; *Tziperman et al.*, 1994; *Wang et al.*, 1998a] can also produce irregular oscillations. It is noted that since nature does not provide constant parameters in a coupled system [e.g., Eqs. (5) and (6)], variations of the model parameters with time may also lead to irregularity.

The model provides a possible explanation for the climate variability of the coupled tropical-extratropical system. However, more realistic coupled tropical-extratropical ocean-atmosphere models are necessary to investigate the validity of the mechanism proposed herein. In particular, the atmospheric Hadley Cell needs to be further investigated since observations indicate its connections to climate variability (e.g., Fig. 3), but its impacts on the interactions between the tropics and extratropics have not been well studied.

Acknowledgments. Support for this work is from a grant by the NOAA, Office of Global Programs, Global Ocean-Atmosphere-Land System (GOALS) Program, Grant Number: NA66GPO119.

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(Received May 11, 1998; revised August 25, 1998;
accepted September 18, 1998.)