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An SST Anomaly Dipole In The Northern Subtropical Pacific And Its Relationships With ENSO

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Abstract. This study examines the links between tropical and subtropical sea surface temperature (SST) anomalies in the Pacific Ocean during ENSO (El Niño-Southern Oscillation) events. A long-term simulation by the UCLA coupled atmosphere-ocean general circulation model is used. It is found that a zonally-oriented SST anomaly dipole in the subtropical Pacific develops almost simultaneously with and is closely related to tropical ENSO events. The dipole is located east of the dateline between 20°N and 40°N and consists of an anomaly center off the coast of the North America and another anomaly center with opposite sign further to the west. It is demonstrated that this dipole feature is primarily driven by anomalous surface heat fluxes associated with the altered atmospheric circulation during ENSO events.

1. Introduction

The sea surface temperature (SST) anomaly field during the 1997-98 warm El Niño-Southern Oscillation (ENSO) event included a dipole-type pattern in the Pacific east of the dateline between 20°N and 40°N [*Liu et al., 1998*]. The dipole consisted of centers of anomalous warming along the coast of California and anomalous cooling further to the west, as is clearly seen in the map of mean SST anomalies for May 1997 (Fig. 1). At the same time, cyclonic surface wind anomalies were observed in the eastern North Pacific. *Liu et al.* [1998] proposed a cause-effect relationship between those atmospheric and oceanic anomalies. In their scenario, warmer SSTs developed in association with reduced evaporative cooling by warm surface southerlies east of the anomalous cyclonic center, while colder SSTs appeared west of the center due to enhanced surface evaporation. In this paper we validate this hypothesis by analyzing a long-term simulation by the UCLA coupled atmosphere-ocean general circulation model (CGCM) that produces realistic simulations of the tropical Pacific climate and its variability. Further, we ask whether or not the dipole feature can be expected to systematically develop during ENSO events. Our analyses are based on the principal modes of SST variability and their associated anomalies in sea level pressure, surface wind stress, and surface heat flux.

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2. Model and Simulation

The UCLA CGCM consists of the UCLA atmospheric GCM (AGCM) [*Mechoso et al.* 2000 and references therein] and the GFDL Modular Ocean Model (MOM) [*Bryan* 1969, *Cox* 1984, *Pacanowski et al.* 1991]. The AGCM is global with a horizontal resolution of 5° longitude by 4° latitude and has 15 layers in the vertical. The oceanic GCM (OGCM) covers the Pacific between 30°S and 50°N and from 130°E to 70°W. The model has a longitudinal resolution of 1° and a latitudinal resolution that varies gradually from 1/3° between 10°S and 10°N to about 3° at both 30°S and 50°N. The OGCM has 27 layers in the vertical. Outside the OGCM domain, SSTs are prescribed based on a prescribed, time-varying SST climatology. In this paper, all OGCM outputs are interpolated to the horizontal grid of the AGCM in order to facilitate the analyses of air-sea interactions

Over the past few years, the atmospheric component of the UCLA CGCM has been extensively revised and upgraded (see a summary in *Yu et al.* [1997] and references therein). The CGCM version used in this study has produced a realistic seasonal cycle [*Yu and Mechoso* 1998]. The 53-year long simulation analyzed for this study produces warm equatorial SST events approximately every 3-5 years [*Yu and Mechoso* 2000]. Large westerly wind stress anomalies are simulated to the west of the maximum SST anomalies in all major warm events (not shown). All these features have observed counterparts.

3. The Simulated SST Anomaly Dipole

We start by applying an Empirical Orthogonal Function (EOF) analysis to the SST anomalies produced by the CGCM. The anomalies are obtained by removing the long-term monthly means (i.e., the annual cycle)

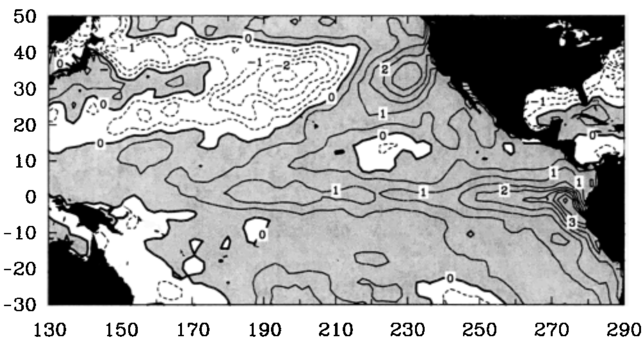

Figure 1. SST anomalies observed in May 1997. Values are obtained from NCEP/NCAR reanalysis corresponding to that time period by removing the long-term (1968-1996) climatological means for May. Contour interval is 1°K. Positive values are shaded.

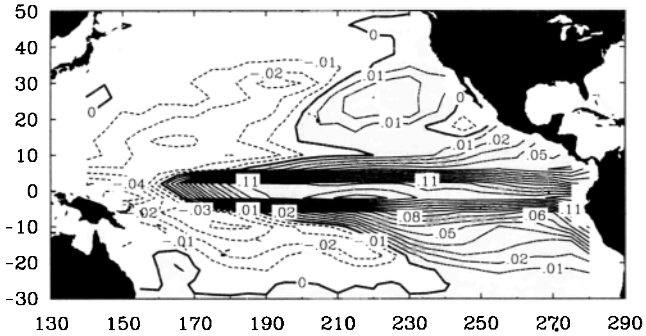

Figure 2. The leading EOF mode of the low-passed SST variability produced from the CGCM simulation. This mode explains 31% of the total SST variance. Variability with time scales shorter than one-year are removed. Contour interval is 0.01. Positive values are shaded.

and the contribution of frequencies shorter than one year. Figure 2 displays the leading EOF, which explains 31% of the low-passed SST variability. This mode shows an ENSO signature around the equator and a dipole-type pattern in the subtropics. The simulated dipole-type variability develops between 15°N and 35°N, which is slightly equatorward of the observed dipole (compare Figs. 1 and 2). This is partially due to the "sponge layer" used in the OGCM north of 30°N, where simulated SSTs are relaxed toward a climatology and no interannual variation can be produced. We also applied an EOF analysis to the SST anomalies between 10°N and 50°N to exclude tropical variability. The leading EOF mode in the reduced domain (not shown) explains 17% of the interannual variability and is still very similar to the SST dipole shown in Fig. 2. The correlation coefficient between the PCs of the leading EOF modes for the entire and reduced OGCM domain is 0.72. Therefore, the SST anomaly dipole of Fig. 2 is also a dominant interannual variability pattern in the subtropical north Pacific.

A power spectrum analysis applied to the principal component (PC) of the leading EOF mode of Fig. 2 reveals a dominant timescale of about 48 months (not shown). There are two other distinct timescales in the spectrum (72 months and 143 months), but only the 48-month spectral peak stands out from the red noise distribution at the 99% significance level. The 48-month timescale is close to the simulated ENSO period, which suggests the existence of tropical-subtropical links during ENSO events.

4. Relationship with ENSO

To further explore the potential for a tropical-sub tropical relationship in the Pacific, we display in Fig. 3 the temporal variations of indices representative of ENSO and of the SST dipole in the simulation. The ENSO index (black curve) is defined as the SST anomalies averaged over a region where they are largest in the central equatorial Pacific (160°W~130°W and 4°S~4°N). The dipole index (gray curve) is defined as the difference between the SST anomalies averaged over the warm center of the dipole (150°W~130°W and 24°N~36°N) and those averaged over the cold center (180°E~160°W and 24°N~36°N). We also apply a low-pass filter to both indices in order to remove variations with timescales shorter than 12 months. Figure 3 shows that most of the simulated ENSO events are accompanied by an SST anomaly dipole in the subtropical Pacific. The correlation coefficient between indices is largest (0.65) when the ENSO index leads the dipole index.

We also use time-lag linear regression coefficients to gain insight into cause/effect relationships between ENSO in the tropics and SST dipole in the subtropics. The regressions are carried out between the PC of the leading EOF mode and the SST anomalies averaged in the latitude bands 4°S-4°N and 20°N-30°N. Figure 4 shows that equatorial warm/cold events and the subtropical SST dipole develop almost simultaneously.

5. Generation Mechanisms

To explore the generation mechanism(s) for the SST dipole, we examine the relationships among different

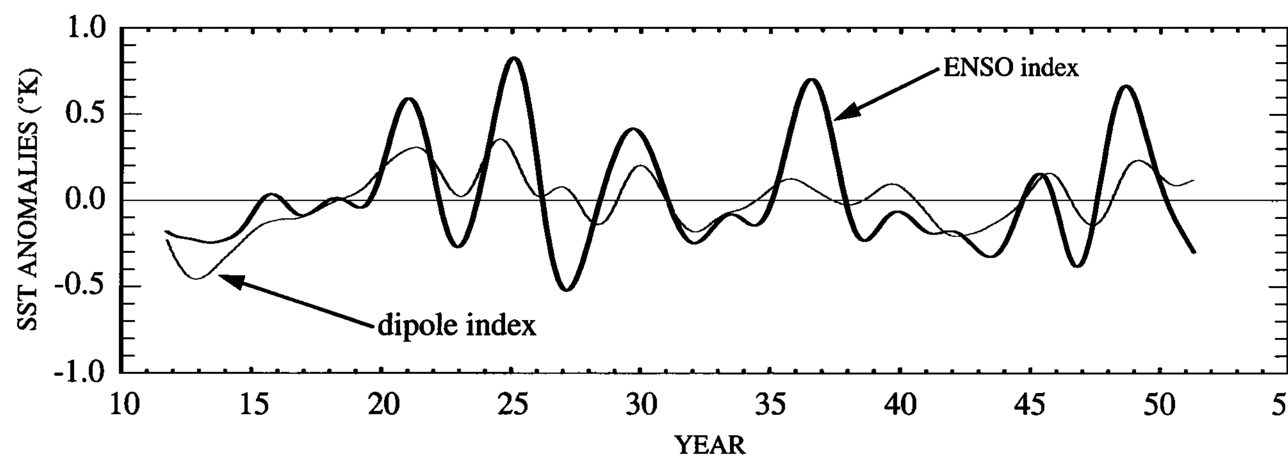

Figure 3. Variations of indices representative of ENSO (dark curve) and dipole in the 53-year CGCM simulation. The ENSO index is obtained by averaging SST anomalies over the central equatorial Pacific (160°W~ 130°W and 4°S~4°N). The dipole index is defined as the difference between the SST anomalies averaged over the warm center (150°W~130°W and 24°N~36°N) and over the cold center (180°E~160°W and 24°N~36°N) of the dipole. A low-pass filter has been applied to both curves to remove variations with timescales shorter than one-year.

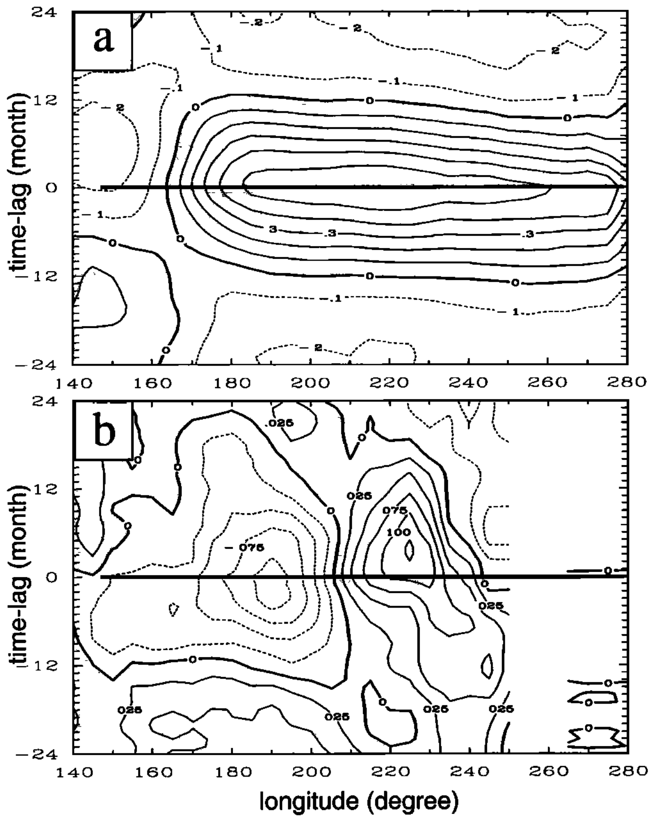

Figure 4. Time-lag regression between the principal component of the leading EOF mode shown in Fig. 2 and SST anomalies (a) at the equator (4°S~4°N) and (b) in the northern subtropics (24°N~36°N). Contour interval is 0.1°K for (a) and 0.025°K for (b).

fields at the atmosphere-ocean interface. Figure 5 displays the linear regression coefficients between the PC of the leading EOF mode and the anomalies in sea-level pressure, surface wind stress, and surface heat flux. For convenience we discuss Fig. 5 in the context of a warm ENSO event. In this case, Fig. 5a shows an enhancement of the Aleutian Low and a cyclonic circulation over the eastern subtropical Pacific. Along the southwesterly branch of this cyclonic circulation, warm and moist air flows from the tropics to the subtropics and the surface heat flux to the atmosphere is reduced (Fig. 5b). Similarly, along the northwesterly branch, dry and cold air flows from higher latitudes to the subtropics and the surface heat flux to the atmosphere is increased. The regions of reduced and enhanced surface heat flux roughly coincide with the warm and cold centers of the subtropical SST anomaly dipole (Fig. 5c). Figure 5, therefore, is consistent with the notion that the SST anomaly dipole is primarily produced by the anomalous thermal forcing of the atmosphere. The short phase lag (about 3 months) seen in Fig. 4 between the developments of the anomaly centers in the eastern and central subtropical Pacific is likely due to the differences in climatological thermal structures of the ocean mixed layers in these two locations.

6. Summary and Discussion

We examined the existence of links between the tropical and subtropical Pacific during ENSO events using a multi-decadal simulation by the UCLA CGCM. Our results showed that an SST anomaly dipole in the subtropical Pacific tends to develop almost simultaneously with ENSO events in the tropics. Further analyses revealed that the SST dipole is consistent with anoma-

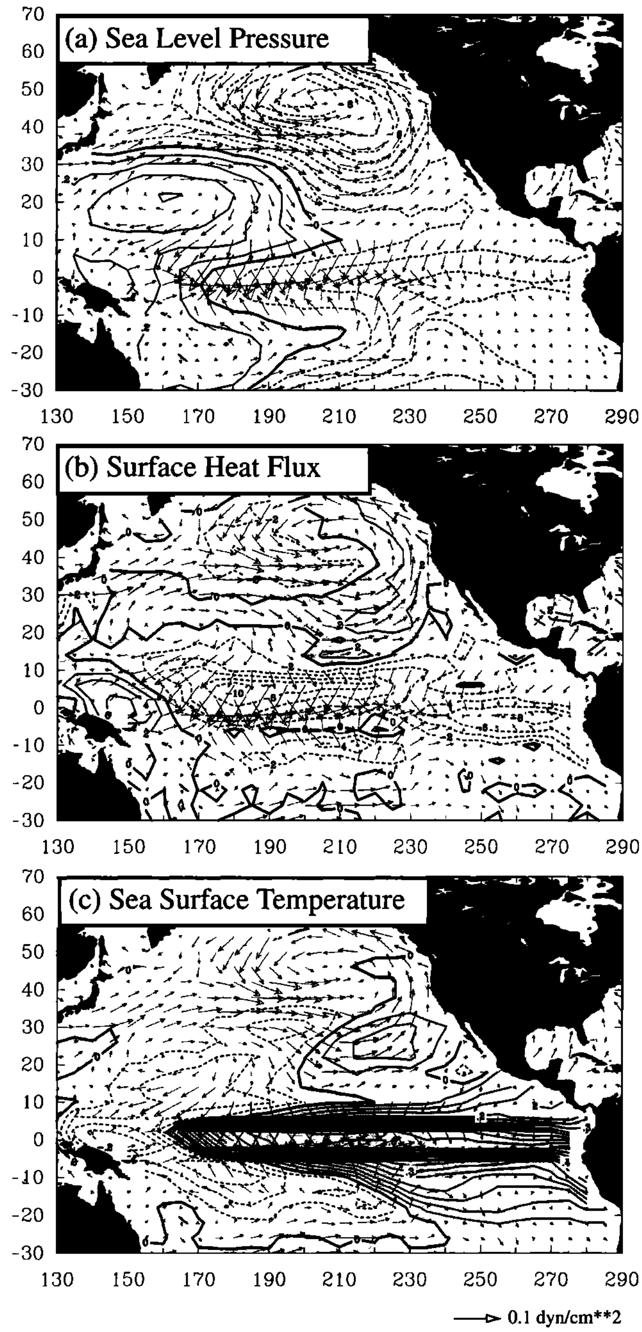

Figure 5. Linear regression coefficients between the principal component of the leading EOF mode of Fig. 2 and anomalies in (a) sea level pressure, (b) surface heat flux, and (c) SST. Vectors represent regression coefficients between the principal component and zonal and meridional wind stress anomalies. Vector magnitudes are in unit of dyn/cm^2. Contours intervals are 0.1mb for (a), 0.2W/m^2 for (b), and 0.05°K for (c). Positive values are shaded. Positive (negative) values in (b) indicate less (more) surface heat flux out of the ocean.

lous surface heat fluxes associated with the altered atmospheric circulation. These findings, therefore, support the cause-effect relationship proposed by [*Liu et al.* 1998] for the 1997-98 ENSO and SST anomaly dipole. The mechanism at work is conceptually similar to the "atmospheric bridge" proposed by *Lau and Nath* [1996], which links tropical SST anomalies with other latitudes via the atmosphere.

The association between ENSO and the SST anomaly dipole in the northern subtropical Pacific is stronger in the simulation than in the observations. This discrepancy may be related to the relatively weak inter-event variability produced by the CGCM. In the observations, there are stronger shifts in the position of anomalous convection in the tropics, to which the extratropical atmospheric circulation associated with ENSO is sensitive [*Mo and Higgins* 1998].

Finally, we emphasize that both the *Liu et al.* [1998] hypothesis and our results complement previous work on North Pacific variability. The subtropical SST dipole discussed in this study is not part of the so-called "North Pacific SST Mode" [*Deser and Blackmon* 1995]. This mode has a broad zonal structure across the northern Pacific poleward at about 40°N (see Fig. 1b of *Deser and Blackmon* 1995), dominant interdecadal timescales, and has been shown to be linearly independent of ENSO [*Zhang et al.* 1996]. Our SST dipole appears related to the so-called "ENSO SST mode" [*Deser and Blackmon* 1995], which has a SST anomaly dipole centered at 30°N and is more confined to the east of the dateline in the Pacific (see Fig. 1a of *Deser and Blackmon* 1995). *Deser and Blackmon* [1995] pointed out that the SST dipoles of the North Pacific and ENSO modes are associated with different atmospheric circulation patterns. The geopotential height anomalies associated with the North Pacific mode closely resemble the Pacific/North American (PNA) pattern [*Wallace and Gutzler* 1981]. The corresponding anomalies pattern associated with the ENSO mode is similar to the PNA pattern but has the subtropical anomaly center in the far western Pacific. The regressed sea level pressure anomalies of our SST dipole (see Fig. 5a) clearly show such an anomaly center over the far western subtropical Pacific. Therefore, the results presented in this study apply to tropical-subtropical SST relationships on interannual, rather than interdecadal, timescales.

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