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Impacts of Central America gap winds on the SST annual cycle in the eastern Pacific warm pool

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[1] The annual cycle of sea surface temperature (SST) in the eastern Pacific warm pool and its relation to Central America gap winds are examined in this study. Locally enhanced annual harmonics of SST are found underneath the regions where the Tehuantepec and Papagayo gap winds blow. The SSTs underneath the Tehuantepec gap wind undergo larger annual variations than those underneath the Papagayo gap wind. This suggests that the Tehuantepec gap wind has a stronger influence on the annual cycle of SST than the Papagayo gap wind. A series of ocean model experiments are performed to demonstrate the enhancement effect of the gap winds. Further heat budget analyses of the experiments show that the gap winds increase the amplitude of the SST annual cycle primarily by enhancing the vertical entrainment process in the ocean. The thermal forcing effect of the gap winds is less important in modulating the SST annual cycle. **Citation:** Sun, F., and J.-Y. Yu (2006), Impacts of Central America gap winds on the SST annual cycle in the eastern Pacific warm pool, *Geophys. Res. Lett.*, *33*, L06710, doi:10.1029/2005GL024700.

1. Introduction

[2] The eastern Pacific warm pool (EPWP) refers to the region of warm sea surface temperatures (SSTs) in the northeastern tropical Pacific between about 6°N and the Mexican coast, extending westward from the Central American landmass to the east of 120°W. The EPWP serves as a reservoir of heat and moisture for the monsoon circulation over parts of Central America and is an important component of the eastern Pacific climate system [*Raymond et al.*, 2004]. SSTs in the EPWP exhibit large annual variations. We examine the amplitude of the annual harmonic of observed SSTs [*da Silva et al.*, 1997] (Figure 1a) in this region and find that there are two patches of large annual amplitudes extending from the Central American coast into the Pacific. These two patches are located near the Gulf of Tehuantepec and Gulf of Papagayo, where strong low-level winds blow from the Gulf of Mexico to the Pacific through gaps in the cordillera. These strong low-level jets are referred to as the Tehuantepec gap wind and the Papagayo gap wind [*Clarke*, 1988; *Schultz et al.*, 1998; *Chelton et al.*, 2000]. These two gap winds are known to go through large annual variations: strong in boreal winter and weak during May through September [*Xie et al.*, 2005]. Figure 1b displays the amplitude of the annual harmonic of observed surface wind stress magnitude derived from the Quick Scatterometer (QuikSCAT) wind data (January 2000–December 2004) [*Centre ERS d'Archivage et de Traitement*, 2002; *Jet Propulsion Laboratory*, 2000]. Corresponding to the Tehuantepec and Papagayo gap winds, there are two patches of large annual amplitudes in the EPWP region. These two patches largely coincide with those of large SST annual amplitude in Figure 1a, suggesting a possible link between the gap winds and the local enhancement of SST annual cycle in these regions.

[3] It is worth noting the annual cycle of the Tehuantepec gap wind has larger amplitude and spreads over a larger area than that of the Papagayo gap wind. Coincidently, the locally enhanced SST annual cycle underneath the Tehuantepec gap wind is also stronger and covers a larger area than that underneath the Papagayo gap wind. Apparently, the Tehuantepec gap wind undergoes a larger annual variation, extends further into the open ocean, and may have a stronger influence on the annual cycle of EPWP SSTs than the Papagayo gap wind. Therefore, our analyses focus on the influence of the Tehuantepec gap wind on local SSTs.

[4] The gap winds can affect SSTs through thermal and mechanical forcing processes. In the thermal forcing process, variations in the gap winds influence local SSTs by changing the air-sea surface heat fluxes through their modulation of cloud coverage, sensible heat flux, and evaporation. In the mechanical forcing process, the wind variations impact the ocean dynamical processes, such as ocean advections, vertical mixing and thermocline depth. In this study, we use observational data and a high resolution ocean model to verify that the local enhancements of SST annual cycle in the EPWP are induced by the Central America gap winds and to determine the relative contributions of thermal and mechanical forcing processes to these enhancements.

2. Data and Model Experiments

[5] The ocean model used in this study is the Regional Ocean Modeling System (ROMS), which is a regional ocean circulation model for solving the free-surface, hydrostatic, primitive equations over a varying topography on an orthogonal curvilinear coordinate in horizontal and a stretched terrain-following coordinate in vertical [*Shchepetkin and McWilliams*, 2005]. The ocean domain covers the Pacific Ocean from 30°S to 50°N and from 130°E to 70°W, with a 0.5° × 0.5° horizontal resolution and has 27 vertical layers. The vertical mixing is parameterized in the model by the K-profile parameterization scheme of *Large et al.* [1994]. The model is forced with monthly climatologies of surface wind stress, heat and freshwater fluxes derived from the "half-degree supplement" product of the Surface Marine Data (SMD) [*da Silva et al.*, 1994], which is also known

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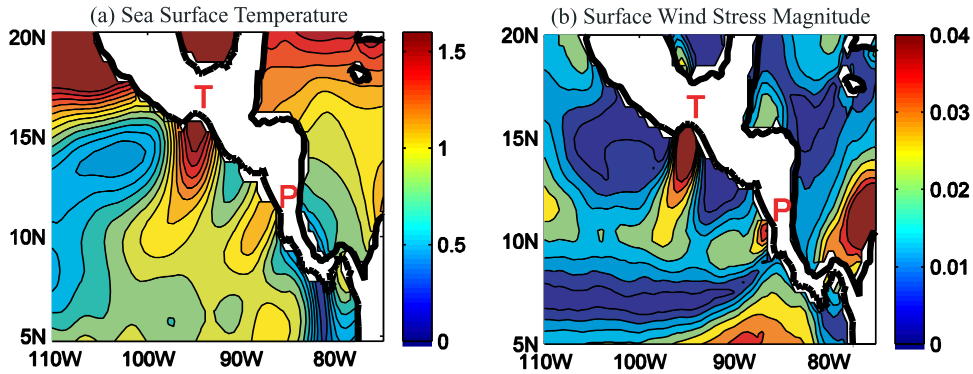

Figure 1. Amplitudes of the annual harmonics of (a) observed SST (K) and (b) surface wind stress (N/m^2) in the eastern Pacific warm pool. "T" and "P" indicate the locations of Gulf of Tehuantepec and Gulf of Papagayo, respectively.

as UWM/COADS data set [*da Silva et al.*, 1997]. This "half-degree supplement" product has a horizontal resolution of 0.5° × 0.5°, which is not an interpolation of the more popular 1° × 1° product of *da Silva et al.* [1994]. Rather, the individual ship reports are averaged on 0.5° × 0.5° boxes and then objectively analyzed. The "half-degree supplement" product of SMD is more accurate than the 1° × 1° data in the regions with large gradients and is suitable for this study. The model has a resting initial state with January climatological temperature and salinity from *Levitus and Boyer* [1994].

[6] In order to assess the relative roles of thermal and mechanical forcing processes of the gap winds, four experiments are performed with the ROMS: (1) the control run, which includes both the thermal and mechanical forcing of the gap winds; (2) the gap-wind-suppressed experiment, which suppresses both the thermal and mechanical forcing of the gap winds; (3) the thermal-forcing experiment, which includes the thermal forcing but suppresses the mechanical forcing; and (4) the mechanical-forcing experiment, which includes the mechanical forcing but suppresses the thermal forcing. The thermal forcing and mechanical forcing of the gap winds are suppressed by removing the local extremes of surface heat flux and wind stress respectively in the gap wind regions via spatial smoothing.

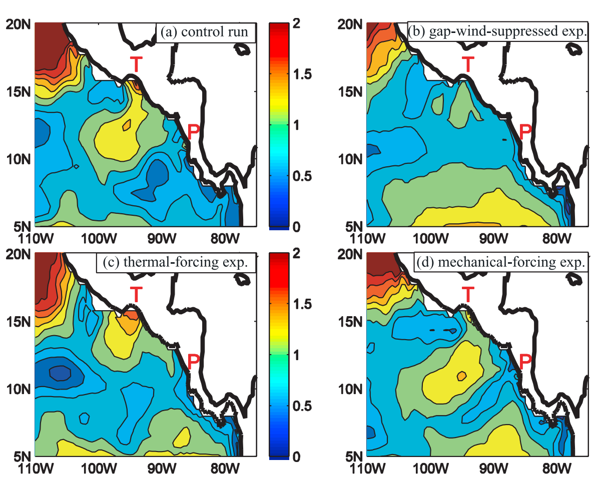

Figure 2. Amplitudes of SST annual harmonic (K) over the EPWP for (a) the control run, (b) the gap-wind-suppressed experiment, (c) the thermal-forcing experiment and (d) the mechanical-forcing experiment.

[7] In the four experiments, the ROMS is forced separately with (1) the original mean monthly wind stress and heat flux (the control run); (2) the smoothed wind stress and heat flux (the gap-wind-suppressed experiment); (3) the smoothed wind stress and original heat flux (the thermal-forcing experiment); and (4) the original wind stress and smoothed heat flux (the mechanical-forcing experiment). All experiments are integrated for 10 years from the end of a 30-year spin-up simulation.

3. Simulated SST Annual Cycle

[8] Figure 2 shows the amplitudes of the SST annual harmonics from the four experiments. The control run (Figure 2a) captures the locally enhanced amplitudes in the region underneath the Tehuantepec gap wind (8°N–13°N, 98°W–92°W; hereafter, Region T), which are close to those shown in Figure 1a. The SST annual harmonics in Region T also exhibit stronger intensities and larger spatial coverage than those underneath the Papagayo gap wind, which is consistent with the observations shown in Figure 1a. Figure 3 shows that the SST annual cycle produced by the control run in Region T is very close to the observed. Both the observation and the control run show cold SSTs in boreal winter when the Tehuantepec gap wind is strong and warm SSTs in late spring and summer when the Tehuantepec gap wind is weak. Figure 2a shows that the control run also produces a local amplitude maximum underneath the Papagayo gap wind, but the spatial exten-

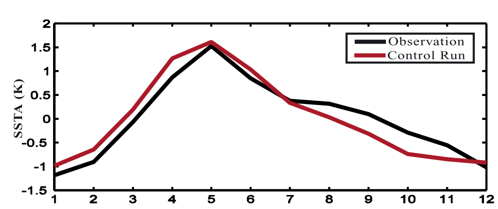

Figure 3. Annual cycles of SST anomalies (K) with the annual mean removed averaged over the region underneath the Tehuantepec gap wind (8°N–13°N, 98°W–92°W; referred as Region T) from the observations (black) and the model control run (red).

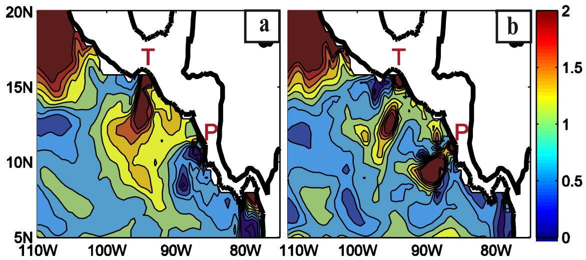

Figure 4. Amplitudes of SST annual harmonic (*K*) over the EPWP: (a) the additional ROMS experiment forced by QuikSCAT wind stress and (b) the additional ROMS experiment forced by the wind stress forcing of the control experiment but with its annual harmonic tripled to its original value in Gulf of Tehuantepec and Gulf of Papagayo.

sions are much smaller than the observed (Figure 1a) and limited more to the coastal regions. An additional control experiment forced with monthly QuikSCAT surface wind stress (0.5° × 0.5°) produces similar weakened amplitudes in the region underneath the Papagayo gap wind (shown in Figure 4a). Therefore, the weakened bias is not caused by the SMD forcing data. It is likely that the small spatial scale of the Papagayo gap wind, together with the underestimation of the gap wind strength in the monthly mean forcing, lead to the weak SST responses in the model. In another additional ROMS experiment, we artificially increase the amplitudes of the annual harmonics of the wind stress forcing at both the Tehuantepec and the Papagayo gap wind regions to three times of the original values to test the model sensitivity to wind forcing. Figure 4b shows that both the intensities and spatial coverage of the SST annual harmonics become more realistic underneath the Papagayo gap wind compared to Figure 2a. This experiment indicates that the weakened SST annual harmonic bias underneath the Papagayo gap wind is not due to the inability of the ocean model to respond to gap wind forcing. To some extent, the underestimation of the SST annual harmonics may be caused by the use of monthly climatology forcing due to the non-linear dependence of wind-induced ocean mixing on the wind stress.

[9] When both the thermal forcing and mechanical forcing from the gap winds are suppressed, Figure 2b shows that the local enhancements of the SST annual harmonics in Region T are significantly reduced compared to the control run. This demonstrates that the gap wind forcing is the major contributor to the local enhancements of the SST annual harmonics in Region T. It should be noted that there are still small residuals of large annual harmonics in the coastal regions, suggesting secondary processes other than the gap wind may also contribute to the SST annual cycle in that region. When only the thermal forcing is included in the experiment, the amplitude enhancement of the SST annual harmonics is only seen near the coast. The SST enhancement in Region T is still small (Figure 2c). When only the mechanical forcing is included, the model produces large amplitudes of SST annual harmonics in Region T (Figure 2d), comparable to the pattern in the control run (Figure 2a). Figures 2c and 2d together indicate that the Tehuantepec gap wind enhances the local SSTs annual cycle in the EPWP primarily through the mechanical forcing process. However, the thermal forcing process is important to the enhancement of the SST annual cycle in the regions immediately off the coast.

4. Mixed Layer Heat Budget Analyses

[10] We apply mixed layer heat budget analyses to the experiments to understand how the gap winds affect the SST annual variations underneath the Tehuantepec gap wind. Following *Qu* [2003], the equation governing the mixed layer temperature can be written as:

$$\frac{\partial T_m}{\partial t} = -u_m \frac{\partial T_m}{\partial x} - v_m \frac{\partial T_m}{\partial y} - w_{ent} \frac{(T_m - T_d)}{h_m} + \frac{Q_0 - q_d}{\rho C_p h_m} \qquad (1)$$

where T_m is the mixed layer temperature, h_m the mixed layer depth, u_m the zonal current, v_m the meridional current, w_{ent} the entrainment rate of cold water from the below, T_d the temperature of water entrained into the mixed layer, taken to be the temperature 10 meters below the mixed layer, ρ the sea water density, C_p the specific heat of sea water, Q_0 net surface heat flux. The shortwave radiative flux at the bottom of the mixed layer, q_d, is determined from an empirical formula of *Paulson and Simpson* [1977]. Here, h_m is defined as the depth where the ocean temperature is 0.5 K colder than the surface temperature [*Hayes et al.*, 1991]. The entrainment rate, w_{ent}, is determined based on the following formula:

$$w_{ent} = \frac{\partial h_m}{\partial t} + w_{mb} + U \cdot \nabla h_m, \quad \text{if} \quad \frac{\partial h_m}{\partial t} + w_{mb} + U \cdot \nabla h_m > 0;$$
$$w_{ent} = 0, \qquad \text{otherwise.} \qquad (2)$$

in which $\frac{\partial h_m}{\partial t}$ is the rate of the mixed layer deepening, w_{mb} the vertical velocity of water parcel at the base of the mixed layer and $U \cdot \nabla h_m$ the horizontal advection of water parcels below the mixed layer.

[11] Figure 5 shows the differences between the heat budget terms of the control run and those of the gap-wind-suppressed experiment for Region T. This figure indicates how the SST annual harmonics are enhanced from the background level (represented by the gap-wind-suppressed experiment) by the gap winds. It shows that the annual harmonic of the vertical entrainment term is the largest contributor to the enhancement of SST annual

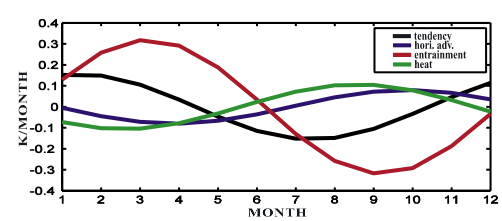

Figure 5. Differences of annual harmonics of the ocean mixed layer heat budget terms (*K/month*) between the control run and the gap-wind-suppressed experiment for Region T: mixed layer temperature tendency (black), horizontal advection (blue), entrainment (red), and heat forcing (green).

harmonics. Smaller horizontal advection contribution to the enhancements is found compared to the vertical entrainment term. The gap wind-related surface heat flux forcing is small and nearly out of phase with the SST tendency. Heat budget analyses of the mechanical and thermal forcing (not shown) experiments show results consistent with those in Figure 5. These results suggest that the vertical entrainment is the main physical process by which the Tehuantepec gap wind enhances the SST annual variation.

[12] We also analyze the annual variations of upper ocean temperatures in Region T for all the experiments (not shown). It is found that the strong gap winds in boreal winter shoal the thermocline while the weak gap winds in late spring and summer deepen the thermocline. The strong annual variations of the thermocline depth together with the enhanced vertical entrainment due to the gap winds lead to the enhancement of the annual cycle in local SSTs. When the gap winds are suppressed, the thermocline is much deeper than that in the control run year-round and shows smaller annual variations. As a result, the vertical entrainment term is small.

5. Summary and Discussions

[13] Most previous observational and numerical model studies of the Central America gap winds and the eastern Pacific warm pool focused on their synoptic and meso-scale features. However, the role of the gap winds in the EPWP climate has been increasingly emphasized [e.g., *Xie et al.*, 2005]. In this study, we examine the influences of the gap winds on the SST annual cycle in the eastern Pacific warm pool. Our results show that the Tehuantepec gap wind undergoes a stronger annual cycle, extends further into the Pacific Ocean, and has a more pronounced influence on the annual cycle of local SSTs than the Papagayo gap wind. Through a series of ocean model experiments, we have demonstrated that the local maxima in the amplitudes of the SST annual harmonics in the EPWP, particularly in the region underneath the Tehuantepec gap wind, are caused by the gap winds. Our ocean mixed layer heat budget analyses show that the gap winds affect the SST annual cycle primarily by shoaling the thermocline which allows cold water to be entrained into the upper ocean in boreal winter when the gap winds are strong while deepening the thermocline in late spring and summer when the gap winds are weak.

[14] It is important to note that our modeling study with monthly forcing is a first order examination of the problem. Meso-scale ocean eddies induced by the gap winds may be important in the response of EPWP SST to the gap winds [e.g., *McCreary et al.*, 1989]. These eddies are not included in this modeling study. The experiment forced by QuikSCAT wind shows a better result in simulating the annual cycle of SST underneath the Tehuantepec gap wind. But it should be noted that the SMD data provide us long-term and more consistent surface wind stress, heat flux and fresh water flux climatologies and thus are most suitable to address the relative importance of mechanical and heat flux forcing mechanisms in this study. Long-term wind and heat flux forcing fields with higher spatial and temporal resolutions are needed to fully explore the climate impacts of the gap winds on the ocean, but such data sets are not currently available.

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References

Centre ERS d'Archivage et de Traitement (2002), QuikSCAT scatterometer mean wind field products user manual, version 1.0, *Doc. C2-MUT-W-03-IF*, Inst. Fr. De Rech. Pour l'Explor. de la Mer, Plouzané, France.

Chelton, D. B., M. H. Freilich, and S. K. Esbensen (2000), Satellite observations of the wind jets off the Pacific coast of Central America. part I: Case studies and statistical characteristics, *Mon. Weather Rev.*, *128*, 1993–2018.

Clarke, A. J. (1988), Inertial wind path and sea surface temperature patterns near the Gulf of Tehuantepec and Gulf of Papagayo, *J. Geophys. Res.*, *93*, 15,491–15,501.

da Silva, A., A. C. Young, and S. Levitus (1994), *Atlas of Surface Marine Data 1994*, vol. 1, *Algorithms and Procedures*, *NOAA Atlas NESDIS*, vol. 6, NOAA, Silver Spring, Md.

da Silva, A., A. C. Young, and S. Levitus (1997), *Atlas of Surface Marine Data 1994*, suppl. B, *Procedures for 1/2° by 1/2° Data Set*, *NOAA Atlas NESDIS*, vol. 17, NOAA, Silver Spring, Md.

Hayes, S. P., P. Chang, and M. J. McPhaden (1991), Variability of the sea surface temperature in the eastern equatorial Pacific during 1986–1988, *J. Geophys. Res.*, *96*, 10,553–10,566.

Jet Propulsion Labortory (2000), QuikSCAT science data product, user's manual, overview and geophysical data products, version 2.0-draft, *Doc. D-18053*, Calif. Inst. of Technol., Pasadena, Calif.

Large, W. G., J. C. McWilliams, and S. C. Doney (1994), Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, *32*, 363–404.

Levitus, S., and T. Boyer (1994), *World Ocean Atlas 1994*, vol. 4, *Temperature*, *NOAA Atlas NESDIS*, vol. 4, NOAA, Silver Spring, Md.

McCreary, J. P., H. S. Lee, and D. B. Enfield (1989), The response of the coastal ocean to strong offshore winds: With application to circulations in the Gulfs of Tehuantepec and Papagayo, *J. Mar. Res.*, *47*, 81–109.

Paulson, C. A., and J. J. Simpson (1977), Irradiance measurements in the upper ocean, *J. Phys. Oceanogr.*, *7*, 952–956.

Qu, T. (2003), Mixed layer heat balance in the western North Pacific, *J. Geophys. Res.*, *108*(C7), 3242, doi:10.1029/2002JC001536.

Raymond, D. J., S. K. Esbensen, C. Paulson, M. Gregg, C. S. Bretherton, W. A. Petersen, R. Cifelli, L. K. Shay, C. Ohlmann, and P. Zuidema (2004), EPIC2001 and the coupled ocean-atmosphere system of the tropical east Pacific, *Bull. Am. Meteorol. Soc.*, *85*, 1341–1354.

Schultz, D., W. E. Bracken, and L. F. Bosart (1998), Planetary- and synoptic-scale signatures associated with Central American cold surges, *Mon. Weather Rev.*, *126*, 5–27.

Shchepetkin, A. F., and J. C. McWilliams (2005), The regional oceanic modeling system (ROMS): A split-explicit, free-surface, topography-following-coordinate ocean model, *Ocean Modell.*, *9*, 347–404.

Xie, S.-P., H. Xu, W. S. Kessler, and M. Nonaka (2005), Air-sea interaction over the eastern Pacific warm pool, gap winds, thermocline dome, and atmospheric convection, *J. Clim.*, *18*, 5–25.

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