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Cause of tropical Pacific warming trend

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Abstract. Combining observations and model simulations, the equatorial upper ocean heat budget is closed to diagnose the cause of the 1945-93 sea surface temperature (SST) trend. The equatorial Pacific SST exhibits a clear warming trend, in spite of a cooling trend in the net downward surface heat flux. This warming is caused primarily by the reduction of wind-driven cold ocean current.

Introduction

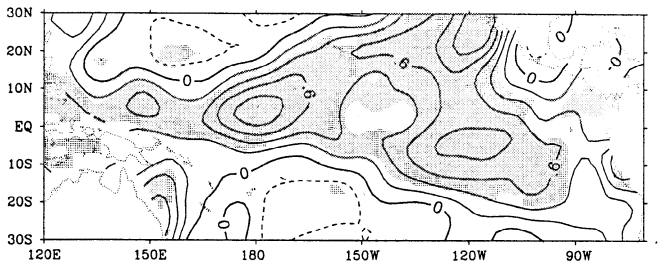
The temperature of the Equatorial Pacific is one of the most important characteristics of global climate. Accompanied with the global warming trend in the last century (IPCC, 1995), a warming trend has been detected in the equatorial Pacific SST (Cane et al., 1997), especially in the last three decades (Latif et al., 1997; Lau and Wen, 1999; Fig.1a). The cause for this warming trend remains elusive. Recent modeling (Latif et al., 1997; Cane et al., 1997) and observational (Curtis and Hastenrath, 1999) analyses ventured conjectures on the cause of the long-term trend. None of these work, however, has been analyzed in the context of a closed oceanic heat budget, which is necessary for a full understanding of SST changes. Here, a diagnostic study is performed to isolate the cause of the warming trend using a closed oceanic heat budget. While the equatorial Pacific becomes warmer, it is found that the net downward surface heat flux would imply a cooling trend. The cause for the upward trend of SST is therefore traced to the reduction of oceanic cold advection, which in turn is generated by a weakening trade wind in the tropical Pacific.

Data and Method

At present, the oceanic heat budget can only be closed by combining observations and ocean model diagnostics, because of the lack of sufficient oceanic observations. The observational data used here is the COADS data from 1945-93 (da Silva et al., 1994). For our study of long term trend, it is important that any systematic bias in the data is corrected. So far there has been no work indicating systematic spurious trends in this COADS data, except for one variable – the surface wind. The COADS wind show a trend of stronger trades in the central/eastern equatorial Pacific that is spurious and results from the decreasing usage of Beaufort wind scale since 1950s (Cardone et al., 1990). This spurious trend can be corrected as (Ward, 1992) $U_c=U\times[1-S(t-t_0)]$, where U_c and U are the corrected and original COADS winds, respectively, t and t_0 are year t and 1945, respectively, and $S=0.25/50year$ is a trend correction factor. The corrected equatorial trade shows a trend of decreasing speed (Fig.1b), opposite to that in the original COADS wind, but consistent with other recent work (Clarke and Lebedev, 1996; Curtis and Hastenrath, 1999). Furthermore, the dynamic consistency of the long term trends between the corrected wind stress forcing and the response in observed subsurface temperature (White, 1995) is confirmed by using the GFDL MOM2 ocean model (Pacanowski, 1996). Forcing the ocean model with the corrected COADS wind, the upper ocean model temperature trend (Fig.2b) strongly resembles that from the XBT observations (Fig.2a) in the equatorial Pacific, with a pattern correlation of 0.81 (in contrast to a correlation of 0.17 when we used the uncorrected COADS wind forcing). The eastern Pacific becomes warmer in the upper thermocline and the western/central Pacific becomes colder in the lower thermocline, corresponding to a reduction of the zonal slope of the equatorial thermocline. This reduction of thermocline slope is caused primarily by the weakening of equatorial trades in the corrected COADS wind. This finding is consistent with that of Clarke and Lebedev (1996), who have found a trend of reduced west/east sea level difference across the equatorial Pacific. The weakening trades will be seen essential to our explanation for the warming trend of the equatorial SST.

Further model output for our diagnostics was obtained by forcing the MOM2 model using the heat flux and wind stress derived from the corrected COADS data. The surface heat flux

(a) COADS SST Trend (1945-93)



(b) Corrected COADS Wind Stress Trend (1945-93)

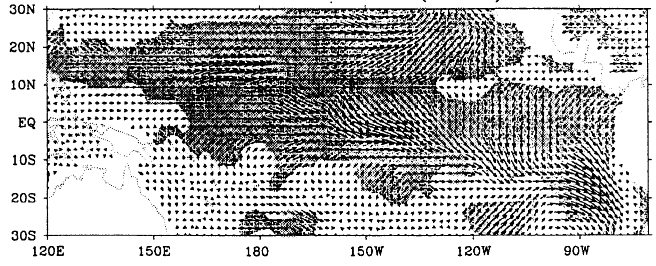


Figure 1. The 1945-1993 linear trend of (a) COADS SST (CI=0.2°C/50year) and (b) the corrected COADS wind stress (unit vector =1 dyn cm^{-2}/50year) in the tropical Pacific Ocean. Shading areas indicate regions of significance over 95%.

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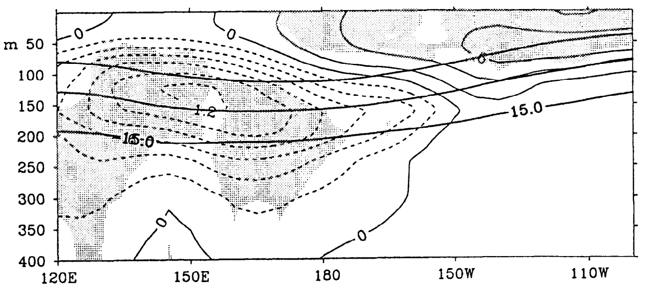
(a)Observed Temperature Trend (1955-93, C°/50yr)



(b)Model Temperature Trend (1955-93, C°/50yr)

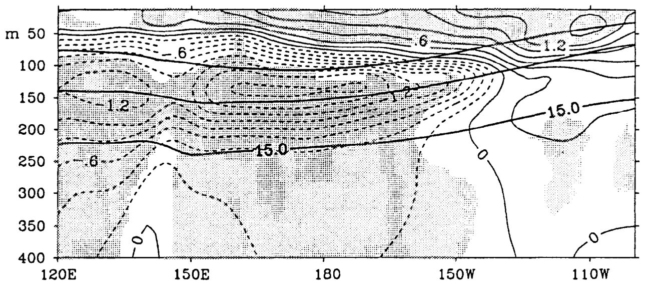


Figure 2. The 1955-1993 linear trend of upper ocean temperature averaged within 10° of the equator in the XBT data (a) and the model simulation (b). (CI=0.2°C/50year). Shading area has a trend of significance over 95%. The mean isotherms of 15°C,20°C and 25°C are also shown in both the observation and model to indicate the structure of the mean thermocline within 10° of the equator. The model is a global ocean model with a 2°×2° horizontal resolution and 40 vertical levels.

was calculated with the surface atmospheric variables and the model SST. The surface salinity was restored towards the Levitus (1982) seasonal climatology. The model was spun-up with the forcing of 1945 for 500 years. Monthly anomalous forcing was then added to simulate the oceanic variability afterwards. The model succeeds in simulating the observed trend of ocean temperature as shown in Fig.2. This success is important because it assures that the model heat budget is reasonable for the purpose of understanding the observed ocean temperature trend. Our model data, with its strong resemblance to observations and its physical consistency, can be thought crudely as an assimilated ocean data set.

Heat Budget Analysis

The heat budget of the top 50-m ocean is obtained by integrating the temperature equation vertically (denoted by < >) as:

$$C_p\rho\partial_t \langle T\rangle = Q_{Net} - Q_{50} + A_U + A_V + A_W + A_H \qquad (1)$$

where C_p is the specific heat for water and ρ is a standard density. The Q_{Net} is the net surface downward heat flux which is calculated from the downward short wave radiation (Q_{SW}), the upward long wave radiation (Q_{LW}), and the upward latent (Q_{LH}) and sensible (Q_{SH}) heat fluxes as $Q_{Net} = Q_{SW} - Q_{LW} - Q_{LH} - Q_{SH}$. These terms $A_U = -C_p\rho \langle u\partial_x T\rangle$, $A_V = -C_p\rho \langle v\partial_y T\rangle$ and $A_W = -C_p\rho \langle w\partial_z T\rangle$ are the oceanic advective fluxes in the zonal, meridional and vertical, respectively. The final term, $A_H = C_p\rho \langle d\nabla^2 T\rangle$, is the horizontal diffusion. The downward entrainment heat flux across the depth of 50-m, Q_{50}, is calculated as $Q_{50} = Q_{Net} - C_p\rho\langle d_V\partial_{zz}T + T_{Conv}\rangle$ where T_{Conv} is the convection temperature source in the model.

It is helpful to first analyze the heat budget that maintains the climatological mean tropical SST. The shortwave radiation warming is balanced mainly by the latent heat cooling (Fig.3a). The westward decrease of shortwave radiation in the central Pacific is mainly caused by the increase of cloud cover towards the warm pool, while the eastward decrease of latent heat cooling arises from the colder SST towards the cold tongue. The net surface heat flux is always positive into the ocean, large in the eastern/central Pacific (~ 50Wm^{-2}), but small in the western Pacific (< 10 Wm^{-2}). The net surface warming is balanced by the oceanic advective cooling (Fig.3b, Table 1): mainly upwelling (A_W) in the eastern Pacific and off-equatorial divergence of cold tongue water (A_V) in the central Pacific. In the west, the weak warming due to net downward surface heat flux and off-equatorial divergence of warm pool water is balanced by a modest cooling due to upwelling and zonal advection, the latter being caused by the South Equatorial Current flowing from the colder tongue towards the warm pool. This summary of the mean heat budget is similar to previous studies (Gent, 1991).

The trend of heat budget balance, however, differs dramatically from the mean heat budget discussed above. Examination of the surface heat flux trend (Fig.3c and Table 1) reveals a surprising feature: while the equatorial Pacific SST increases, the net downward surface heat flux contributes to a cooling trend across most of the equatorial Pacific Ocean. This cooling trend is caused mainly by the reduction of short wave radiation in the central/eastern Pacific. The short wave radiation is reduced by the increase of cloud cover, as discussed by Curtis and Hastenrath (1999). West of 160°E, the solar radiation is increased slightly due to a small reduction of cloud cover (not shown); but this weak short wave warming is overwhelmed by the enhanced cooling in the other three surface heat fluxes.

It is now clear that the SST warming trend has to be caused by the change in the oceanic advection, because our upper ocean heat budget is closed by the surface and oceanic advective heat fluxes. As shown in Fig.3d (and Table1), in the eastern and central Pacific, the surface warming is caused by a trend of warm meridional and vertical advection due to the reduction of cold

Table 1. Components of surface heat flux and advective heat flux as discussed in eqn. (1). For each component, the mean heat flux (Wm^{-2}) and the trend of heat flux (Wm^{-2}/50year) are averaged in the western (130°E-170°E), central (170°E-150°W) and eastern (150°W-110°W) equatorial Pacific within 10° of the equator. The mean SSTs (°C) and their trends (°C/50year) are also listed. The horizontal diffusion term is small and not shown.

	Western		Central		Eastern	
	Mean	Trend	Mean	Trend	Mean	Trend
SST	29.6	0.44	28.5	0.85	26.7	0.83
Q_{SW}	215	2.6	229	-9.3	239	-7.7
Q_{LW}	39	2.7	37	3.0	41	-0.6
Q_{LH}	160	0.2	153	-2.1	143	0.3
Q_{SH}	9	1.1	6	3.3	6	1.1
Q_{Net}	5.9	-1.3	31.9	-13.6	49.2	-8.5
A_U	-2.3	2.6	-10.3	0.6	-4.9	-0.7
A_V	7.6	1.1	-19.7	22.0	-20.8	9.3
A_W	-8.5	1.0	-8.5	3.8	-23.2	5.3
$-Q_{50}$	-1.9	-3.7	7.0	-12.0	-0.1	-4.6

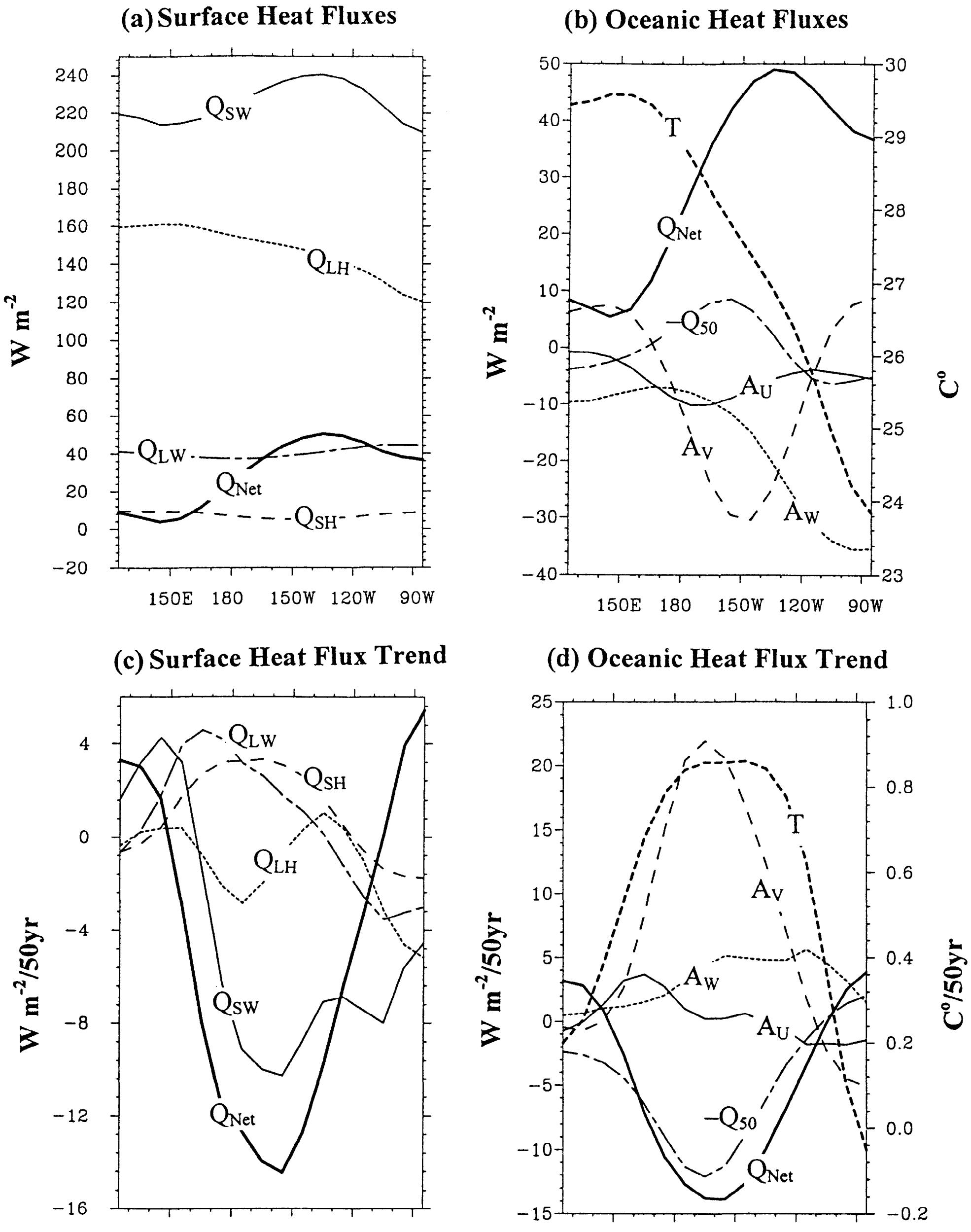


Figure 3. Ocean heat budget averaged within the top 50-m and 10° of the equator in the model simulation. The heat budget is performed on each 10° longitude band. (a) Components of the mean surface heat fluxes (Wm^{-2}) as discussed regarding eqn. (1). (Q_{SW} in thin solid, Q_{LH} in dot, Q_{LW} in dash-dot, Q_{SH} in dash and Q_{Net} in thick solid). (b) components of mean oceanic heat fluxes (Wm^{-2}/50year) following eqn. (1). (Q_{Net} in thick solid, $-Q_{50}$ in dash-dot, A_U in thin solid, A_V in dash, A_W in dot). The mean temperature (thick dash) is also plotted (scale on the right) for reference. The horizontal diffusion term is small and not shown. (c) and (d) are the same as (a) and (b), respectively, but for the linear trend (Wm^{-2}/50year).

off-equatorial divergence and upwelling. In the western Pacific, however, the warming trend is caused by the trend towards warm zonal advection, which corresponds to a reduction of the cold zonal advection. Ultimately, the reduction of oceanic advective cooling is caused by a trend of weaker surface wind stress (Fig.1b), which reduces the South Equatorial Current, the off-equatorial Ekman divergence and upwelling.

Discussions

The warming trend of the equatorial Pacific is shown to be caused directly by the reduction of cold oceanic advection, rather than by the increase of net downward surface heat flux. Therefore, changes in ocean dynamics are essential for explaining the long term trend of the observed equatorial SST. It is important to notice that the major terms contributing to the SST trend are not necessarily the same as those terms that provide the long term balance and explain the climatological mean SST. For the climatological mean, the surface heat flux is undoubtedly important in maintaining the surface equatorial SST against the cooling of upwelling water (Fig.3a,b). However, our study suggests that, in the last 50 years, the trend in net surface heat flux does not force the warming trend of SST directly.

The role of ocean advection is perhaps most intriguing in the western Pacific warm pool. Earlier studies of tropical SST regulation have focused on surface and atmospheric processes (Newell, 1979; Ramanathan and Collins, 1991; Fu et al., 1992; Wallace, 1992; Pirrehumbert, 1995). Ocean advection was thought to be unimportant in determining the long term SST change in the warm pool, because of the small net surface heat flux there (Ramanathan and Collins, 1991). Later studies, mainly based on theoretical and numerical models, suggest that oceanic advective processes could be important for explaining the long term tropical SST not only in the eastern Pacific, but also in the western Pacific (Sun and Liu, 1996; Liu and Huang, 1997; Cane et al., 1997). Our study provides a strong support for the latter view from an observational perspective. In spite of a nearly zero climatological net surface heat flux, the warming trend in the western Pacific warm pool is found to be caused mainly by the reduction of wind-driven cold oceanic advection. Furthermore, the temperature trend seem to respond to the long term trend of climatic forcing almost linearly. In a sensitivity experiment where only the linear trend of COADS atmospheric variables are used to calculate the forcing, the forced ocean temperature trend is virtually the same as in the full COADS forcing experiment that is discussed in Fig.2b and Fig.3 (not shown).

The causality diagnosis above is limited to the oceanic perspective. The ultimate cause for the climate trend, from a coupled ocean-atmosphere point of view, should also address why the trade wind is weakened in the last half century. Our study of the ocean heat budget analysis has important implications to the long term SST trend in the tropical Pacific coupled ocean-atmosphere system. The reduced cold oceanic advection may promote the Bjerknes ocean-atmosphere feedback (i.e., the surface warming may cause further reduction of trades) and therefore contribute to the accelerating tropical Pacific warming which has been observed in the last two decades (Lau and Weng, 1999). The weaker trade wind forces a SST warming trend that is stronger in the central/eastern Pacific than in the west; the accompanied reduction of west/east SST contrast should further reduce the trade wind. In addition, the reduction in west/east SST contrast and trade winds seem to be consistent with some coupled ocean-atmosphere model simulations that are forced by increased CO_2 (Knutson and Manabe, 1995; Meehl and Washington, 1996). This may imply that the recent warming is related to global warming. The warming trend may also be closely associated with the behavior change of El Nino. The trend of SST and trades are somewhat similar to those occurred during an El Nino event, both being characterized by a warmer central/eastern equatorial Pacific and a relaxed trade. Therefore, the warming trend may be caused by a trend of stronger warm El Nino event in the last two decades (Trenberth and Hoar, 1996). On the other hand, the pattern of SST trend also differs from that of El Nino, most noticeable in the western equatorial Pacific. The western Pacific SST shows little warming or even cooling during an El Nino event, but a rather comparable (about half) warming to the central/eastern Pacific for the trend (Fig.1, Table 1). In addition, the observed upper ocean temperature trend, with a warming in the upper thermocline and cooling in the lower thermocline (Fig.2), tends to shallow the equatorial thermocline, favoring stronger El Nino variability (Ziebiak and Cane, 1987). This trend in upper ocean temperature may therefore contribute to the seemingly enhanced El Nino activity in the last two decades. More careful analysis is needed to address the relationship of the warming trend and El Nino. Observations, ocean models and oceanic data assimilation should be improved to derive a better heat budget for the understanding of the SST trend.

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