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Short communication

The relationship between sea surface temperature anomaly and wind energy input in the Pacific Ocean

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Abstract

The relationship between sea surface temperature anomaly (SSTA) and wind energy input in the Pacific Ocean over the period of 1949–2003 is studied by using daily-mean NOAA/NCEP wind stress and monthly mean Reynolds SST data. The results indicate the strong negative correlation between SSTA and local wind energy input to surface waves in most of the domain at low and middle latitudes. The SST is low (high) during the years with more (less) wind energy input. The correlation coefficients are high in the central and eastern tropical Pacific and the central midlatitude North Pacific at the decadal scale, and in the central tropical Pacific at the interannual scale. Vertical mixing processes in the upper ocean are closely associated with wind energy input, indicating that wind energy input may play an important role in interannual and decadal variability in the Pacific Ocean via regulating vertical mixing.

Keywords: Wind energy; Interannual and decadal variability; SSTA; Vertical mixing

1. Introduction

It is well known that the Pacific Ocean exhibits prominent climate variations on interannual to interdecadal time scales, in which the interannual variation is primarily associated with the ENSO phenomenon [1], while the variability on time scales longer than interannual is dominated by the Pacific decadal oscillation [2–4]. Previous studies indicated that vertical mixing processes play an important role in these variations due to their strong effects on air–sea interactions. Miller et al. [5] argued that vertical mixing anomalies were one of the important factors inducing the 1976–1977 climate regime shift in the central Pacific. Wang and McPhaden [6] analyzed the surface-heat budget and suggested that mixing processes can affect interannual variability in the equatorial Pacific Ocean.

Vertical mixing processes in the ocean are sustained by external mechanical energy input from winds and tides [7–9]. Wind energy input plays a key role in regulating vertical mixing in the upper ocean. According to estimates in recent studies, wind energy input to the geostrophic current is roughly 0.9 TW in the global ocean [10,11]; those to the Ekman layer are 0.5–0.7 TW over near-inertial frequencies [12,13], and about 2.4 TW over sub-inertial ranges [14]. However, wind energy input to surface waves is estimated as 60–70 TW [15,16].

It is obvious that wind energy input to surface waves is much larger than the mechanical energy from other sources in the ocean. Recently, Huang et al. analyzed the mechanical energy budget to sustaining vertical mixing in the upper ocean, and found that near the surface the mechanical energy budget is dominated by surface waves, and the mixing induced by surface waves is overwhelmingly larger than those by other processes (to be published).

Over the past decades, wind energy input to the surface waves varied greatly at interannual and decadal time scales [15]. Since wind energy input varied greatly, the vertical

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mixing in the upper ocean should vary accordingly, which may affect sea surface temperature (SST) and then the climate system. The relationship between sea surface temperature anomaly (SSTA) and wind energy input to surface waves in the Pacific was examined in this study. Since mixing processes near the surface are primarily controlled by wind energy input to surface waves, it is hoped that our study can improve our understanding about the impact of vertical mixing on interannual and decadal variability in the Pacific Ocean.

2. Results

Surface waves can affect vertical mixing in the upper ocean through different physical processes, and some models have taken partly into account these effects, such as wave breaking [17], wave–turbulence interaction [18], and Langmuir cells [19]. However, there have been no models coupled with these effects in a comprehensive manner, so that a systemic model study is unfeasible at present. Therefore, the relationship between SSTA and wind energy input was studied through data analysis.

Wind energy input to surface waves was calculated using the method proposed by Wang and Huang [15], in which daily-mean wind stress data of NOAA/NCEP from 1949 to 2003 [20] was used. These wind stress data have a zonally uniform spacing of 1.875°, but a meridionally nonuniform spacing. SST is based on monthly mean data from NOAA/OAR/ESRL PSD from 1949 to 2003 with a resolution of $2° \times 2°$ [21]. These data have been interpolated linearly to the regular grids of $1° \times 1°$ in the calculation.

In the Pacific Ocean, SST has shown prominently interannual and decadal variability, in which decadal variability has its most outstanding signal in the midlatitude North Pacific, and interannual variability has its largest anomaly in the tropical Pacific. Moreover, there have also been notable decadal anomalies in the tropical Pacific and interannual anomalies in the midlatitude North Pacific [2,22]. Fig. 1 shows the spatial distribution of correlations between SSTA and local wind energy input to surface waves on decadal time scales. There have been significant negative correlations with values of up to 0.5 in the central and eastern tropical Pacific and the central midlatitude North Pacific, which are in rough agreement with the regions with the most outstanding anomalies in decadal variability. Correlations are positive in some regions, such as near the boundaries of the basin and in the Southern Ocean, indicating that the effect of wind energy input is not important for SSTA in these regions.

Five-year low-pass filtered SSTA, wind energy input in the central and eastern tropical Pacific (90°W–180°W and 15°S–15°N) and wind energy input in the central midlatitude Pacific (160°E–140°W and 30°N–45°N) from 1949 to 2003 are shown in Fig. 2. During the past decades, both SSTA and wind energy input exhibit prominent decadal variability in these two regions. Generally speaking, there is a low SST during the years with more wind energy input; and vice versa. The correlation coefficients between SSTA and wind energy input to surface waves are −0.74 in the central and eastern tropical Pacific, and −0.81 in the central midlatitude North Pacific. In other regions with prominent decadal variability, such as in the Atlantic Ocean [23], these significant negative correlations are also present. For example, the correlation coefficient between the 5-year low-pass filtered SSTA and wind energy input to waves is −0.63

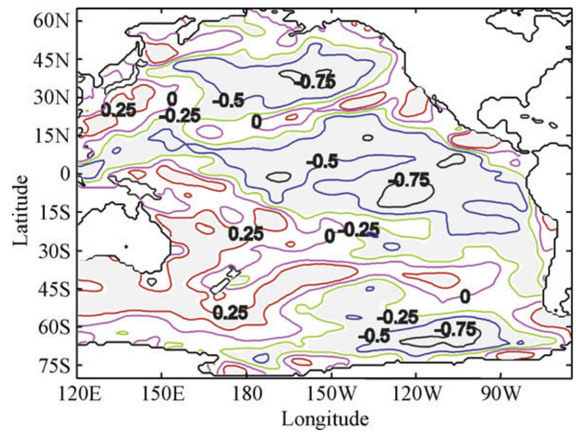

Fig. 1. Correlation coefficients between 5-year low-pass filtered SSTA and wind energy input to surface waves in the Pacific from 1949 to 2003. The shaded regions are significant at the 95% confidence level (±0.27).

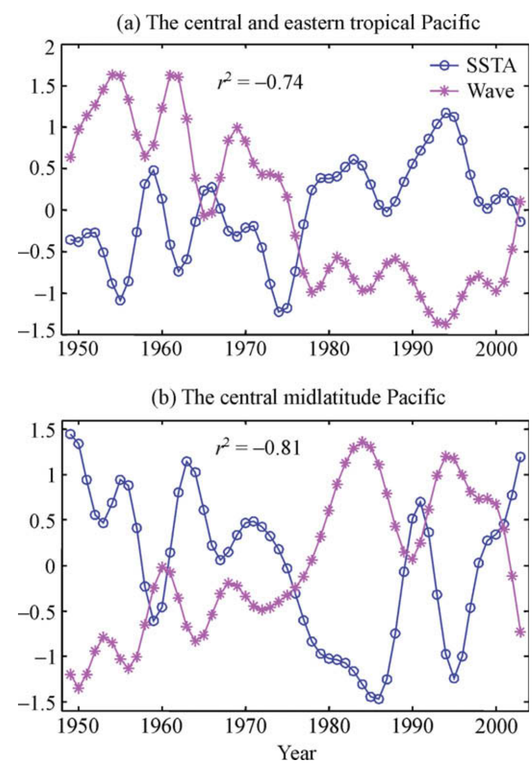

Fig. 2. The relationship between 5-year low-pass filtered SSTA and wind energy input to surface waves in (a) the central and eastern tropical Pacific (90°W–180°W, 15°S–15°N), and (b) the central midlatitude North Pacific (160°E–140°W, 30°N–45°N) (All data have been standardized; r^2 is the correlation coefficients between SSTA and wind energy input to surface waves).

in the Atlantic Ocean between 10°N and 20°N over the period of 1949–2003.

SSTA is also strongly correlated with local wind energy input at interannual scales (Fig. 3). The most significant correlation occurs in the central tropical Pacific Ocean. SSTA in the area of Nino3.4 (5°S–5°N and 120°W–170°W) is an index usually used in ENSO [24]. The correlation coefficient between the 5-year high-pass filtered SSTA and the local wind energy input to surface waves can reach −0.85 (Fig. 4). The negative correlations are significant at the 95% confidence level in the central midlatitude Pacific. However, the correlations are positive near the coast of South America and California.

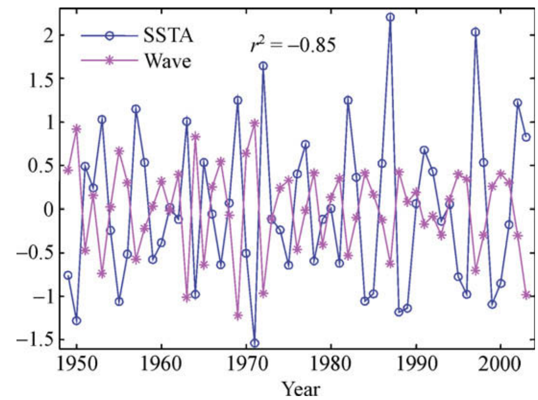

Fig. 4. As in Fig. 2, but in Nino3.4 and the data have been processed by a 5-year high-pass filter.

3. Discussion

The significant negative correlations between SSTA and local wind energy input to surface waves are mainly inferred from changes in vertical mixing associated with changes in wind energy input. Mixing processes in the upper ocean are sustained by wind energy input, and more wind energy input can result in stronger vertical mixing. Stronger mixing can transport more heat from the surface to the subsurface. Thus, there has been a low SST during the years with more wind energy input. On the contrary, during the years with less wind energy input, mixing is weaker so that solar radiation is cumulated within the surface layer and, therefore, results in a high SST.

On the other hand, changes in wind energy input can affect the oceanic circulation. For example, large wind energy input at low latitudes can enhance the meridional overturning circulation and poleward heat flux via regulating vertical mixing in the ocean interior [25], as well as mixed layer depth [26]. These processes can reduce SST in low latitudes and increase SST in the middle and high latitudes. During the past decades, the meridional overturning circulation in the upper Pacific had changed greatly and, thus, affected SST of the tropical Pacific [27], which may be partly due to changes of wind energy input.

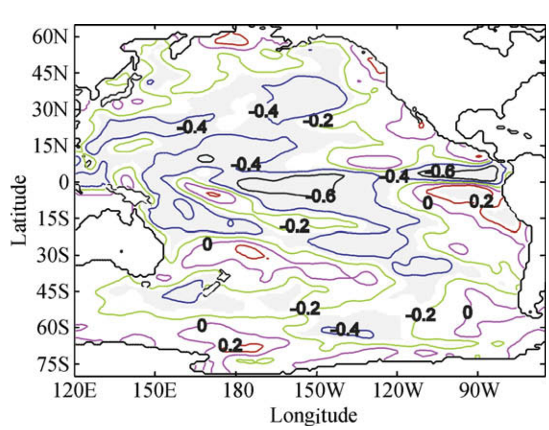

Fig. 3. As in Fig. 1, but the data have been processed by a 5-year high-pass filter.

Besides mixing processes, other factors, such as surface heat flux, advection, and large-scale waves, can also affect SST in the Pacific at interannual and decadal scales [5,22,28]. The correlation between SSTA and wind energy input is not significant (at the 95% confidence level) or positive in some regions (Figs. 1 and 3), which implies that their SSTs are primarily affected by other factors, instead of surface wave mixing. For example, decadal variability is dominated by surface heat flux input anomalies in the California coastal region because of its weak wind variability [5], while dominated by geostrophic current changes in the western North Pacific [29]. Moreover, the background thermal structure of the upper ocean is also important to reflect the effect of surface waves. It is believed that the mixing induced by surface waves is mainly confined to the upper oceans with a depth on the order of k^{-1} (k is the wave number) [30]. Thus, for the regions with large surface isothermal layers, such as at high latitudes and the western equatorial Pacific [31], the effect of surface waves is not so evident.

The amount of wind energy input to surface waves is mainly determined by the magnitude of wind stress [15]. In fact, the impact of local wind stress on SST has been noticed in previous studies, which argued that interannual and decadal variability in the Pacific is primarily induced by changes of the local wind stress [22,32,33]. However, these studies emphasized the effects of changes in horizontal advection, latent and sensible heat flux associated with changes in wind stress; the effect of changes in vertical mixing on SST is ignored or not considered sufficiently.

It should be pointed out that wind energy input in the tropical Pacific and the midlatitude North Pacific has a significant negative correlation (Fig. 2). Wind energy input to surface waves decreased by about 28% from 2.94 TW in the 1950s to 2.12 TW in the 1990s in the tropical Pacific, while at the same time it increased by 14% from 3.88 to 4.41 TW in the midlatitude Pacific. In these two regions the correlation coefficients of the 5-year low-pass filtered wind energy input can reach −0.85 over the period of 1949–2003. The relationship may be due to the difference of the pattern of wind stress in these regions [22]. Since mixing processes near the surface are primarily dominated by wind energy input to surface waves (unpublished data), it implies that the phase of local mixing is opposite in the tropical Pacific and the midlatitude North Pacific, which may explain partly the phenomenon of opposite phase in SSTA between the tropical Pacific and the midlatitude North Pacific on decadal time scales.

As the origin of interannual and decadal wind stress variability, it is beyond the scope of this study. Moreover, it should be noted that we have not made an attempt to explore the cause of interannual and decadal variability in the Pacific; instead, our results suggest that wind energy input to surface waves can affect interannual and decadal variability via regulating vertical mixing near the surface.

4. Conclusions

Wind energy input is an important constituent of mechanical energy budget in the ocean. Mixing processes near the surface are closely associated with wind energy input to surface waves. Changes in wind energy input can regulate mixing processes and, therefore, affect SST. The relationship between SSTA and local wind stress in the Pacific Ocean was studied from a mechanical energy budget point of view in this paper. The results showed that there has been a prominently negative correlation between SST and local wind energy input in most of the domain at low and middle latitudes. Generally, there has been a low SST during the years with more wind energy input, and vice versa. This implies that wind energy input to surface waves has an important impact on interannual and decadal variability via regulating the wave mixing process in the upper ocean. Thus, changes of the wind energy input (or vertical mixing) must be considered sufficiently in future studies on interannual and decadal variability.

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