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Interannual variability of summer coastal upwelling in the Taiwan Strait

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ABSTRACT

This study dealt with the interannual variability of summer coastal upwelling in the Taiwan Strait, based on empirical orthogonal function (EOF) analysis. Three datasets were used for the analysis: the National Oceanic and Atmospheric Administration (NOAA), Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature dataset from 1985 to 2005; hydrographic records at two coastal stations from 1970 to 2001; and cruise measurements in 1988 and 2004. The results indicated that the first mode (85.3%) of the spatial variance showed a persistent front, which was generally aligned north-east–southwestward in the western Taiwan Strait. This front separated colder water on the west side from warmer water on the east side. The eigenvector time series showed that the variability of this front with time was closely correlated with the change in the wind stress anomaly of the alongshore wind component, derived from 17 years of the European remote sensing (ERS) satellite and QuickScat wind dataset from 1992 to 2005. Records of water temperature and salinity anomaly at Pingtan Island (Is.) located in the northwestern Taiwan Strait, and Dongshan Is. located in the southwestern Taiwan Strait, showed that a negative temperature anomaly appeared along with a positive salinity anomaly in some years. This suggested a dominant influence of cold and saline upwelling water at the surface. The years of notable cooling events derived from the station measurements were generally consistent with the time series of the EOF Mode 1. The change in upwelling derived from cruise measurements further confirmed the change shown by the EOF Mode 1 time series. These 1985–2005 results indicated that for the entire western Taiwan Strait summer coastal upwelling was strong in 1987, 1993, and 1998, and that upwelling in the northwest and the southwest Taiwan Strait showed different behavior. A delayed ENSO (El Niño Southern Oscillation) effect was suggested as a major mechanism for the interannual variability of Taiwan Strait coastal upwelling.

1. Introduction

Previous investigations indicate that coastal upwelling ecosystems, such as the Peruvian (Chavez and Barber, 1987), the Californian (Pennington and Chavez, 2000), and the Benguelan upwelling systems (Shannon, 1985) have great ecological significance since, as a result of their cold, nutrient-rich water and high biological production, they make a significant contribution to marine fisheries. All coastal upwelling ecosystems vary with the time scales of wind stress. Interannual variability is of most concern, since it contributes to variability in biological productivity. The Peruvian upwelling system is a typical example. During El Niño years, the trade winds weaken or reverse, resulting in a significant decline of fish stock along the Peruvian coast (Barber et al., 1985).

The Taiwan Strait (TS) is a shallow shelf channel that connects the South China Sea (SCS) with the East China Sea (ECS) as shown in Fig. 1. In summer, the prevailing southwest monsoon facilitates the northward transport of warm, saline, and oligotrophic water from the SCS to the ECS (Wang and Chern, 1988; Jan et al., 2002, 2006). Meanwhile, upwelling along the west coast of the TS develops, driven by the prevailing southwest monsoon which runs parallel to the coast due to Ekman transport (Brink, 1983; Hu et al., 2003). Upwelling cools and injects nutrients into the upper water, thus contributing to local fisheries. In addition, the rivers distributed on the west coast (Min R., Jin R., Jiulong R. and Han R.; Fig. 1) provide warm fresh water to the TS. Thus, there are three major factors controlling summer hydrographic conditions in the TS: warm and saline SCS water, cold and saline upwelling water, as well as warm and fresh river runoff.

Shang et al. (2004) report short-term variability of coastal upwelling and associated chlorophyll *a* changes in the TS, based on SeaWiFS chlorophyll *a* data, AVHRR sea surface temperature (SST) images, and field measurements taken in August 1998. They

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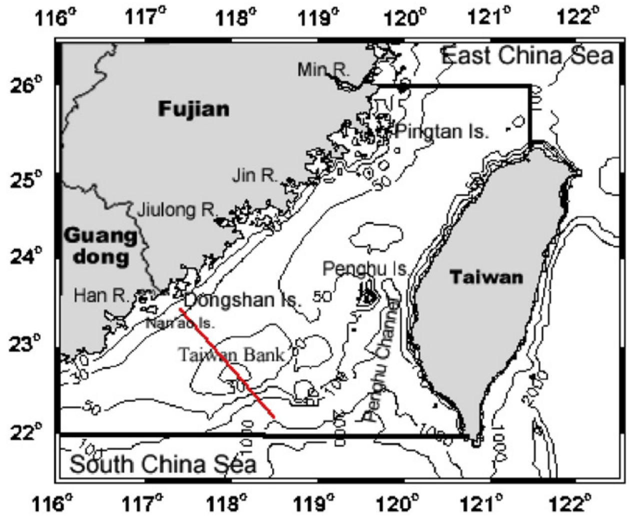

Fig. 1. The Taiwan Strait. The area enclosed by the solid lines and the coastlines of the China mainland and Taiwan was used to estimate the average properties in the Strait.

show that large areas of eutrophic waters (SeaWiFS Chl $\geqslant 1\,mg/m^3$) are always accompanied by colder upwelling waters (indexed by AVHRR SST 1 °C colder than the spatial mean SST over the whole TS), implying a close relationship between chlorophyll concentration and the development of upwelling. Upwelling behavior in the north TS is different from that in the south, implying that they are generated by different mechanisms, i.e., the one in the north is closely connected with the circulation system in the ECS and the one in the south with the SCS. Tang et al. (2004) analyze the interannual variability of two summer upwelling zones, one in the vicinity of the Taiwan Bank and another near Dongshan Is., and note that the area of the upwelling zone near Dongshan Is. is larger in 1989, 1990, 1993, and 1995, and that the mean SST of this zone is lower in most cases.

These previous studies provide a preliminary scenario regarding the temporal variability of upwelling in the TS. However, many questions still remain unanswered. For instance, how does coastal upwelling respond to the interannual variability of the monsoon winds? Do differences of upwelling in the south and the north TS occur on an interannual scale? Do ENSO events have any effects on upwelling? The answers to these questions are of significance to the management and protection of fishery resources and to the environment. This study aimed to find the answers to these questions. EOF methods were used to analyze remotely sensed SST fields from 1985 to 2005. The results, combined with analyses of hydrographic station records from 1970 to 2001, 2 years of cruise data, and remotely sensed wind data, were used to reveal the variability and mechanisms of upwelling in the TS.

2. Data and methods

In this study, the TS was defined as the ocean area enclosed by the China mainland coastline, the west coastline of Taiwan Is., and latitudes 22°N, and 26°N, as shown in Fig. 1. The monthly mean SST data used in this study were derived from NOAA AVHRR Pathfinder SST products for 1985–2005, with a spatial resolution of 4 by 4 km. The monthly mean wind stress data were retrieved from the ERS satellite and Quik Scatterometer (QuikSCAT) observations from 1991 to 2005. The spatial resolution was 1 by 1° for ERS winds, and 0.25 by 0.25° for QuikSCAT winds. The summer (June, July and August) averages of each pixel in each year were calculated, and then from these averages the spatial means over the TS were derived. The mean wind stress vectors were further decomposed into alongshore and cross-shore components. The temporal anomalies of the alongshore wind stress were thus calculated as deviations from the area-averaged summer climatological means. Spatial anomalies of SST were calculated as the difference of the SST value at each AVHRR pixel from the mean SST value over the TS. In order to extract the principal components accounting for the most dominant interannual variation of SST, the EOF analysis was applied to the spatial SST anomaly fields by adopting the approach of Lagerloef and Bernstein (1988).

The field data used in this study included the records of the daily coastal SST and sea surface salinity (SSS) at Pingtan Is. and Dongshan Is. from 1970 to 2001, and conductivity–temperature–depth profiles observed in summer 1988 and 2004 along a transect in the south TS, marked as a red line in Fig. 1. The summer averages of SST and SSS at Pingtan Is. and Dongshan Is. for each year were calculated, and then the SSTA and the temporal anomalies of SSS (SSSA) were calculated as deviations from the summer climatological means for 1970–2001. The occurrence of El Niño events were inferred from the overlapping bimonthly mean multivariate ENSO index (MEI), promulgated by the NOAA Climate Diagnostic Center (Wolter, 2004).

3. Results and discussion

3.1. Spatial EOF modes of SST fields

The first EOF mode accounted for 85.3% of the SST spatial variance. Its amplitude function showed strong temperature gradients, including one aligned northeast–southwest along the western coast, one in the vicinity of Penghu Is., and another along the Penghu Channel as shown in Fig. 2a. The strong temperature gradients close to Pingtan Is. and Dongshan Is. were consistent with the boundaries of coastal upwelling zones revealed by cruise investigations (Hong et al., 1991). The strong gradient close to Penghu Is. was probably induced by island steering (Simpson and Tett, 1986). The strong temperature gradient along the Penghu Channel showed the boundary of the northward flow of the SCS warm water into the TS (Jan and Chao, 2003; Liang et al., 2003).

The behavior of this mode in a time domain was represented by its eigenvector as shown in Fig. 2b. One can see that there were three maxima in 1987, 1993, and 1998, and three minima in 1994, 2001, and 2004. The variation of the EOF Mode 1 after 1992 was correlated with the alongshore wind stress anomaly, with a correlation coefficient (r) of 0.632 (Fig. 2c, 0.514 for 95% significance and 13 degrees-of-freedom), indicating the wind-driven nature of the coastal upwelling. Additionally, the second and third modes (not shown) accounted for 1.9% and 1.3% of the spatial variance, respectively; implying that these higher modes were little related to the main oceanographic features in this region.

3.2. Long-term variability at Pingtan Is. and Dongshan Is

Fig. 3 shows a 32 year record of the SSTA and SSSA at Pingtan Is. and Dongshan Is from 1970 to 2001. The appearance of negative SSTA along with positive SSSA suggested a dominant influence of cold and saline upwelling water at the surface. Considerable cooling along with a positive SSSA at Pingtan Is. occurred in 1983, 1987 and 1993, when SSTA $\leqslant -0.5$ °C, indicating the occurrence of strong summer upwelling.

On the other hand, strong upwelling events (SSTA $\leqslant -0.5$ °C) occurred in 1977 and 1987 at Dongshan Is. A strikingly high value of SSSA (+1.6) accompanied by an SSTA of -0.2 °C appeared in

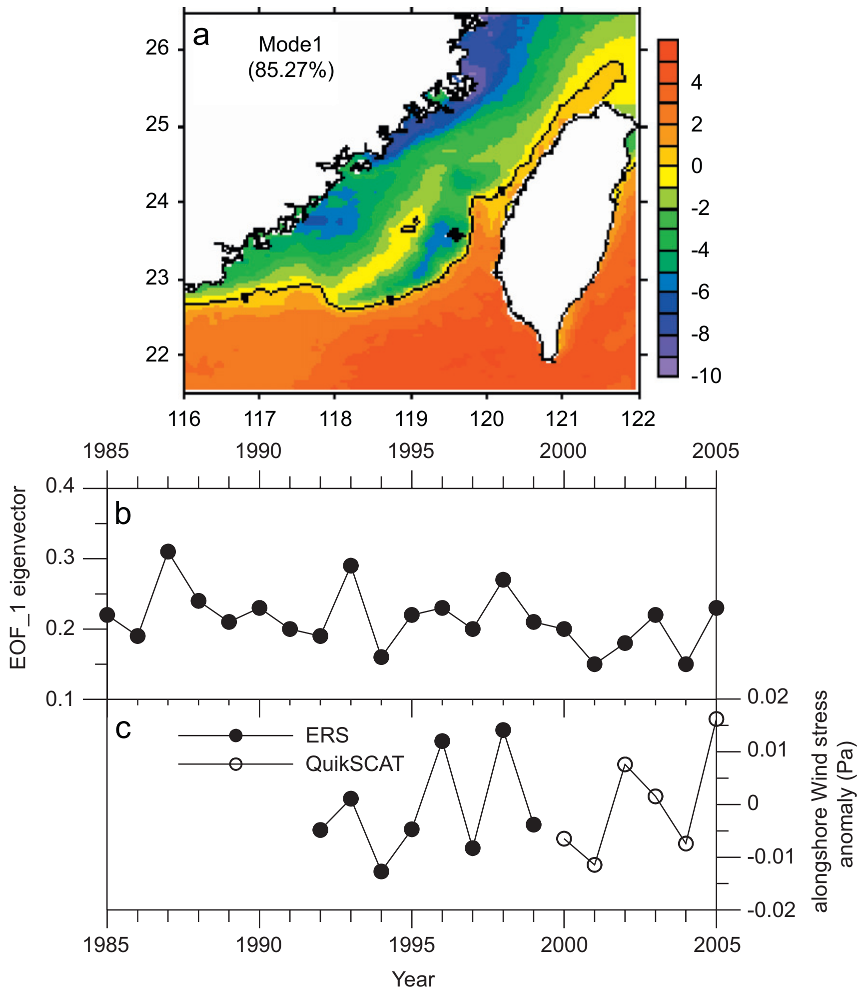

Fig. 2. (a) Image pattern for the first spatial variance EOF mode amplitude function; (b) its corresponding EOF eigenvector; (c) the alongshore wind stress anomaly.

1998. Such a high value of SSSA indicated a strong influence of upwelling water; but considerable cooling did not occur. The relatively small SSTA (−0.2 °C) in 1998 was probably associated with the warm event (SSTA ⩾+0.5 °C) which occurred in the SCS, from where the upwelling water near Dongshan Is. originates (Li and Li, 1989). The warm event lasted for 18 months from spring 1997 to spring 1999, and was the strongest one on record over the past few decades (Wang et al., 2002). This is the reason why the upwelling became warmer.

The variation of SSTA and SSSA at the two sites was further compared with the EOF Mode 1 eigenvector. Obviously the occurrence of strong upwelling events in 1987, 1993 and 1998 was reflected in all the SSTA and SSSA series (Fig. 3). The eigenvector was negatively correlated with SSTA, with a correlation coefficient (r) of −0.63 and −0.69 for Dongshan Is. and Pingtan Is., respectively. It was positively correlated with SSSA, with a correlation coefficient (r) of 0.58 and 0.45 for the two sites. All the correlation coefficients were significant at the 95% level based on a t-test.

The different behavior of upwelling in the vicinity of Pingtan Is. from that in the vicinity of Dongshan Is. agreed with the previous findings concerning different short-term variation patterns of coastal upwelling in the north and south portions of the west TS (Shang et al., 2004). A possible reason was that the upwelled water was supplied from different sources. The temperature–salinity (T–S) diagram of the two stations (Fig. 4) can serve as evidence. One can see that the data points of the two stations occupy quite different areas even though there is an overlapping area around 26 °C and 33.5 psu. This indicated that the waters in the two upwelling zones were from different sources.

When a positive SSTA appeared, the situation became complicated, since this possibly implied either a weakened upwelling; or that more warm water was supplied by river runoff if the SST anomaly was associated with a negative SSSA; or that more warm water was supplied by an intensified intrusion of the SCS warm current, if this was associated with a positive SSSA. Further investigation is necessary in order to clarify the relationship of these warm events to various forcings. The warmest events (SSTA ⩾+0.5) coincided with a negative SSSA, which implied the dominance of warmer and less saline water at the surface, at Pingtan Is. in 1978 and 2001, and at Dongshan Is. in 1986, 1994 and 2001.

3.3. *Interannual variability derived from cruise measurements*

Cruise surveys, along an offshore transect starting from the Dongshan Is. area in the south TS (marked as a red line in Fig. 1), were repeated in 1988 and 2004. Two-dimensional distribution of temperature (T) and salinity (S) along the transect derived from these measurements is shown in Fig. 5. One can see clearly the difference in T and S between these 2 years. In 1988 (top two panels), cold and saline water with $T<22$ °C and $S>34.5$ occupied the water column below 10 m of the near shore section of the

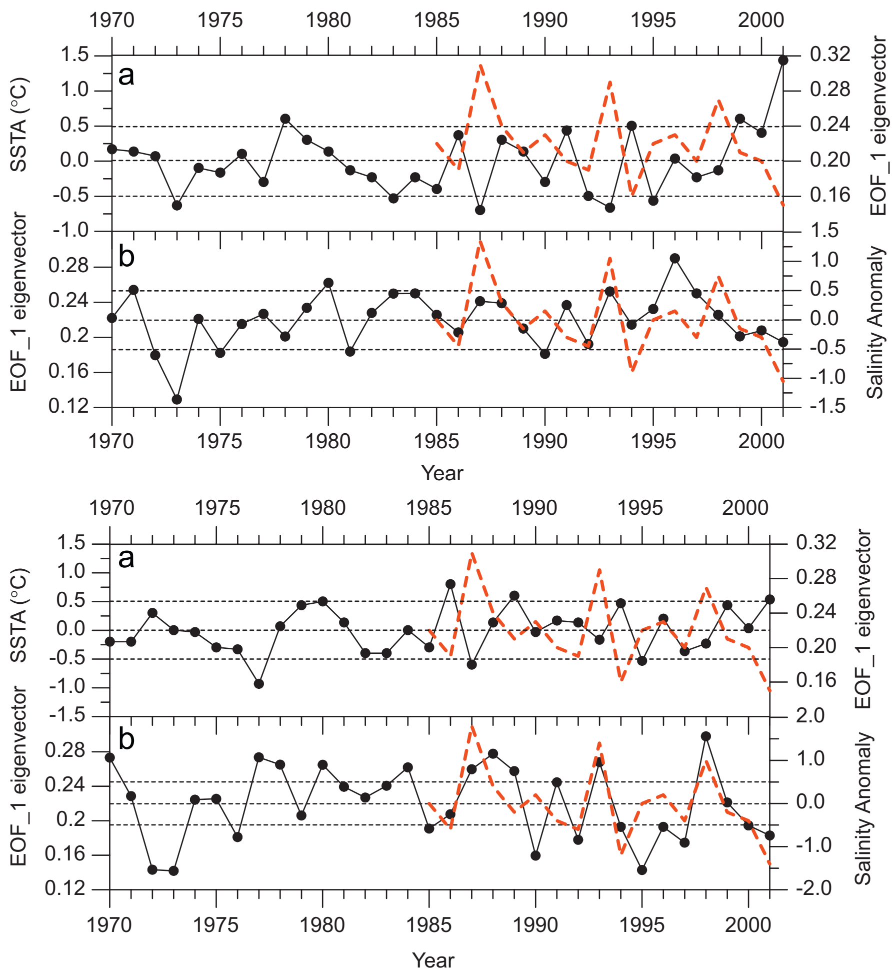

Fig. 3. Interannual changes of SSTA (a) and SSSA (b) during the summer at Pingtan Is. (top panel) and Dongshan Is. (bottom panel) from 1970 to 2001. Dashed red lines are the eigenvector of the first spatial variance EOF mode.

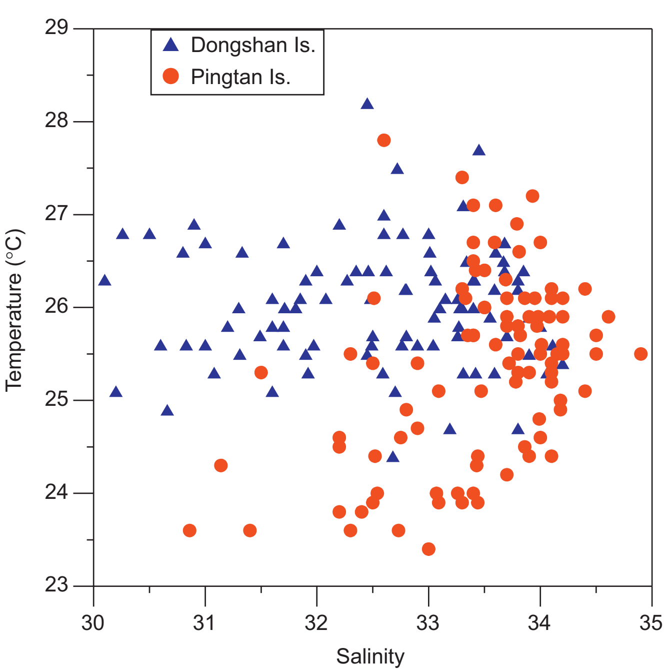

Fig. 4. Temperature–salinity diagram of the waters at Pingtan Is. and Dongshan Is. hydrological stations. The data points are summer (June, July and August) monthly means taken from 1970 to 2001.

survey transect (on the left). The 24 °C isobath was lifted towards the surface while approaching the Dongshan Is. area. In contrast, in 2004, warmer and less saline water (T~26 °C, S~34) occupied the same water column. At the surface T was ~24 °C and S was ~34 in 1988, while in 2004 these values became ~28 °C and ~ 33.5. The reasons leading to these differences might be complex. One possibility is that the coastal upwelling was stronger in 1988 than in 2004, which was consistent with the interannual variability given by EOF Mode 1 as shown in Fig. 2b.

3.4. Correlation with ENSO

This study demonstrated that for the entire western TS, coastal upwelling had considerable interannual variability. Comparison of SST EOF Mode 1 eigenvector with the MEI time series shown in Fig. 6 indicated that in the year subsequent to the onset of a strong El Niño event, a strong summer upwelling event occurred in the west TS, regardless of whether the El Niño event persisted throughout the entire year. Previous investigators suggest that the East Asian summer monsoon is always weaker at the peak of El Niño, but becomes stronger when El Niño starts to decay (Wang et al., 2001; Chen, 2002). This suggested that the stronger southwesterly wind in the summer subsequent to an El Niño onset in the previous year drove a stronger northward warmer SCS current and a stronger coastal upwelling, resulting in greater SST gradients in the west TS. Statistical analysis revealed that the EOF

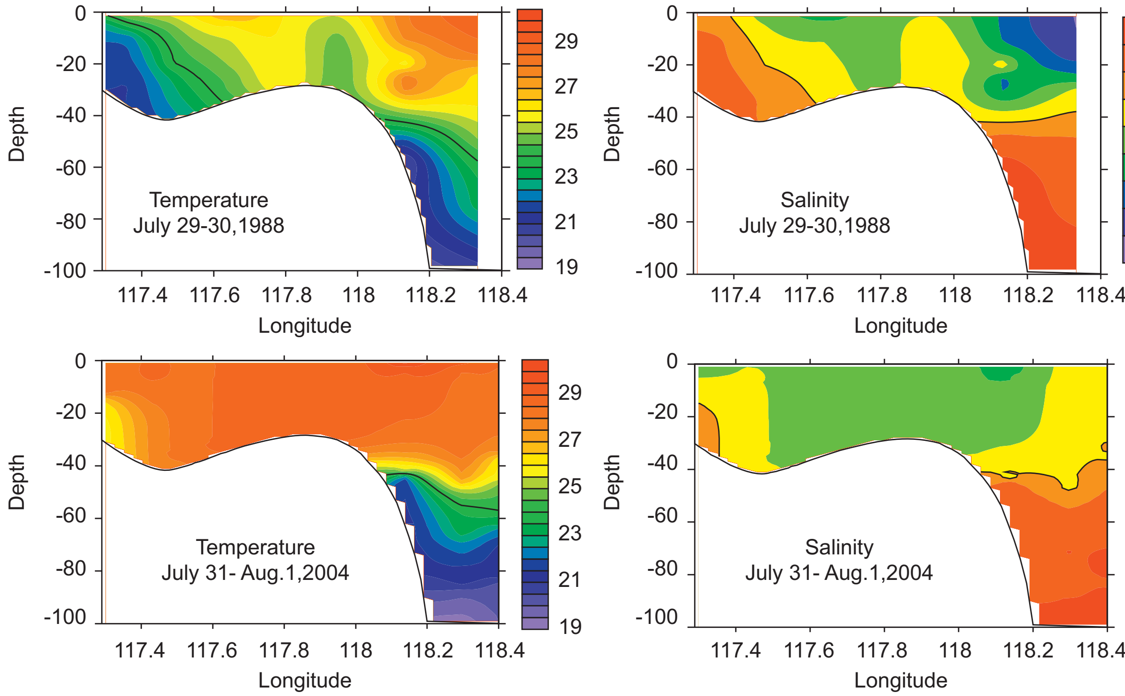

Fig. 5. Two-dimensional distribution of temperature and salinity along the cruise transect in the south Taiwan Strait (the location marked as a red line in Fig. 1) during July 29–30, 1988 (top panels) and July 31–August 1, 2004 (bottom panels).

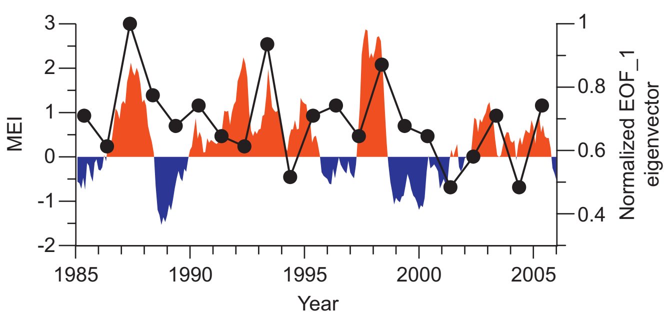

Fig. 6. Variation of the eigenvector of SST EOF Mode 1 in the Taiwan Strait (black dots) and monthly MEI three months ahead of the EOF eigenvector (shaded areas) for the period 1985–2005. The EOF eigenvector is normalized with its maximum for the period 1985–2005.

Mode 1 time series is correlated with MEI with a time lag of 3–6 months (Fig. 7, 0.413 is significant at the 95% level for 21 degrees-of-freedom). A delayed ENSO effect was thus likely to be a major mechanism contributing to the TS summer coastal upwelling variability.

Kuo and Ho (2004) and Shang et al. (2005) suggest that ENSO events can affect wind patterns in the TS, thereby modulating the sea surface currents and resulting in SST changes at an interannual scale. Li et al. (2007) note that the intensity of the SCS warm pool is highly correlated with MEI with a time lag of 3–12 months. These conclusions are consistent with the results of this study, i.e., the interannual variability of TS coastal upwelling is a local response to ENSO events.

4. Conclusion

Spatial EOF decomposition was carried out on the remotely sensed SST field from 1985 to 2005. Dominant Mode 1 suggested that coastal upwelling was strong in 1987, 1993 and 1998, and weak in 1986, 1994, 2001 and 2004. Hydrographic records measured at Pingtan Is. and Dongshan Is. from 1970 to 2001 showed different temporal behavior of upwelling at the two sites. Cruise measured two-dimensional T and S profiles obtained along a transect in the south TS in 1988 and 2004 suggested weaker upwelling in 2004 compared to 1988, which coincided with the trend shown by the eigenvector of EOF Mode 1.

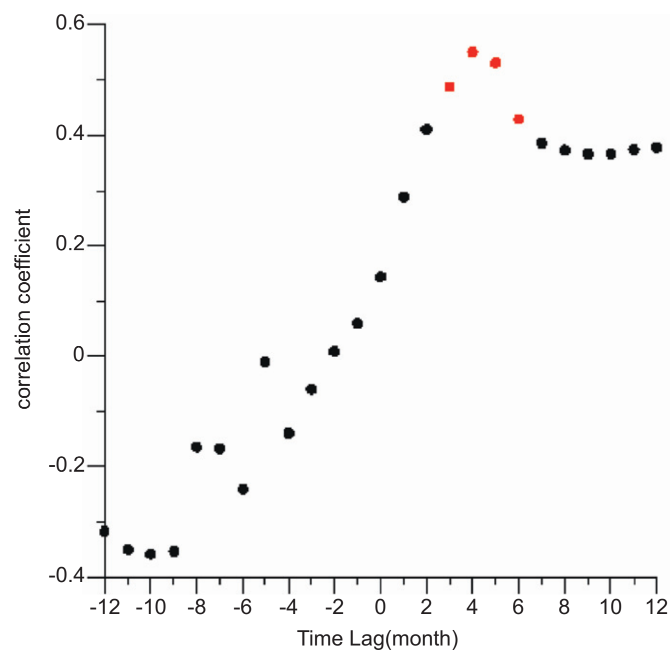

Fig. 7. Correlation coefficients (r) between MEI and the eigenvector of SST EOF Mode 1 versus time lag; red dots refer to the r values of statistical significance (0.413 is significant at the 95% level for 21 degrees-of-freedom)

In conclusion, for the entire west TS, summer coastal upwelling had notable interannual variability. Wind variations were responsible for the interannual variability of the upwelling through Ekman transport. The upwelling was stronger in years when the southwesterly winds in the TS were intensified. The wind variations can be traced back to the anomaly of the East Asian Monsoon, which developed after ENSO onset in the previous year. Also, the temporal variability of upwelling in the northwestern TS was different from that in the southwestern TS, implying different sources of upwelled water in the two zones. Further research is needed in order to better understand these phenomena.

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