Journal of
Marine Science and Technology

Volume 20 | Issue 6 Article 14

# INTERANNUAL VARIABILITY OF WINTERTIME SEA SURFACE TEMPERATURES IN THE EASTERN TAIWAN STRAIT

Mu-Tun Tzeng
*Department of Environmental Biology and Fisheries Science, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.*

Kuo-Wei Lan
*Center of Excellence for Marine Bioenvironment and Biotechnology, Keelung, Taiwan, R.O.C.*, d96310002@mail.ntou.edu.tw

Jui-Wen Chan
*Taiwan Ocean Research Institute, National Applied Research Laboratories, Kaohsiung, Taiwan, R.O.C.*

Recommended Citation
Tzeng, Mu-Tun; Lan, Kuo-Wei; and Chan, Jui-Wen (2012) "INTERANNUAL VARIABILITY OF WINTERTIME SEA SURFACE TEMPERATURES IN THE EASTERN TAIWAN STRAIT," *Journal of Marine Science and Technology*: Vol. 20: Iss. 6, Article 14.
DOI: 10.6119/JMST-012-0913-1
Available at: https://jmstt.ntou.edu.tw/journal/vol20/iss6/14

# INTERANNUAL VARIABILITY OF WINTERTIME SEA SURFACE TEMPERATURES IN THE EASTERN TAIWAN STRAIT

## Acknowledgements

This study was financially supported by the National Science Council, Taiwan (NSC100-2621-M-019-001 and NSC100-2611-M-019-005) and the Center of Excellence for Marine Bioenvironment and Biotechnology at National Taiwan Ocean University. The authors especially thank Changtai Shih of National Taiwan Ocean University for his assistance in revising the manuscript.

*Journal of Marine Science and Technology, Vol. 20, No. 6, pp. 707-712 (2012)*
DOI: 10.6119/JMST-012-0913-1

# INTERANNUAL VARIABILITY OF WINTERTIME SEA SURFACE TEMPERATURES IN THE EASTERN TAIWAN STRAIT

Mu-Tun Tzeng[1], Kuo-Wei Lan[2], and Jui-Wen Chan[3]

Key words: eastern Taiwan Strait, empirical orthogonal function, sea surface temperature.

## ABSTRACT

Using Advanced Very High Resolution Radiometer (AVHRR) sea surface temperatures (SSTs) at a 1.1-km spatial resolution, we investigated the long-term SST variability in winter in the eastern Taiwan Strait (TS) in 1995~2008. We performed an empirical orthogonal function (EOF) analysis of spatial and time series variances for 15-day mean images.

The first three modes in the EOF analysis respectively accounted for 25.9%, 16.61% and 4.59% of variances. In the first mode, the spatial amplitude showed positive values in the northeastern TS and negative values south of Chang-Yuen Rise (CYR). This suggests that warmer water occurred south of the CYR and a southwesterly intrusion of cold water extended north of study area. In the second mode, the lowest SSTs appeared over the CYR from the middle of December to the end of January. Results of the EOF analysis revealed heat exchange and the formation of an oceanic front boundary at the CYR in winter. We also found that average SSTs at the CYR were highly and positively correlated with latitudinal variations of 20°C isotherm, implying that variations in SSTs at the CYR could be applied to examine variation in the China Coastal Current in the eastern TS.

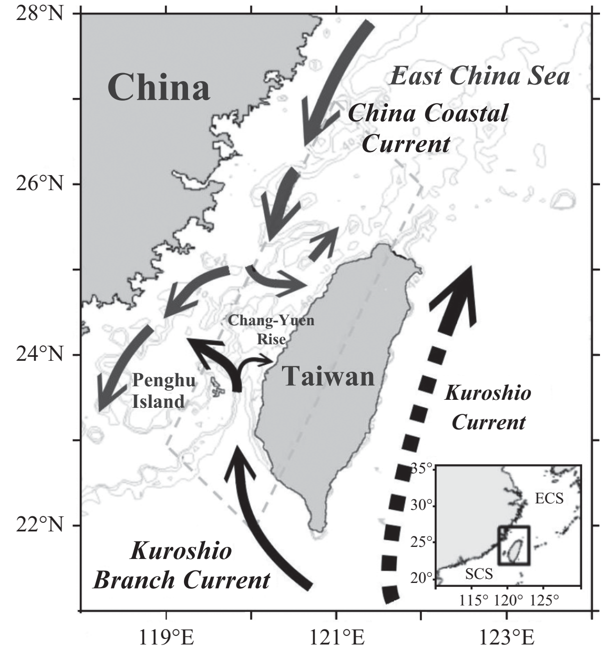


**Fig. 1. Map of the bottom topography and oceanic current flow patterns of the Taiwan Strait in winter. The black contours are the isobars in meters. The study area was within the dashed box. Gray and black arrows respectively indicate the China Coastal Current and Kuroshio Branch Current, and dashed arrows indicate the Kuroshio Current (redrawn from Jan *et al*. 2002).**

## I. INTRODUCTION

The Taiwan Strait (TS) is a channel connecting the East China Sea with the South China Sea in the western North Pacific Ocean between Taiwan and Mainland China (Fig. 1). A distinct topographic feature in the TS is the Chang-Yuen Rise (CYR), which extends westward from the middle of the west coast of Taiwan. It separates the TS into two basins, and forms a barrier for the ocean circulation : China Coastal Water in the north, and the South China Sea Warm Current and Kuroshio Branch Current in the south [15]. In winter, the flow patterns shown in Fig. 1 reveal that the main China Coastal Current in the western TS moves southward along the Chinese coast [8, 15]. A portion of the China Coastal Current is blocked by the CYR and turns back northward at the expense of southward intrusion (gray arrows in Fig. 1). Meanwhile the Kuroshio Branch Current from the Penghu Channel is blocked at the CYR (black arrows in Fig. 1) [7, 8].

---

*Paper submitted 01/31/12; revised 02/28/12; accepted 09/13/12. Author for correspondence: Kuo-Wei Lan (e-mail: d96310002@mail.ntou.edu.tw).*

[1] *Department of Environmental Biology and Fisheries Science, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.*

[2] *Center of Excellence for Marine Bioenvironment and Biotechnology, Keelung, Taiwan, R.O.C.*

[3] *Taiwan Ocean Research Institute, National Applied Research Laboratories, Kaohsiung, Taiwan, R.O.C.*

Sea surface temperatures (SSTs) are one of the most basic oceanographic parameters associated with climate and weather systems. With increasing availability of satellite SST data, it has become possible to monitor temporal and spatial variations in SSTs. At present, the Advanced Very High Resolution Radiometer (AVHRR) on board NOAA polar-orbiting satellites is the most popular instrument for regional/global SST retrieval [14]. It has been functioning since 1978 with three infrared channels [1]. Lee *et al*. [14] showed that the AVHRR derived-SSTs through Multi-Channel and nonlinear SST algorithms were linearly related to in situ SSTs with correlation coefficients of 0.985 and 0.98, respectively, and proved that AVHRR-based SSTs were highly accurate in the seas around Taiwan. In waters around Taiwan, remotely sensed SSTs were applied to oceanography, such as SST variability [2, 9, 15], fronts [3, 11], and marine ecology [6, 13].

Previous studies showed that SST patterns in the TS are more complicated in winter than summer [9, 15], and large-scale climatic oscillations such as El Niño-Southern Oscillation (ENSO) events can also cause SST changes on an inter-annual scale [2, 9]. The purpose of the present study was to investigate and describe long-term variability of wintertime SSTs in the eastern TS at 119.0°~122.0°E and 22.0°~27.0°N (dashed box in Fig. 1) with satellite SSTs at a 1.1-km spatial resolution. The bathymetric features are more complex in the eastern TS including the CYR (< 50 m), Taiwan Bank (< 50 m), and Penghu Channel (< 100 m). The empirical orthogonal function (EOF) analysis used in this study decomposed the time-series dataset into its orthogonal component modes and demonstrated dominant patterns of SST variability [10, 15].

## II. MATERIALS AND METHODS

### 1. High-Resolution Satellite SSTs

The High Resolution Picture Transmission (HRPT) data of the NOAA-12~19 including AVHRR scenes were received at a ground station of National Taiwan Ocean University.

High-resolution (1.1 km) SST images were produced by the Multi Channel SST algorithm [17]. The bias and root of the mean square between AVHRR and in situ data were 0.01 and 0.64°C respectively in waters around Taiwan [14]. All received images of HRPT data for winter (November~February) from 1995 to 2008 were processed for this study. Because the availability of daily AVHRR SSTs is seriously reduced by cloud coverage, we produced 15-day mean images during the study period and removed images for which missing data (due to cloud cover) exceeded 25%.

In totally, 99 images of 15-day means with good coverage were selected and used for the EOF analysis. EOF decomposition requires a dataset without gaps. Therefore, missing data were replaced using the distance weight interpolation (a raster-based interpolation) [21]. Data were normalized by dividing each pixel by the standard deviation of the time series [18].

### 2. EOF Analysis

The EOF analysis provides a compact description of the spatial variability of time-series data in terms of orthogonal functions or statistical modes [4].

Satellite SST data in the EOF analysis were arranged in a two-dimensional array, an M × N matrix, $T(x, t)$, where M is the number of elements in the spatial dimension (in this case, the number of pixels in an image), and N is the number of elements in the temporal dimension (in the case the number of images). Paden *et al*. [20] suggested that the removal of the temporal means of the data matrix be performed before the EOF analysis.

Removal of the temporal means revealed features that strongly varied in time and space. In this study, the temporal mean was removed by finding the mean over the time-series at each pixel, and subtracting the mean from each pixel (Eq. (1)).

$$T'(x,t) = T(x,t) - \frac{1}{N}\sum_{t=1}^{N} T(x,t) \tag{1}$$

Amplitude scores of $T'(x, t)$ SST images were used to decompose the data matrix using the singular-value decomposition method to elucidate spatial patterns and time-series variations of SSTs in the eastern TS. These analyses were described in detail by Emery and Thomson [4] and Lee *et al*. [15]. Following North *et al*. [19], we only considered a mode to be significant if the sampling error [λ(2/N)0.5] of its associated eigenvalue, λ, was smaller than the space between λ and a neighboring eigenvalue, where N is the number of realizations on each mode of EOF analysis.

## III. RESULTS AND DISCUSSION

Only the first three modes were selected in the EOF analysis due to the sampling error of its associated eigenvalue was smaller than the space between eigenvalue and a neighboring eigenvalue. The first three modes in the EOF analysis respectively accounted for 25.9%, 16.61% and 4.59% of variances, (Fig. 2). Figs. 2~4 depict the spatial amplitude patterns and temporal variations of the first three EOF modes. In the first mode, the spatial amplitude showed positive values in the northeastern area of our study and negative values south of the CYR (Fig. 2).

The intra-seasonal variation of the eigenvectors (Fig. 3(a)) showed a decreasing trend from November to February and the time series variation of the eigenvectors (Fig. 4(a)) also varied from positive to negative values in each year. It indicated that SSTs in the study area were dominated by a unique pattern in winter. This indicates that warmer water was located to the south of CYR and a southwestward intrusion of cold water covered the northeastern portion of the study area (Fig. 5(a)). Wu *et al*. [24] reported that the CYR blocks part of China Coastal Current and forces a U-shaped flow pattern in the northern TS in winter. The isopleths line of zero in the

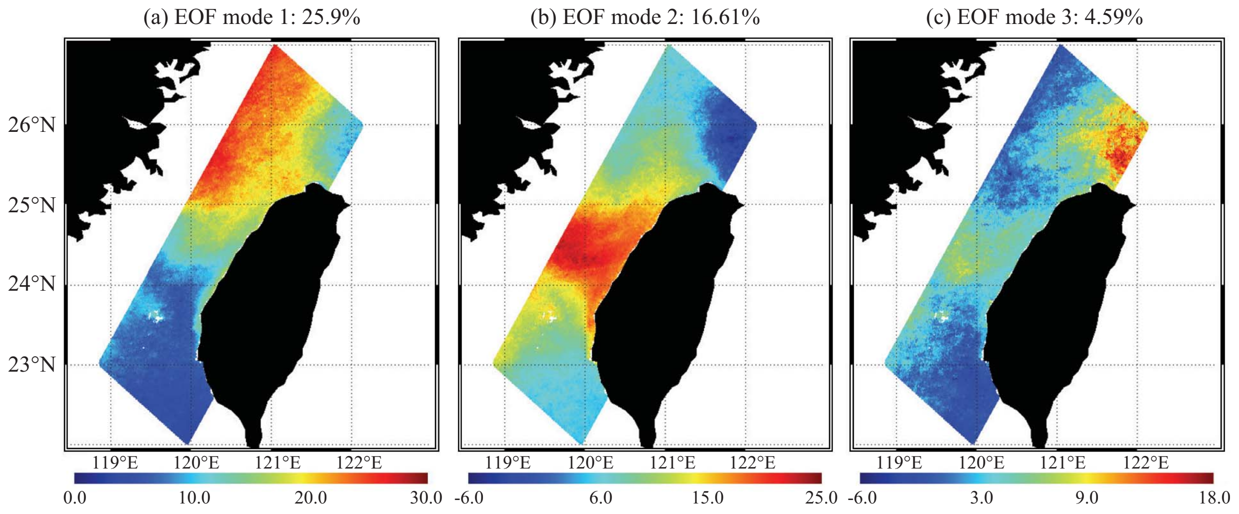


**Fig. 2. Spatial amplitude patterns of the first three empirical orthogonal function modes ((a): first; (b): second; and (c): third) in the eastern Taiwan Strait.**

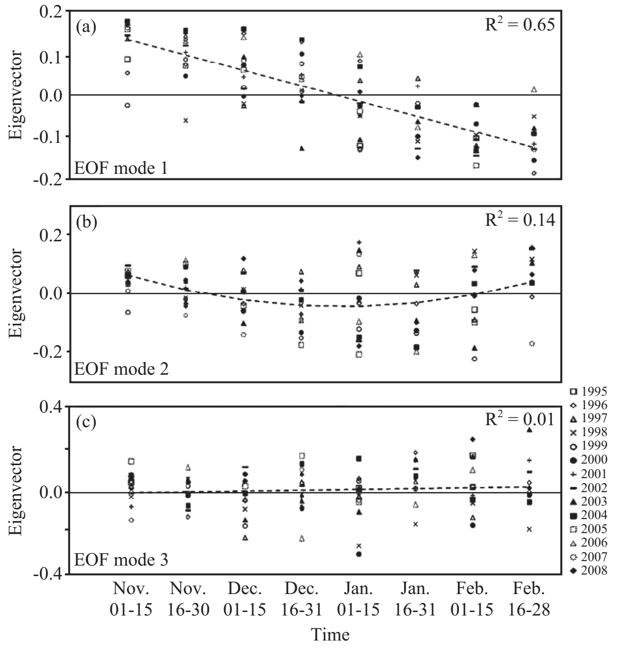


**Fig. 3. Intra-seasonal eigenvectors of the first three empirical orthogonal function modes: (a) first, (b) second, and (c) third. Different symbols on the same row indicated the eigenvector of different years in the same period (15-day mean).**

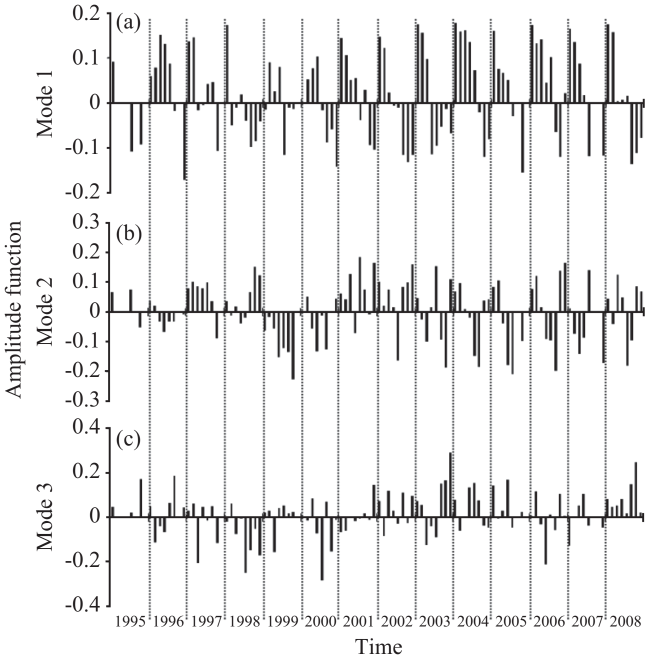
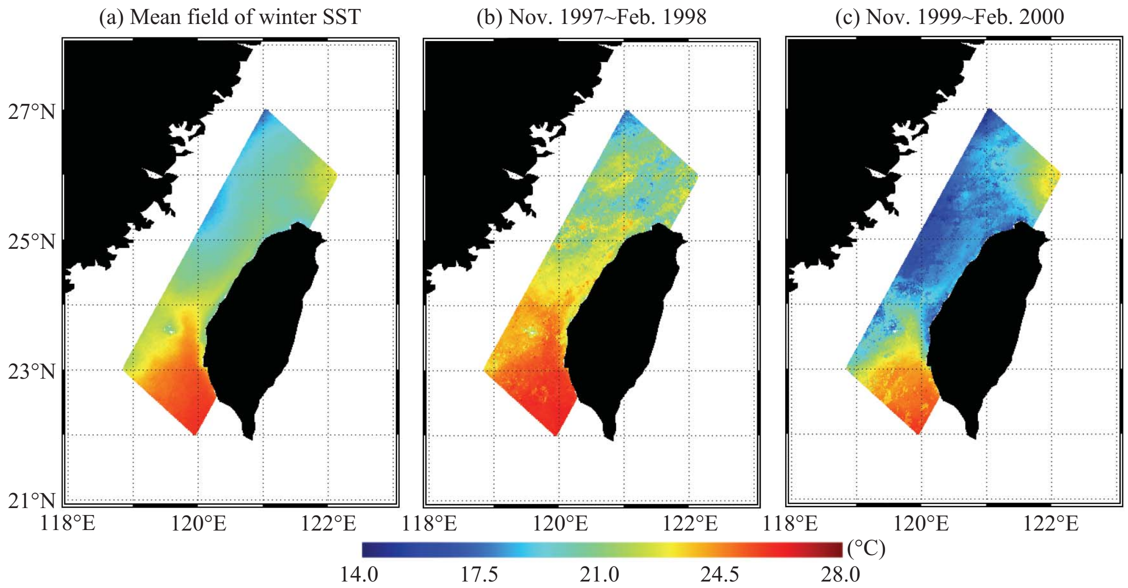


**Fig. 4. Time series variations in eigenvectors of the first three empirical orthogonal function modes: (a) first, (b) second, and (c) third. The x-axis is the wintertime (November~February) for each year (e.g., the number 1995, indicates the period November 1995 to February 1996) and the black bar is the eigenvector of each 15-day mean image.**

spatial amplitude (Fig. 2(a)) also illustrated the signal to be consistent with the heating balance and the formation of an oceanic front boundary at the CYR. The boundary at the CYR might be the border between the Kuroshio Branch Water and the China Coastal Water (Figs. 2(a), 5(a)). Jan *et al*. [8] indicated that the northward intrusion of the Kuroshio Branch Current was severely blocked by the This corresponds with Chang *et al*. [3] who found a Peng-Chang front north of the CYR in winter.

This boundary was studied by many researchers [3, 8, 15] and might shift according to interactions and strengths of the China Coastal Current and Kuroshio Branch Current. Spatial amplitude patterns of the second mode showed high positive values around the CYR and negative values in the northwestern portion of the study area. During winter, a typical feature of the southward penetration of the China Coastal Current was



(a) Mean field of winter SST

(b) Nov. 1997~Feb. 1998

(c) Nov. 1999~Feb. 2000

Fig. 5. Mean field of AVHRR sea surface temperature images of wintertime (a), the entire study period of 1995~2008 (b), November 1997~February 1998 (c), and November 1999~February 2000.

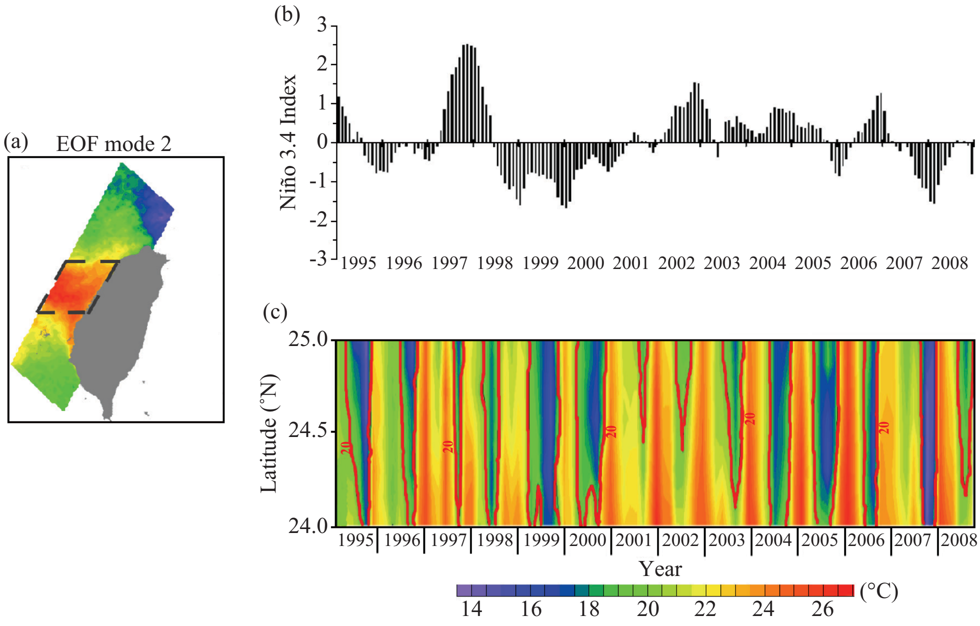


Fig. 6. Temporal variations of the Niño 3.4 index (b) and the zonal average of sea surface temperatures (c) at the Chang-Yuen Rise for the period 1995~2008. The area used for zonal averaging of sea surface temperatures is within the black dashed box in (a). The 20°C isotherms is indicated by red lines in (c).

a peak in January [2]. Intra-seasonal trends showed the large scattering of the eigenvectors (Fig. 3(b)) and the annual trend of eigenvectors also showed yearly variations from 1995 to 2008 (Fig. 4(b)), e.g., positive and negative values of the eigenvectors respectively appeared in the winter of 1997 (November 1997~February 1998, El Niño) and 1999(November 1999~February 2000, La Niña), although not all El Niño/La Niña events have positive/negative values.

This phenomenon suggested that the SSTs were warmer in the El Niño (e.g., 1997/1998, Fig. 5(b)) than La Niña (e.g., 1999/2000, Fig. 5(c)) winters at the CYR, consistent with previous studies which found that changes in wind stress resulted in warmer SST in El Niño winters than in La Niña winters [2, 9, 24].

Reduced speeds of northeasterly winds in El Niño winters strengthened the northward moving warm current and interrupted the southward invasion of the cold China Coast Current into the eastern TS [9].

The amplitude patterns showed high positive values around the CYR and annual variations of eigenvectors in the second mode; we then calculated temporal variations of zonal average SSTs at the CYR (black dashed box in Fig. 6(a)) for the period 1995~2008 (Fig. 6(c)). Based on results reported by Lee *et al*. [14], we regarded latitudinal variation of the 20°C isotherm as an indicator of the intrusion of the China Coastal Current (Fig. 6(c), thin red contour). In El Niño winters (1997 and 2002), the position of the 20°C isotherm was restricted to the north of CYR, and average SSTs at the CYR were warmer than those in La Niña winters (1995, 1998, 1999, 2000 and 2007). On the contrary, the 20°C isotherm crossed 24.5°N and the cold water reached to the south of the CYR in La Niña winters, especially in late winters of 1999 and 2007, at which time,average SSTs of the CYR were lower than 17°C and the position of the 20°C isotherm reached south to 24°N near the Penghu Channel.

Chang *et al*. [2] noted that monthly SSTs in late winter 2007 (February 2008) were about 7°C lower than those of the 12-year average and suggested that the effect of climate change on wind speed was responsible for changes in the current.

Continuous strong winds in La Niña winters may cause the more- southward intrusions of the cold China Coast Current around the CYR and Penghu Islands [2]. Average SSTs at the CYR were highly and positively correlated with latitudinal variations of the 20°C isotherms (r = 0.742) (Fig. 7), and this hints that variation in SSTs at the CYR could be an indicator of winter variations of the China Coastal Current in the eastern TS.

The spatial amplitude of the third mode showed positive values around the northern part of the TS and negative values in the northeastern and southern parts of the study area (Fig. 2(c)).

The annual trend of eigenvectors also varied with time (Fig. 4(c)). This mode may provide a signal when the northeastern portion of the study area showed negative values with the northward intrusion of the Kuroshio Current moving seaward and shoreward, respectively. Wu *et al*. [25] found that the upper Kuroshio seasonally migrates off northeastern Taiwan, moving shoreward in fall-winter and seaward in spring-summer.

In winter, the Kuroshio Current moves close to and onto the northern shelf of Taiwan and interacts with the southward intruding China Coastal Water [16, 23]. On the other hand, the China Coastal Current may advance southward from the northwestern tip of the TS when the northeasterly monsoon temporally strengthens with time [8, 15, 24].

## IV. CONCLUTIONS AND REMARKS

In this study, we investigated the long-term SST variability in wintertime in the eastern TS in 1995~2008 using the NOAA AVHRR SSTs at a 1.1-km spatial resolution. An EOF analysis of spatial and time series variances for 15-day mean images was performed. The first three modes in the EOF analysis respectively accounted for 25.9%, 16.61% and 4.59% of the variances.

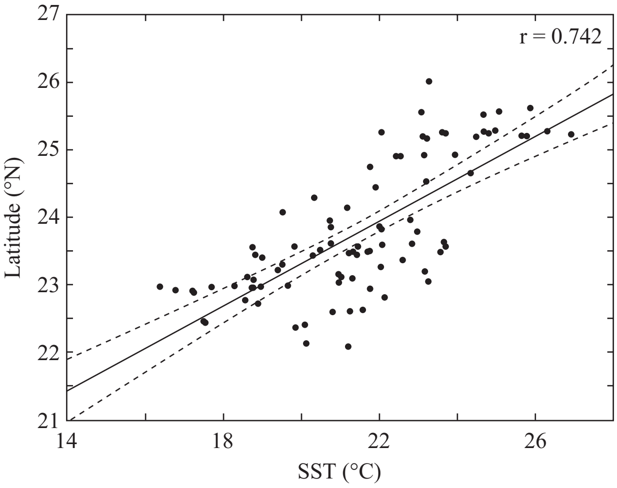


**Fig. 7. Relationship between average sea surface temperatures at the Chang-Yuen Rise and latitudinal variations of the 20°C isotherm in the eastern Taiwan Strait. The dashed-black line encloses regions of > 95% confidence.**

The first mode suggested that warmer waters were south of the CYR and the southwesterly intrusion of cold water covered the northeastern portion of the study area. In the second mode, the lowest SSTs appeared at the CYR from the middle of December to the end of January. The EOF single-field observations revealed heating exchange and the formation of an oceanic front boundary at the CYR in winter. We also found average SSTs at the CYR to be highly and positively correlated with latitudinal variations of the 20°C isotherm. This correlation implies that variation in SSTs at the CYR might be a parameter for examining the variations in the China Coastal Current in the eastern TS.

Based on our study, the intrusion of the China Coastal Current varied with time and might be affected by climatic variability (e.g., ENSO events) in the North Pacific Ocean. Climatic oscillations, anomalies, and changes result in interannual changes in SSTs and clearly affect population dynamics and many ecological processes in marine ecosystems [5, 12, 22]. However, large uncertainty remains, particularly not all El Niño/La Niña events have the same phenomenon with SSTs in the eastern TS. For example, there appeared negative value during the El Niño winters of 2003 and 2004 in the second EOF mode, and the 20°C isotherm also reached south to 24°N suggesting that other factors influence the spatial distribution of SST which remains for further study. It was difficult to identify the relationship between cold-water intrusion and climatic variability; understanding the effects and mechanisms of wind speeds might be instrumental in resolving this problem. Thus, performing an EOF analysis on wind stress and its curl should be further studied. Additionally, analysis of in situ data combined with modeling simulation should be able to improve our understanding of such SST variations in the TS.

## ACKNOWLEDGMENTS

This study was financially supported by the National Science Council, Taiwan (NSC100-2621-M-019-001 and NSC100-2611-M-019-005) and the Center of Excellence for Marine Bioenvironment and Biotechnology at National Taiwan Ocean University. The authors especially thank Chang-tai Shih of National Taiwan Ocean University for his assistance in revising the manuscript.

## REFERENCES

1. Bernstein, R. L., "Sea surface temperature estimation using the NOAA 6 satellite advanced very high resolution radiometer," *Journal of Geophysical Research*, Vol. 87, pp. 9455-9465 (1982).
2. Chang, Y., Lee, K. T., Lee, M. A., and Lan, K. W., "Satellite observation on the exceptional intrusion of cold water in the Taiwan Strait," *Terrestrial, Atmospheric and Oceanic Sciences*, Vol. 20, No. 4, pp. 661-669 (2009).
3. Chang, Y., Shimada, T., Lee, M. A., Lu, H. J., Sakaida, F., and Kawamura, H., "Wintertime sea surface temperature fronts in the Taiwan Strait," *Geophysical Research Letters*, Vol. 33, L23603, DOI: 10.1029/2006GL027415 (2006).
4. Emery, W. J. and Thomson, R. E., "Empirical orthogonal functions," *Data Analysis Methods in Physical Oceanography*, Elsevier Science Limited, pp. 319-343 (2001).
5. Hollowed, A. B., Barange, M., Ito, S. I., Kim, S., Loend, H., and Peck, M. A., "Effects of climate change on fish and fisheries: forecasting impacts, assessing ecosystem responses, and evaluating management strategies," *ICES Journal of Marine Science*, Vol. 68, No. 6, pp. 984-985 (2011).
6. Hsieh, C. H., Chen, C. H., Chiu, T. S., Lee, K. T., Hsieh, F. J., Pan, J. Y., and Lee, M. A., "Time series analyses reveal transient relationships between abundance of larval anchovy and environmental variables in the coastal waters southwest of Taiwan," *Fisheries Oceanography*, Vol. 18, No. 2, pp. 102-117 (2009).
7. Jan, S., Sheu, D. D., and Kuo, H. M., "Water mass and through flow transport variability in the Taiwan Strait," *Journal of Geophysical Research*, Vol. 111, C12012, DOI: 10.1029/2006JC003656 (2006).
8. Jan, S., Wang, J., Chern, C. S., and Chao, S. Y., "Seasonal variation of the circulation in the Taiwan Strait," *Journal of Marine Systems*, Vol. 35, pp. 249-268 (2002).
9. Kuo, N. J. and Ho, C. R., "ENSO effect on the sea surface wind and sea surface temperature in the Taiwan Strait," *Geophysical Research Letters*, Vol. 31, L13309, DOI: 10.1029/2004GL 020303 (2004).
10. Lagerloef, G. S. E. and Bernstein, R. L., "Empirical orthogonal function analysis of advanced very high resolution radiometer surface temperature patterns in Santa Barbara Channel," *Journal of Geophysical Research*, Vol. 93, No. C6, pp. 6863-6873 (1988).
11. Lan, K. W., Kawamura, H., Lee, M. A., Chang, Y., Chan, J. W., and Liao, C. H., "Summertime sea surface temperature fronts associated with upwelling around the Taiwan Bank," *Continental Shelf Research*, Vol. 29, No. 7, pp. 903-910 (2009).
12. Lan, K. W., Lee, M. A. Lu, H. J., Shieh, W. J., Lin, W. K., and Kao, S. C., "Ocean variations associated with fishing conditions of yellowfin tuna (Thunnus albacares) in the equatorial Atlantic Ocean," *ICES Journal of Marine Science*, Vol. 68, No. 6, pp. 1063-1071 (2011).
13. Lan, Y. C., Lee, M. A., Liao, C. H., Lee, D. A., Liu, D. C., and Su W. C., "Copepod community change in the southern East China Sea between early and late northeasterly monsoon," *Zoological Studies*, Vol. 47, No. 1, pp. 61-74 (2008).
14. Lee, M. A., Chang, Y., Sakaida, F., and Kawamura, H., "Validation of satellite-derived sea surface temperatures for waters around Taiwan," *Terrestrial, Atmospheric and Oceanic Sciences*, Vol. 16, No. 5, pp. 1189-1204 (2005).
15. Lee, M. A., Yeah, C. D., Cheng, C. H., Chan, J. W., and Lee, K. T., "Empirical orthogonal function analysis of AVHRR sea surface temperature patterns in Taiwan Strait," *Journal of Marine Science and Technology*, Vol. 11, No. 1, pp. 1-7 (2003).
16. Liu, K. K., Gong, G. C., Shyu, C. Z., Pai, S. C., Wei, C.L., and Chao, S. Y., "Response of Kuroshio upwelling to the onset of the northeast monsoon in the sea north of Taiwan: observations and a numerical simulation," *Journal of Geophysical Research*, Vol. 97, pp. 12511-12526 (1992).
17. McClain, E. P., Pichel, W. G., and Walton, C. C., "Comparative performance of AVHRR based multichannel sea surface temperatures," *Journal of Geophysical Research*, Vol. 90, pp. 11587-11601 (1985).
18. Navarro, G. and Ruiz, J., "Spatial and temporal variability of phytoplankton in the Gulf of Cadiz through remote sensing images," *Deep-Sea Research II*, Vol. 53, pp. 1241-1260 (2006).
19. North, G. R., Bell, T. L., Cahalan, R. F., and Moeng, F. J., "Sampling errors in the estimation of Empirical Orthogonal Functions," *Monthly Weather Review*, Vol. 110, pp. 699-706 (1982).
20. Paden, C. A., Abbot, M. R., and Winant, C. D., "Tidal and atmospheric forcing of the upper ocean in the Gulf of California, 1: Sea surface temperature variability," *Journal of Geophysical Research*, Vol. 96, No. C10, pp. 18337-18359 (1991).
21. Radiarta, I. N. and Saitoh, S. I., "Satellite-derived measurements of spatial and temporal chlorophyll-a variability in Funka Bay, southwestern Hokkaido, Japan," *Estuarine, Coastal and Shelf Science*, Vol. 79, pp. 400-408 (2008).
22. Stenseth, N. C., Ottersen, G., Hurrel, J. W., and Belgrano, A., *Marine Ecosystems and Climate Variation*, Oxford University Press, New York (2004).
23. Wang, J. and Chern, C. S., "On the Kuroshio branch in the Taiwan Strait during wintertime," *Progress in Oceanography*, Vol. 21, pp. 469-491 (1988).
24. Wu, C. R., Chao, S. Y., and Hsu, C., "Transient, seasonal and interannual variability of the Taiwan Strait Current," *Journal of Oceanography*, Vol. 63, pp. 821-833 (2007).
25. Wu, C. R., Lu, H. F., and Chao, S. Y., "A numerical study on the formation of upwelling off northeast Taiwan," *Journal of Geophysical Research*, Vol. 113, C08025 (2008).