Hydrographic and Biological Changes in the Taiwan Strait During the 1997-1998 El Niño Winter

S. Shang

C. Zhang

H. Hong

Q. Liu

G. T. F. Wong
Old Dominion University, gwong@odu.edu

See next page for additional authors

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Hydrographic and biological changes in the Taiwan Strait during the 1997–1998 El Niño winter

S. Shang,[1] C. Zhang,[1] H. Hong,[1] Q. Liu,[2] G. T. F. Wong,[3] C. Hu,[4] and B. Huang[1]

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[1] During the 1997–1998 El Niño event, the average sea surface temperature (SST) in the Taiwan Strait (TWS) in the winter was ~1.4°C higher than that of the winter climatological mean. The areal ratio of the warm water (≥2°C above the regional mean) to the cold water (≥2°C below the regional mean) in the TWS increased by 25% while the area of the eutrophic water (chlorophyll *a* >1 mg m^{-3}) was halved. Field observations also indicate that the mixed layer in the TWS became more nutrient-poor during this winter. These observations are consistent with a diminished advection of the cold and eutrophic Zhe-Min Coastal Water, and, concomitantly, an expansive intrusion of the warm and oligotrophic South China Sea Warm Current/Kuroshio Branch Water to the TWS as the northeast monsoon was weakened. Thus, El Niño events potentially can have significant ecological impacts on the TWS.

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1. Introduction

[2] The Taiwan Strait (TWS), with an average water depth of 60 m, is a shallow shelf-channel that connects the South China Sea (SCS) with the East China Sea (ECS) (Figure 1). Warm, saline, and oligotrophic water enters the TWS from the southeast from the SCS through the Penghu Channel as the South China Sea Warm Current (SCSWC) and the Kuroshio Branch Water (KBW) while cold, fresh, and eutrophic water intrudes into the TWS from the northwest from the ECS along the Chinese coast as the Zhe-Min Coastal Water (ZMCW, also known as Zhejiang-Fujian Coastal Water). The relative influence of the SCSWC/KBW and the ZMCW, which varies seasonally in response to changes in the monsoonal wind, is a major determining factor of the hydrographic conditions and biological productivity in the TWS. The northeast monsoon in the winter drives the ZMCW towards the south and keeps the remotely driven SCSWC/KBW trapped in the Penghu Channel. The southwest monsoon in the summer, on the other hand, favors the input from the south [*Wang and Chern*, 1988; *Jan et al.*, 2002; *Hsueh and Zhong*, 2004].

[3] During an El Niño event, the northeast monsoon in the winter is weakened and the SCS basin-wide surface circulation and vertical advection rate are reduced [*Chao et al.*, 1996; *Liu et al.*, 2004]. These would lead to a warming of the surface water of the SCS, as indeed reported by *Wang et al.* [2002] and *Kuo and Ho* [2004]. Conceivably, the weakened northeast monsoon would reduce the input of the cold and eutrophic water to the TWS from the north, and facilitate the intrusion of the warmer SCSWC/KBW water to the TWS from the south. Thus, during an El Niño event, the water in the TWS may become warmer and less nutrient-rich, and thus less productive. The El Niño event of 1997–1998 was one of the strongest on record and it reached its peak in the winter of 1998 [*Chavez et al.*, 1999] (Winter in a given year is defined in this paper as the three-month period between December 1 of the preceding year through the February of the given year). Here, we test the above hypotheses on the effect of El Niño in the TWS by examining the changes in its hydrographic and ecological conditions in winter during this event.

2. Methods

[4] The TWS was defined in this study as the area between the China Mainland coast or the 116.5°E longitude and the west coast of Taiwan, and between 22 and 25.5°N (Figure 1). The monthly mean sea surface temperature (SST), surface chlorophyll *a* concentration (Chl), and wind stress in the TWS were derived from AVHRR (Advanced Very-High Resolution Radiometer), SeaWiFS (Sea-viewing Wide Field-of-view Sensor), and ERS (European Remote Sensing Satellite) images, respectively. The resolution was 9×9 km^2 for the former two and $1 \times 1°$ for the latter. The records of SST, Chl, and wind stress were constructed for the periods of January 1985 to May 2003, September 1997 to August 2004, and January 1991 to December 2000, respectively, as data availability permitted. The winter averages in each year were then calculated over the TWS. Anomalies in SST (SSTA) and meridional wind stress (MWSA) were calculated as the deviation from the winter climatological means between 1985 and 2003 and between 1991 and 2000, respectively. In each year, the difference in SST between the value in each AVHRR pixel and the mean value over the TWS was estimated. The ratio of the area with differences ≥+2°C to that with differences ≤−2°C, or R, was estimated as an index to indicate the relative influence of the warm SCSWC/KBW and the cold ZMCW. A SST difference of 4°C should be sufficient for distinguishing these two water masses from each other since the minimum difference that has been used for characterizing them in winter was 2°C [*Jan et al.*, 2002]. The area in the TWS with high biomass or HChl, and thus high biological productivity, was defined as the eutrophic water with

[1]State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, China.
[2]Physical Oceanography Laboratory and Ocean-Atmosphere Interaction and Climate Laboratory, Ocean University of China, Qingdao, China.
[3]Department of Ocean, Earth and Atmospheric Sciences, Old Dominian University, Norfolk, Virginia, USA.
[4]College of Marine Sciences, University of South Florida, St. Petersburg, Florida, USA.

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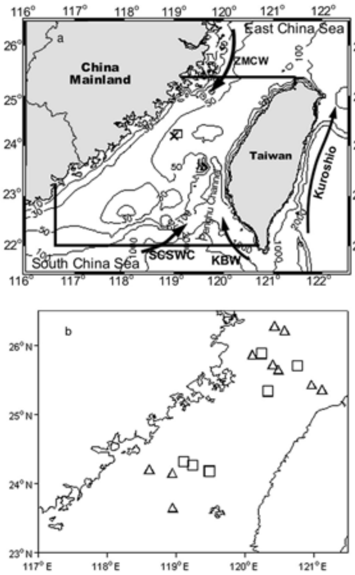

Figure 1. (a) The Taiwan Strait. The area enclosed by the solid lines and the coasts of the China Mainland and Taiwan is used for estimating the average property in the Strait. Crosses (118.94°E/24.15°N) and squares (119.11°E/24.32°N) annotate two stations for field observations on 3 March 1995 and 7 March 1998, respectively. (b) Sampling stations in the Taiwan Strait in February–March 1995 (triangles) and 1998 (squares).

SeaWiFS-derived surface Chl exceeding 1 mg m^{-3} [*Kahru and Mitchell*, 2000]. In a previous study [*Shang et al.*, 2004], the distributions of surface Chl in the TWS that were derived from SeaWiFS were found to be consistent with those derived from concurrent field observations.

[5] Four daily high-resolution (1×1 km^2) AVHRR SST images with minimal cloud cover were obtained between February and March of 1995 and 1998. The location and strength of the front between the SCSWC/KBW and the ZMCW on each day was deduced from the temperature gradient across the frontal region by the method of *Wang et al.* [2001].

[6] The distributions of salinity, temperature, nitrate, and Chl were determined at selected locations in the TWS in February to March in 1995 and 1998 (Figure 1), prior to and during the 1997–1998 El Niño event. Salinity and temperature were recorded with a SeaBird conductivity-temperature-depth recorder. Discrete seawater samples were collected and analyzed for nitrate and Chl with standard methods [*Parsons et al.*, 1984].

[7] The record of the occurrence of El Niño events was inferred from the overlapping bimonthly mean Multivariate ENSO Index (MEI) promulgated by the Climate Diagnostic Center of the National Oceanic and Atmospheric Administration (K. Wolter, Multivariate ENSO Index (MEI), http://www.cdc.noaa.gov/people/klaus.wolter/MEI/index.html, 2004).

3. Results and Discussion

[8] Changes in SSTA and R between 1986 and 2003, HChl between 1998 and 2004, and MWSA between 1992 and 2000 in the winter together with the overlapping bimonthly mean MEI are shown in Figure 2. The MEI record indicates the occurrence of the warm El Niño phases in 1986–1988, 1990–1995, 1997–1998, and 2001–2003. The strongest warm event occurred in 1997–1998, which was in fact the second strongest since the beginning of the MEI record in 1950. In the TWS, winter SSTA varied between −1 and +1.4°C between 1986 and 2003. Four winter warm periods, which corresponded approximately with the El Niño warm phases, were found in 1988–1991, 1994–1996, 1998–1999, and 2003. Among these winter warm periods, the highest SSTA was also found in 1998 when the strongest El Niño occurred. R ranged between 1 and 1.5 with a long-term average of 1.2. The maximum value, which was about 25% higher than the long-term average, was also reached in 1998. It suggests that a larger area of the Strait was likely covered by the warm SCSWC/KBW during this major El Niño event so that the water became warmer.

[9] HChl varied between 1.5 to 3.3×10^4 km^2 in the winters between 1998 and 2004. The lowest HChl was found in the winter of 1998 and it was only about half of that in 2001 when the El Niño event had subsided. MWSA varied between −0.5 to 0.5×10^{-2} N m^{-2} (Figure 2e). Southerly wind anomaly, represented by the positive MWSA, was associated with the El Niño events of 1990–1995 and 1997–1998. This is consistent with the notion of a weaker northeast monsoon during an El Niño year so that the advection of the cold and nutrient-rich ZMCW into the TWS from the north is reduced while the intrusion of the warm and oligotrophic SCSWC/KBW from the south is enhanced [*Jan et al.*, 2002]. Conceivably, the weakened wind could also lead to reduced latent heat losses to the atmosphere and a resulting warming of the surface water. Hence the warming of the TWS in the winter of 1998 could have been explained by a change in the exchange of heat with the atmosphere or by a change in the circulation pattern during an El Niño year. However, contrary to what was observed, the former would have led to an increase in HChl,

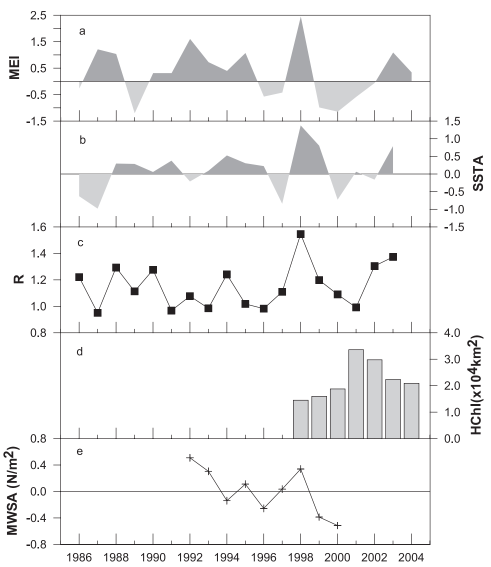

Figure 2. (a) Time series of overlapping biweekly mean MEI and (b) winter SSTA, (c) R, (d) HChl, and (e) MWSA during various time periods between 1986 and 2004.

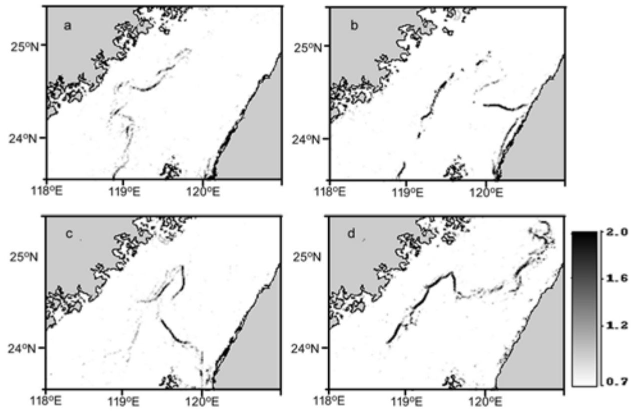

Figure 3. Frontal maps of the Taiwan Strait on (a) 28 February and (b) 9 March 1995 and (c) 8 February and (d) 25 February 1998. The strength of fronts (°C/km) is shown in gray scale.

since the growth of phytoplankton in winter in the nutrient-rich water influenced by ZMCW is limited by temperature [*Zhang et al.*, 1997]. On the other hand, the latter could account for the lower HChl observed since the SCSWC/KBW is oligotrophic and an expanded coverage of the TWS by this water would result in a reduction in the phytoplankton biomass. Thus, the latter is a more reasonable explanation. It is consistent with the suggestion of *Kuo and Ho* [2004] that the ENSO events can affect the wind patterns in the TWS and therefore modulate the sea surface currents to result in the SST change in interanuual scale.

[10] The locations and strength of the front between the SCSWC/KBW and the ZMCW on February 28 and March 9 of 1995 and February 8 and 25 of 1998, prior to and during the 1997–1998 El Niño event respectively, are shown in Figure 3. They suggest a northward propagation of the warm SCSWC/KBW from the south during the winter-spring transition in both years. However, the front was stronger and progressed further to the north at an earlier time in 1998. These results are consistent with a diminished southward propagation of the cold coastal water from the north and an enhanced northward intrusion of the warm water during this major El Niño event.

[11] The vertical profiles of salinity, temperature, nitrate, and Chl at two stations in the center of the TWS (Figure 1a) sampled on 3 March 1995 and 7 March 1998 are shown in Figure 4. In 1998 there was an increase in salinity of >1 salinity unit from <33.8 to >34.8 and an increase in temperature of >3°C from <16°C to >19°C in the entire water column. Concomitantly, the concentration of nitrate and Chl in the mixed layer in the top 20 m of water dropped from 6 μM to undetectable and from 1.3 to 0.7 mg m^{-3}. The relationships between salinity and temperature and between nitrate concentration and temperature in the surface mixed layer of the TWS (0–20 m depth) in February to March of 1995 and 1998 are shown in Figure 5. The relationships followed the same general trend, indicating that inter-annual variations in these relationships between these two years were minor. Above 20°C, salinity stayed at about 34.6 while the concentrations of nitrate were at undetectable levels. Below 20°C, salinity decreased while the concentration of nitrate increased steadily with decreasing temperature. Between 12 and 20°C, the relationship between salinity, S, and temperature, T, was

$$S = 0.68(\pm 0.04)T + 21.98(\pm 0.61), \quad r^2 = 0.82, n = 61 \qquad (1)$$

while the concentration of nitrate, $[NO_3^-]$, and temperature were also linearly related to each other such that

$$[NO_3^-](\mu M) = -1.9(\pm 0.1)T + 38.1(\pm 1.2), \quad r^2 = 0.90, n = 61 \qquad (2)$$

These consistent relationships also indicate that the effect of the reduction in heat loss to the atmosphere on the distribution of temperature during the El Niño year as a result of reduced wind stress was probably small since such a process would affect temperature, salinity and nitrate differently and should result in inter-annual differences in these relationships. Since the average SST of the TWS in the surface mixed layer in the winters of 1995 and 1998 before the onset of and during this major El Niño event were 15.15 and 16.38°C, the corresponding average salinity and concentrations of nitrate would have been 32.28 and 9.3 μM, and, 33.12 and 7.0 μM, respectively. Thus, the water in the surface mixed layer of the TWS was elevated in salinity and depleted in nutrients during the 1997–1998 El Niño

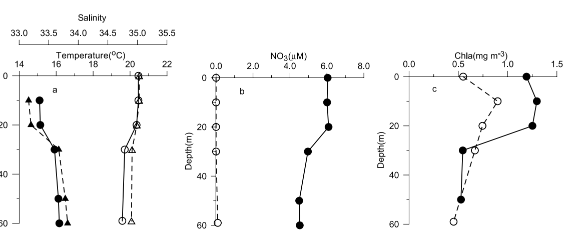

Figure 4. Vertical profiles of several parameters at the center of the Taiwan Strait (Figure 1a) on 3 March 1995 (solid symbols) and 7 March 1998 (open symbols). (a) Circles: temperature; triangles: salinity; (b) nitrate; (c) chlorophyll *a*.

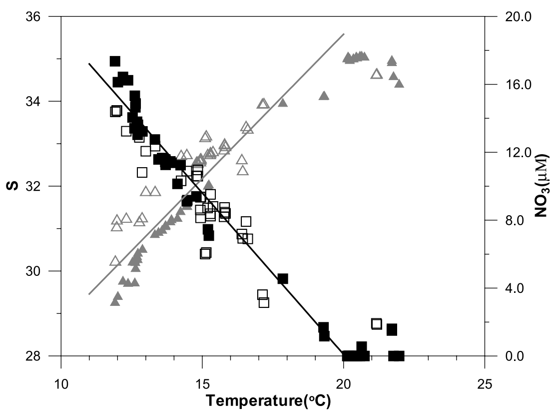

Figure 5. Relationships between salinity and temperature and between nitrate and temperature in the surface mixed layer (0 to 20 m) in the TWS in February–March in 1995 and 1998. Open triangles– 1995 salinity; open squares– 1995 nitrate; shaded triangles–1998 salinity; solid squares– 1998 nitrate; the data at 0 m depth in 1995 was missing and thus only 10–20 m data in both years were shown and used for curve fitting.

winter and these observations were consistent with the higher R, which indicated the expanded coverage of the TWS by the warm, saline and oligotrophic SCSWC/KBW, and lower HChl, which indicated a reduction in biomass.

4. Conclusion

[12] During the El Niño event in 1997–1998, the SST in the winter in the TWS was elevated by >1°C over the long-term climatological mean probably as a result of the weakened northeast monsoon which would lead to a reduced advection of the cold, fresh and nutrient-rich ZMCW from the north and an enhanced intrusion of the warm, more saline and oligotrophic SCSWC/KBW from the south. Consequently, the ratio of the area in the TWS covered by the warm water relative to that covered by the cold water increased by 25% while the area that was covered with the biomass-rich water shrank by about 50%. Field observations also suggest that the concentrations of the nutrients were reduced during this El Niño event. Thus, although the TWS is far away from the equatorial Pacific where the impact of El Niño can be most conspicuously demonstrated, El Niño may still have a significant ecological effect on this body of water. These results also show that while on average the global ocean became more productive during the 1997–1998 El Niño [*Behrenfeld et al.*, 2001], for a particular region, the effect could be significantly different.

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H. Hong, B. Huang, S. Shang, and C. Zhang, State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen 361005, China. (hshong@xmu.edu.cn)

C. Hu, College of Marine Sciences, University of South Florida, St. Petersburg, FL 33701, USA.

Q. Liu, Physical Oceanography Laboratory and Ocean-Atmosphere Interaction and Climate Laboratory, Ocean University of China, Qingdao 266003, China.

G. T. F. Wong, Department of Ocean, Earth and Atmospheric Sciences, Old Dominian University, Norfolk, VA 23529–0276, USA.