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An overview of physical and biogeochemical processes and ecosystem dynamics in the Taiwan Strait

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ABSTRACT

The Taiwan Strait is an important channel in the west Pacific Ocean transporting water and chemical constituents between the East China Sea and the South China Sea. Due to its complex bottom topography, alternating monsoon forcing and conjunction of several current systems [such as the Zhejiang–Fujian (Zhe–Min) Coastal Current, the Kuroshio intrusion and the extension of the South China Sea Warm Current], the physical and biogeochemical processes and ecosystem dynamics in the Taiwan Strait vary significantly both in space and in time. Our recent interdisciplinary studies, combining *in situ* and remote sensing observations with numerical modeling, allow us to address several important issues concerning the Taiwan Strait. The temporal and spatial variation of circulation in the Taiwan Strait is modulated by strong monsoon forcing, complex topography and circulation in the northern South China Sea as well as coastal water input and the Kuroshio intrusion. The biogeochemical processes of carbon and nutrients in the Taiwan Strait depend largely on the physical forcing (external input) and the community structure (internal cycling). The primary producers in the Taiwan Strait are dominated by nano- and pico-phytoplankton, and the contribution of the microbial food web to the traditional food web is estimated to be about 30%, implying the fundamental significance of the microbial food web in this subtropical region. Upwelling is a predominant feature in the Taiwan Strait and shows dynamic short-term, seasonal and interannual variations. Combined hydrographic and satellite-derived information provides evidence on the teleconnection between the Taiwan Strait upwelling variation and the El Nino-Southern Oscillation (ENSO) climate variability. Upwelling has a tremendous impact on biogeochemical processes, biological productivity and ecosystem structure. Not only the biological productivity, but also dramatic changes in the phytoplankton community structure reveal the dynamic ecosystem responses to the variations in upwelling, which should have significant impact on the fishery resources. In this overview, we summarize the hydrographical features with an emphasis on upwelling, which is the key driver of biogeochemical processes and ecosystem dynamics in the Taiwan Strait.

1. Introduction

The Taiwan Strait (TWS), located between the Taiwan Island and southeast Mainland China, is not only an important channel in the west Pacific Ocean transporting water and chemical elements between the East China Sea (ECS) and the South China Sea (SCS), but also an important pathway for ship navigation and fish migration. It is approximately 180 km wide and 350 km long, with an average depth of 60 m. The northern boundary of the Taiwan Strait is usually defined as the line between Pingtan (or Haitan Island) and Fuguijiao, and the southern boundary between Dongshan and Maobitou (Fig. 1). The bottom topography is very complex in the TWS. The Taiwan Bank, a mesa with hundreds of sandbanks, lies in the southern part of the TWS and has an average water depth of 20 m. To the east of the Taiwan Bank is the Penghu Channel where depth is 200–100 m from south to north. The shallow Zhangyun Ridge is located to the north of the Penghu Channel, and the deeper Pengbei Channel is between the Penghu Islands and the Zhangyun Ridge (Fig.1).

The TWS is in the East Asian monsoonal region, and winds over the TWS are dominated by stronger northeasterly winds during October–March and weaker southwesterly winds from June to August, with April–May and September being the transitional periods (Fig. 2). Circulation in the TWS is modulated by the changing wind field and shows strong seasonal variations.

As a corridor connected the SCS and ECS, the outflow through the TWS has a direct impact on the circulation and the biogeochemical processes in the ECS (Chen and Wang, 1999; Isobe,

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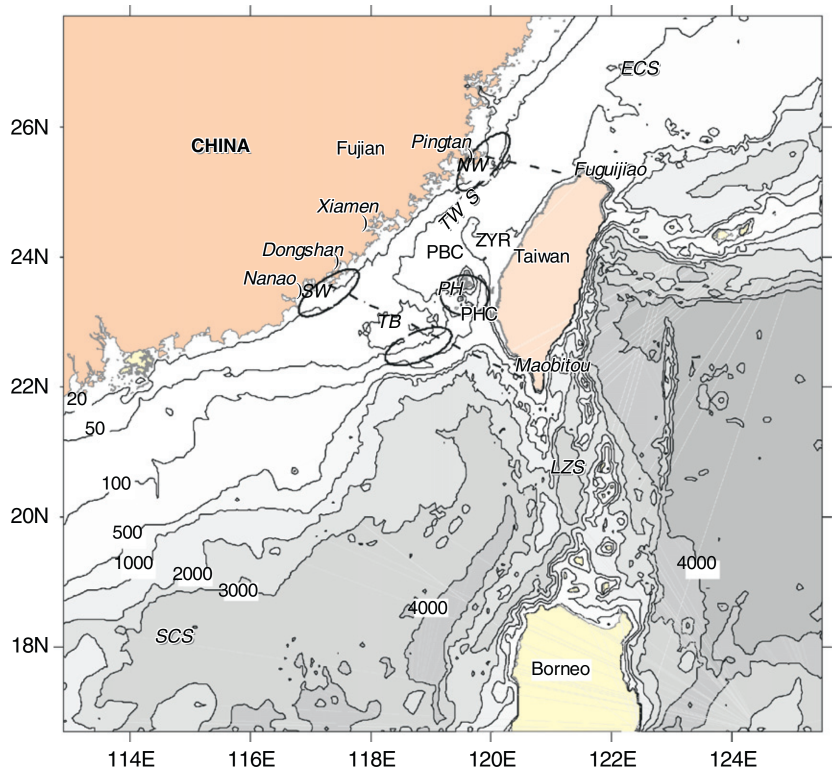

Fig. 1. Location and bathymetry (isobaths in meters) of the Taiwan Strait. Dashed lines represent the schematic boundaries of the Taiwan Strait. Schematic positions of four upwelling regions are indicated by four ellipses or circle in the figure, in the Taiwan Strait (cited from Hu et al., 2003). [Acronyms: **TWS**, Taiwan Strait; **TB**, Taiwan Bank; **PHC**, Penghu Channel; **PH**, Penghu Island; **ZYR**, Zhangyun Ridge; **PBC**, Pengbei Channel; **LZS**, Luzon Strait; **ECS**, East China Sea; **SCS**, South China Sea; **NW**, NW-upwelling area and **SW**, SW-upwelling area.].

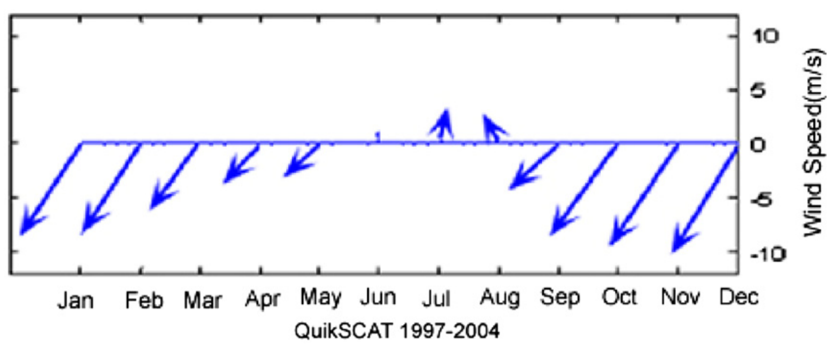

Fig. 2. Diagram of monthly mean wind speed over 8 years of QuikSCAT data (1997–2004) covering the western part of the Taiwan Strait.

1999; Katoh et al., 2000; Liu et al., 2000). Thus, understanding the oceanography of the TWS is of broader regional interest. However, lack of direct measurements and well coordinated studies in this region makes it difficult to present a clear picture of the temporal variation in circulation and volume transport in the TWS (Wyrtki, 1961; Liu et al., 2000). Furthermore, problems, such as how biogeochemical processes and upwelling in the TWS respond to strong monsoons and how the large-scale interannual climate variability affects biological productivity and biogeochemical processes in the TWS, are still not fully understood.

Nevertheless, field observations in the TWS region have been intensified since the 1980s, and these observations help to advance our understanding of the circulation and ecosystem dynamics. This overview summarizes the hydrographical and biogeochemical features as well as some of the recent studies that focus on how physical forcing affects upwelling ecosystem dynamics and causes biogeochemical consequences in the TWS. Section 2 summarizes key hydrographical features in the TWS; Section 3 describes the biogeochemical processes; Section 4 discusses the variability of the upwelling and its teleconnection with the ENSO events and Section 5 addresses the interannual variation of physical and ecosystem dynamics in the TWS.

2. Hydrographical features

2.1. Circulation

The TWS circulation and its temporal and spatial variations are modulated by strong monsoon forcing and complex topography. It is influenced by the flow patterns in the northern SCS, the intrusion of the Kuroshio and the coastal current from the ECS (Wang and Chern, 1988; Jan et al., 1994; Jan et al., 1998; Hu et al.,

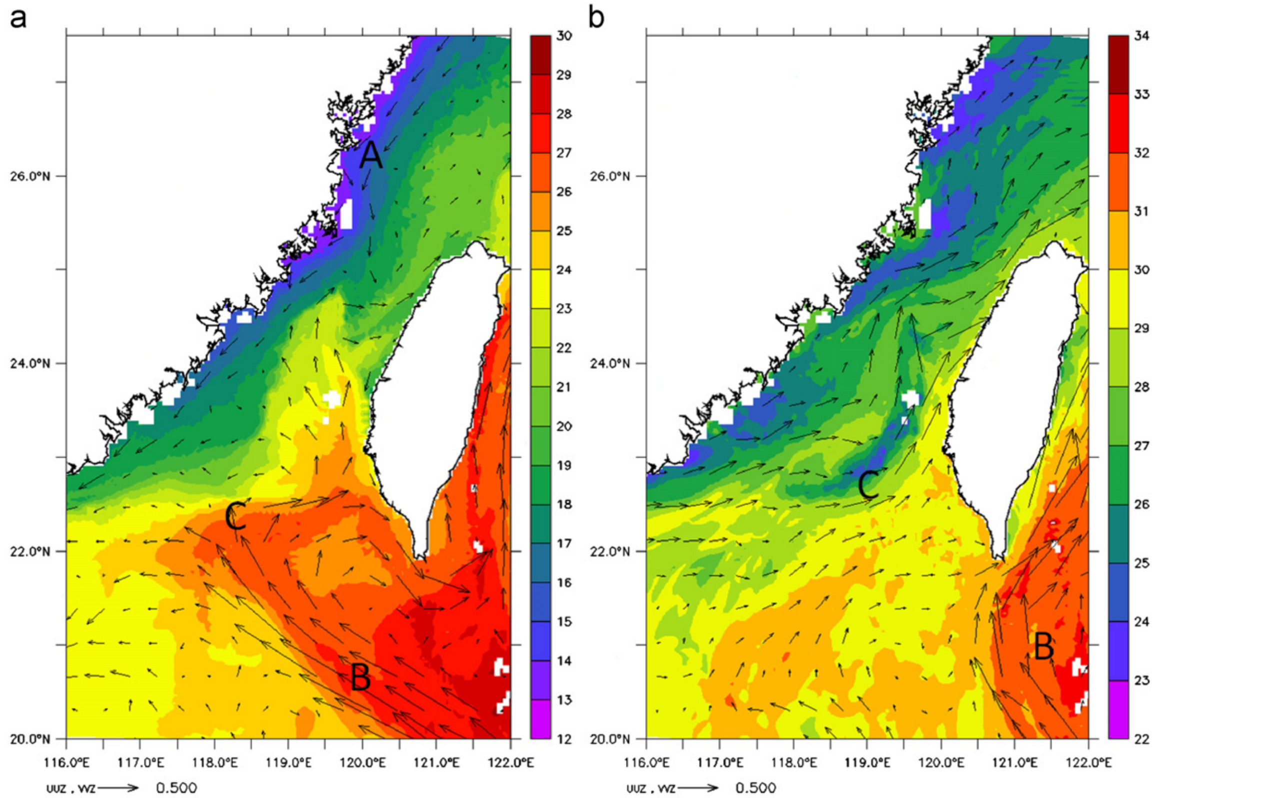

Fig. 3. A schematic diagram of surface current and temperature in the Taiwan Strait. (a), January and (b) July; (A) Zhe–Min Coastal Current; (B) the Kuroshio intrusion; (C) the extension of the SCS Warm Current (outputted from numerical model; from Jiang (2007)).

2000; Jan et al., 2002; Chen et al., 2003; Jan and Chao, 2003; Liang et al., 2003; Hu et al., 2010). The general flow patterns during winter and summer are shown in Fig. 3, which are produced from a numerical model (Jiang, 2007). In winter (Fig. 3a), the TWS is under the control of three currents: the Zhe–Min Coastal Current, the Kuroshio intrusion and the extension of the SCS Warm Current. The Zhe–Min Coastal Current flows southwestward in the upper layer along the coasts of Zhejiang and Fujian. It extends as far as the area near Dongshan. The Kuroshio intrudes into the northern SCS through the Luzon Strait, and a part of the intrusion extends northward resulting in a flow through the Penghu Channel. The extension of the SCS Warm Current flows northeastward against the prevailing wind, and a part of it also flows northward through the Penghu Channel. Together with the Kuroshio intrusion water, the northward current is mostly blocked by the Zhangyun Ridge, but a small portion manages to continue flowing northward over the Zhangyun Ridge and branches northwestward through the Pengbei Channel. In summer (Fig. 3b), the entire TWS is dominated by northeastward currents. The SCS Warm Current extends northeastward along the eastern and central parts of the TWS. This steady northeastward current was confirmed by Zhu et al. (2008) after analyzing the current measurements from the high frequency ground wave radar systems and moored Acoustic Doppler Current Profiler (ADCP) observations. The Yuedong (the eastern Guangdong) Coastal Current, with higher temperature, lower salinity and lower density in the upper layer, also flows northeastward through the channel west of the Taiwan Bank. This coastal current appears offshore because of the summertime coastal upwelling. Moreover, the Kuroshio intrusion water can extend northward through the Penghu Channel as the Kuroshio takes a loop form near the Luzon Strait (Jan et al., 2002; Chen et al., 2003; Jan and Chao, 2003; Liang et al., 2003).

2.2. Tides

The TWS has unique tidal features and tides play an important role in determining circulation in the TWS (Hu et al., 2001a). The M_2, S_2, K_1 and O_1 tidal constituents are the four main tidal constituents in the TWS, with M_2 and S_2 being the two most important ones. The M_2 or S_2 tidal wave from the northwestern Pacific Ocean enters the TWS in two ways: one propagates from the north of Taiwan Island and then turns southwestward through the TWS, while the other enters the northern SCS from the Luzon Strait and partially branches northward to the TWS. The highest amplitude of the M_2 tide can reach 160–200 cm along the western TWS (Hu et al., 2001a). Except in the southern part of the TWS, most areas are characterized by regular semi-diurnal tidal currents. Stronger tidal currents usually appear in the Penghu Channel and in the area off Pingtan (Jan et al., 2004). Using about 2.5 years (1999–2001) of shipboard ADCP data, Wang et al. (2003) indicated that the average tidal current is 0.46 m/s, with maximum amplitude of 0.80 m/s at the northeastern and southeastern entrances and minimum amplitude of 0.20 m/s in the middle of the TWS.

2.3. Upwelling

Upwelling is a predominant feature in the TWS. A series of multi-disciplinary surveys has been conducted to study the upwelling dynamics since the 1980s (Chen et al., 1982; Fu, 1984; Hong et al., 1991; Li and Li, 1989; Hong and Li, 1999). Numerical modeling (Cai and Lennon, 1988; Hu and Chen 1991; Zhang et al., 1991) and satellite remote sensing (Hu et al., 2001b; Tang et al., 2004; Zhang et al., 2006) have also been used to investigate the upwelling dynamics in the TWS. These studies confirmed the existence of upwelling areas and elucidated their variations in the TWS.

Hu et al. (2003) provided a comprehensive review of upwelling dynamics in the TWS. There are four main upwelling areas in the TWS (shown in Fig.1). The first two are the wind-driven with topographic forcing upwelling areas located near Dongshan and Nanao in the southwestern TWS (called SW-upwelling for convenience hereafter) and near Pingtan in the northwestern TWS (NW-upwelling), where upwelling occurs during the summer monsoon. The other two are the topographically induced upwelling areas near the Taiwan Bank (TB-upwelling) and around the Penghu Islands (PH-upwelling) (Fig. 1). Upwelling near the coast (SW-upwelling and NW-upwelling) is more dependent upon the prevailing southwesterly winds in summer, which generates Ekman pumping, whereas upwelling around the Taiwan Bank and the Penghu Islands is more persistent due to the interaction between the bottom topography and the year-round northward flow (Hong et al., 1991).

Recently, a high resolution model has been developed based on the Princeton Ocean Model (POM) with nested domains, which cover the Northwest Pacific with a $\frac{1}{5}^{\circ}$ grid and the TWS area with a $\frac{1}{25}^{\circ}$ grid (Jiang, 2007). The model is validated with both *in situ* and remote sensing data, and can be used to investigate the upwelling dynamics and controlling mechanisms in the TWS (Jiang et al., Submitted). The numerical model output demonstrates that although the southwesterly wind induced Ekman pumping plays an important role, the ascending onshore near-bottom current from the southwest is also a major driver for the upwelling. It also reveals that the source water for the SW-upwelling is from the subsurface layer of the northern SCS. For the TB-upwelling, the current with a year-round positive vertical velocity carries the cold water up to the subsurface layer, where the strong tidal processes enhance vertical mixing that brings the upwelled water to the surface (Jiang et al., Submitted). The source water of the TB-upwelling includes the Kuroshio intrusion water mixed with the northern SCS subsurface water. The source of the NW-upwelling water may also have a portion of the Kuroshio intrusion water from the mixed water that flows northwestward. Such water usually shows lower temperature and higher salinity as compared to water of the SW-upwelling region (Hong et al., 1991; Jiang et al., Submitted).

2.4. Intrusion of Zhujiang diluted water

Another important hydrographical feature in the TWS is the intrusion of Zhujiang (Pearl River) diluted water, which brings nutrients and fresh water. Evidence for this notion was obtained by underway measurements of Sea Surface Temperature (SST) and sea surface salinity in August 1999. It was observed that a 20 km zone with a high SST (up to 28.6 °C) and a low sea surface salinity (about 33) extended to the south of the Taiwan Bank, several hundred kilometers from the coast (Chen et al., 2002). This low salinity tongue, characterized by high temperature, 3–6 °C higher than the coastal water, and the salinity 2.5–7 lower than the surrounding waters, was also observed in summer 2005. Hong et al. (2009a) confirmed, using numerical model result, that this water was originated from the Zhujiang River Estuary. However, the spatial distribution and temporal variability of the Zhujiang diluted plume water and its impact on the physical and biological processes in the TWS are still unclear.

2.5. Volume transport through the TWS

Northward volume transport through the TWS is an important source of nutrients for the ECS (Liu et al., 2000; Fang, 2004). Chen and Wang (1999) estimated that the TWS outflow contributes 36% in summer and 11% in winter of the total nutrient budget in the ECS. According to Chung et al. (2001), nutrient fluxes through the TWS to the ECS in spring and summer are comparable to the total input from the Changjiang (Yangtze River) and other smaller rivers in terms of the nitrogen budget, but are 8–17 times larger than that for the phosphate budget. It was also found that, although the water fluxes are comparable, the nutrients fluxes in August were significantly higher than those in May due to the coastal upwelling in summer (Liu et al., 2000). Obviously, the nutrient fluxes through the TWS depend on not only the northward volume transport, but also the nutrient concentrations in the source waters.

However, the seasonal volume transports through the TWS, estimated in different studies, show large discrepancies, which probably result from assessment under different conditions, such as during intensification or relaxation of the monsoons, and also from the different methods employed, e.g., numerical simulation, hydrographic data analysis or direct current measurement (Fang et al., 1991; Ko et al., 2003; Wang et al., 2003; Wu and Hsin, 2005; Jan et al., 2006). Earlier studies suggested that the transport in the TWS in winter is mostly southward due to the strong northeasterly wind, as the low salinity, cold, nutrient-rich water flows southward, especially along the western Taiwan Strait, while in summer, the volume transport responds to large-scale southwesterly winds that drive the shelf circulation (Wyrtki, 1961; Chao et al., 1996). However, more recent evidence showed that a northward transport seems to prevail in the TWS even in winter (Fu et al., 1991; Fu and Hu, 1995; Liu et al., 2000; Chai et al., 2001; Chen, 2003).

There were many studies on the mechanism of the volume transport through the TWS and suggested that the volume transport through the TWS is not only affected by the wind stress, but also by circulation in the northern SCS and by the Kuroshio intrusion (Wang and Chern, 1988; Jan et al., 2002; Jan and Chao, 2003). Chuang (1986) proposed that a pressure gradient at the southern end of the TWS is the mechanism for maintaining a steady northward flow. Other studies tended to support this mechanism for the year-round northward transport through the TWS (Jan et al., 2002; Chen, 2003; Liang et. al., 2003; Lin et al., 2005). Using ADCP observations around the Taiwan Island, Liang et al. (2003) demonstrated that the local wind is not the dominant external force for volume transport, and concluded that the Kuroshio intrusion plays an important role in determining the northward transport in the TWS. The Kuroshio intrusion occurs in the Luzon Strait and interacts with the SCS current, most of the Kuroshio intrusion water returns to the Kuroshio main path by going around the southern tip of Taiwan in winter, but a portion of this intrusion water funnels through the Penghu Channel and flows persistently northwards through the TWS (Xue et al., 2004). Jan and Chao (2003) investigated the volume transport through the Penghu Channel and its seasonal variation and showed that the northward current is weak (<10 cm/s) in winter and very strong (~ 100 cm/s) in summer. The mean transport calculated from 8 cruises of ADCP measurements is 0.86 Sv (northward). The volume transport is generally northward, with strong variations correlated with changes of the along-Penghu Channel sea-level gradients as well as monsoonal winds, little affected by the local wind. Lin et al. (2005) monitored the current velocity across the TWS in winter and found that the cold China coastal water flowed southward nears the surface, but the current at depth flowed primarily northward, which was against the surface wind. These studies illustrate the complex seasonal variation of circulation and volume transport in the TWS, controlled mainly by the Kuroshio intrusion and the monsoons.

It should be noted that under normal summer conditions, the transport generally flows northward but may be altered significantly by episodic events such as typhoons. Using a two-way nested coupled tide-surge model (Zhang et al., 2007), Zhang et al. (2009) estimated that the mean transport during the period 27 August to 5 October 2005 is 0.35 Sv, markedly smaller than the climatological transport estimate for September (2.01 Sv northward) estimated by Chai et al. (2001). During this period, five typhoons caused five current reversing events in the TWS, during which the flow direction through the TWS was reversed temporarily from northward to southward. Consequently, the mean transport was still northward but reduced in magnitude. Shiah et al. (2000) found that, after a typhoon event in summer 1996, the measured concentrations of chemical and biological constituents were much greater than those during normal summer periods, and the primary production and particulate organic carbon inventory increased at least twofold. Normally, several typhoons may affect the TWS in one summer, and, therefore, the disturbances caused by typhoon events should not be ignored but need be studied further.

3. Biogeochemical processes

Biogeochemical processes in the TWS have been investigated in several studies over the past 20 years (Hong et al., 1991; Hong and Dai, 1994; Hong and Wang, 2001; Chen et al., 2004; Naik and Chen, 2008). Hong et al. (1991) conducted a comprehensive upwelling ecosystem study in the Minnan–Taiwan Bank Fishing Ground during the period 1987–1989. Their early results showed that the nutrients and biological productivity are strongly influenced by physical processes, e.g. circulation and different water masses, in the TWS. In winter, the Zhe–Min Coastal Current brought highest nutrient concentration water has significant impacts on the coastal area, but for most areas, vertical mixing is the dominant process enhancing phytoplankton growth during the northeasterly monsoon. In summer, upwellings during the southwesterly monsoon supply nutrients, especially phosphate, to the surface along the west coast in the TWS (Hong et al., 1991). It is estimated that the summertime upwelling could contribute up to 16% of phosphate of the total phosphate demanded for the photosynthesis at the surface water, which is important in maintaining the high productivity during summer in the TWS (Wu and Ruan, 1991; Wu et al., 1997; Hong and Wang, 2001). The newly upwelled nutrients not only support the local biological productivity (Hong et al., 1991; Wu and Ruan, 1991), but also can be exported to the ECS through the northward transport (Chung et al., 2001).

The spatial distribution and seasonal variation of phytoplankton biomass and primary productivity are largely controlled by the input of nutrients from various water masses. Using the surface chlorophyll *a* data from SeaWIFS observations during 1997–2004, we can see that the average surface chlorophyll *a* in the TWS is higher in winter than that in summer (Fig. 4). Also, relatively higher depth-integrated chlorophyll inventories were observed in February 1995 than in August 1994 during field observations (Hong et al., 1997). The highest concentration of surface chlorophyll *a* in the northern TWS was observed in the near-shore region in winter, while the maximum in the southern TWS occurred in the upwelling area in summer (Fig. 4; Hong et al., 1997). Naik and Chen (2008) also found the same pattern based on their observations during 2001–2003. This suggests that the production peaks of phytoplankton are different between the northern and southern TWS, coinciding with the major inputs of nutrients to different parts of the TWS (Hong and Dai, 1994; Hong et al., 1997; Naik and Chen, 2008).

Moreover, our recent studies indicate that there is a significant difference in the temporal variation patterns of chlorophyll *a*

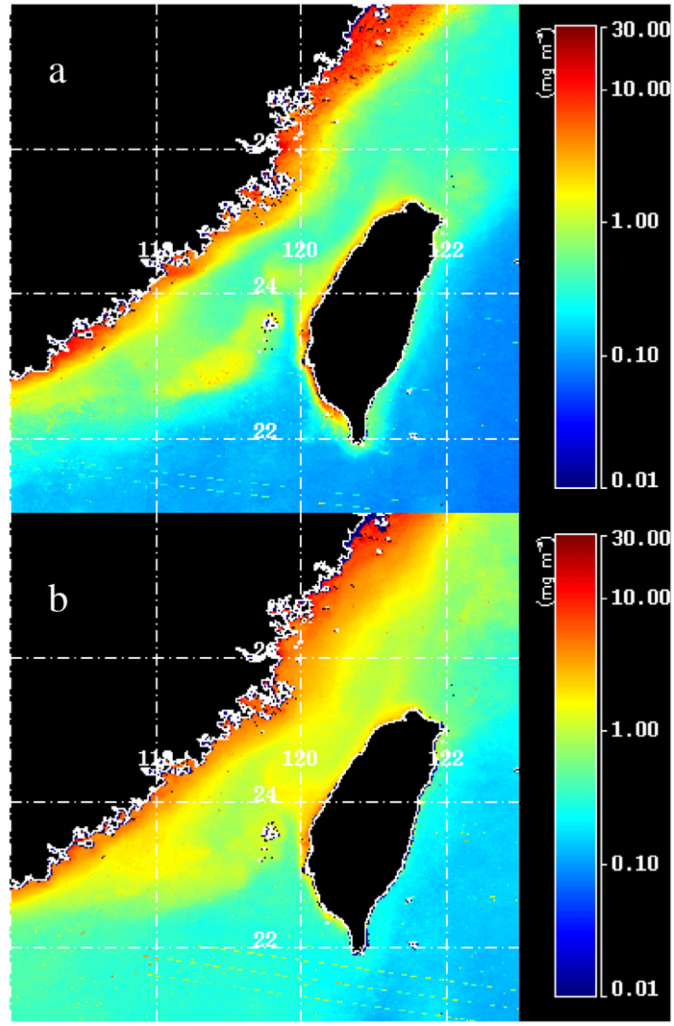

Fig. 4. Average surface chlorophyll *a* from the SeaWIFS images during 1997–2004. (a) summer and (b) winter.

concentrations in the three sub-areas of southern TWS based on the satellite seasonal climatological chlorophyll *a* data (SeaWiFS and MODIS). In the coastal area (with water depth less than 75 m but excluding the Taiwan Bank area), two chlorophyll *a* peaks were observed, corresponding to the occurrence of upwelling during the southwesterly monsoon and the onset of the Zhe–Min Coastal Current during the northeasterly monsoon, respectively. In the Taiwan Bank ($<$ 40 m), the high chlorophyll *a* occurring throughout the year was due to the topographically induced upwelling all year-round. In the shelf break area ($>$ 75 m), higher chlorophyll *a* concentrations observed during the northeasterly monsoon were attributable to vertical mixing. Different patterns of phytoplankton seasonal variation in these three sub-areas of the southern TWS suggest that the nutrient availability is the key factor controlling its variation (Hong et al., this issue).

Primary productivity in the TWS is regulated by large scale nutrient distribution as well as by the phytoplankton community structure and zooplankton grazing (Wang et al., 1997; Huang et al., 1997; Guo et al., 1999; Huang et al., 1999; Zhu et al., 2000; Huang et al., 2002; Lin et al., 2002; Wang et al., 2002). The nano- and pico-phytoplankton ($<$ 20 μm) are dominant in the TWS and could account for 60–80% of the total chlorophyll *a* and 80% of primary productivity, respectively (Wang et al., 1997; Huang et al., 1999). Furthermore, higher abundance and carbon biomass of the major groups of pico-phytoplankton, *Synechococcus* and pico-eukaryotes, were found in summer (in 1997 and 1998 August) than in winter (February–March, 1998), suggesting that temperature is an important factor influencing the distribution of *Synechococcus* and pico-eukaryotes in the TWS (Huang et al., 2009).

Not only the total phytoplankton biomasses differ considerably between the northern and southern TWS, but the phytoplankton community structures are also very different. The nanophytoplankton (3–20 μm) is dominant in the northern TWS (59% and 57% of the total biomass for summer and winter, respectively), while the pico-phytoplankton is more abundant in the southern TWS (71% and 63% of the total biomass for summer and winter, respectively) (Wang et al., 1997). This is mainly due to the different degrees of nutrient enrichment associated with different water masses in the northern and southern TWS. The phytoplankton structure in the northern TWS closely resembles the size-structure in the ECS, while the structure in the southern TWS resembles that in the SCS. This indicates the importance of phytoplankton structure transition from SCS to ECS in the TWS (Hong et al., 1997).

The biomass of the zooplankton is dominated by the small-size species collected with the medium mesh plankton net (Huang et al., 1997; Zhu et al., 2000). The Photosynthetic Dissolved Organic Carbon (PDOC) accounts for about 25% of primary production, and the heterotrophic activities of bacteria are positively correlated with the PDOC. According to model estimation, the contribution of the microbial food web to the whole food web is about 30%, revealing the fundamental significance of the microbial loop in the transfer of biogenic organic carbon in this subtropical region (Hong et al., 1997; Peng et al., 1997; Hong and Wang, 2001; Zheng et al., 2002). The dilution experiments indicate that there is almost a balance between phytoplankton growth and microzooplankton grazing in the non-upwelling area, while phytoplankton growth is higher than grazing in most cases examined in the upwelling area. This suggests that the microbial loop dominates in the shelf-break non-upwelling area, while the traditional food web (grazing via mesozooplankton) contributes more in the coastal upwelling waters (Huang et al., this issue).

Complex physical and biological processes also affect carbon cycling and air–sea CO_2 fluxes in the TWS. Zhang et al. (2000), measuring the TCO_2 and pCO_2 in August 1994 and February 1995, reported that the variation of TCO_2 in the water was correlated to the different water masses and showed seasonal variation. The estimated air–sea CO_2 fluxes are negative (flux from seawater to air) in August and positive in February. The estimated average annual flux is positive, suggesting that the TWS serves as a net sink of atmospheric CO_2 (Zhang et al., 2000). By means of underway pCO_2 measurement in July–August 2000, Zhai et al. (2005) observed that, in the coastal upwelling region of the southern TWS, the pCO_2 in surface seawater reached as high as 400–600 μ atm, suggesting a significant source of CO_2 during the upwelling event. During the summer cruises of July–August 2004, July 2005 and June–July 2006, the air–sea CO_2 fluxes were investigated in detail during different stages of the upwelling events. The results suggest that mixing of different water masses contributes nearly 50% to the variability of surface pCO_2. The alternation between the source and sink of CO_2 in these upwelling areas depends on the stage of development and the intensity of the upwelling events. Calculated air–sea CO_2 fluxes show that the inshore areas with low pCO_2 values acted as a strong sink for atmospheric CO_2, but they changed to a weak CO_2 source during the peak of an upwelling event. The front between coastal and upwelling water becomes biologically productive and enhances sequestration of atmospheric CO_2 into the water. In general, the southern TWS region acts as a sink of atmospheric CO_2 both in summer and in winter, but it is about five times larger in summer than that in winter when upwelling occurs. By contrast, the areas with coastal upwelling occurring in summer show large temporal variation: the net air–sea CO_2 flux was negative in the early stage of upwelling as observed during the cruise of 2004; the net flux became positive in the relaxation period between upwelling events as observed during the cruise of 2005 (Chen, 2008). The above studies demonstrate the complexity of carbon cycling in the TWS, whereby it may act either as a source or as a sink of atmospheric CO_2 depending on the initial TCO_2 in the seawater, the temperature and the biological effects.

4. Variability of the upwelling and its teleconnection with the ENSO events

SST is often used as a proxy for upwelling features with lower SST indicating strong upwelling. A time series of SST data derived from Advanced Very High Resolution Radiometer (AVHRR) measurements and sea surface chlorophyll *a* data derived from Sea-Viewing Wild Field-of-View Sensor (SeaWiFS) images illustrate the short-term variation of size and shape of the Dongshan upwelling zone (one part of the SW-upwelling area) and the TB-upwelling area between August 8 and 17 of 1998, which are consistent with the field measurements (Tang et al., 2002). By combining the remote sensing data with *in situ* CTD mapping data obtained in August 1998, the spatial synoptic features associated with coastal upwelling events and their temporal evolution were observed. It was concluded that the episodic coastal upwelling events during southwesterly monsoons are controlled by the variation of surface wind stress. The short term variability of chlorophyll associated with upwelling events, which reflects the state of phytoplankton growth, normally shows a lag of about two days with respect to the peak of the upwelling (Shang et al., 2004).

Monthly variation of the SW-upwelling region was observed on a series of cruises in summer 1988. The upwelled cold water (23 °C, a 2–4 °C SST difference compared with the surrounding water) reached the 10 m depth in June, the 5 m depth in July and the surface in August (Hong et al., 1991). In other words, the upwelling started in June, strengthened in July and intensified in August, coinciding with the succession of surface wind intensification. The salinity reached 34.6, suggesting that the upwelling water came from deeper layer. This was supported further by the abundance of zooplankton species such as *Pareuchaeta russelli*, which normally resides at 200 m depth but was found near the surface in the whole upwelling region (Hong et al., 1991).

From AVHRR-derived SST images in the TWS during June–August 1996–1999, several distinct areas with lower SST can be easily observed, and these corresponded to the four upwelling areas discussed earlier (Fig. 1; Hu et al., 2001b). The bi-monthly AVHRR SST images from 1996–1999 also illustrate the interannual variability of upwelling. The SST images indicate that upwelling is stronger in the summers of 1998 and 1999, but weaker during the summers of 1996 and 1997 (Hu et al., 2001b).

Fig. 5 shows the time series of area of the High Chlorophyll *a* zone (HChl) with chlorophyll *a* concentration ≥ 1.0 mg/m^3, chlorophyll *a* anomaly, area of the low temperature zone with SST difference ≤ 1 °C below the regional mean, alongshore wind stress anomaly, sea surface temperature anomaly and the overlapping biweekly mean multivariate ENSO index during the period between 1985 and 2005. The area of the low temperature zone in 1987 was 75% above average, while, in 2001, it was 67% below average. Obviously, the coastal upwelling intensity in summer fluctuates from year to year. The variation of area of the low temperature zone shows positively correlated with the alongshore component of the upwelling-favorable wind stress

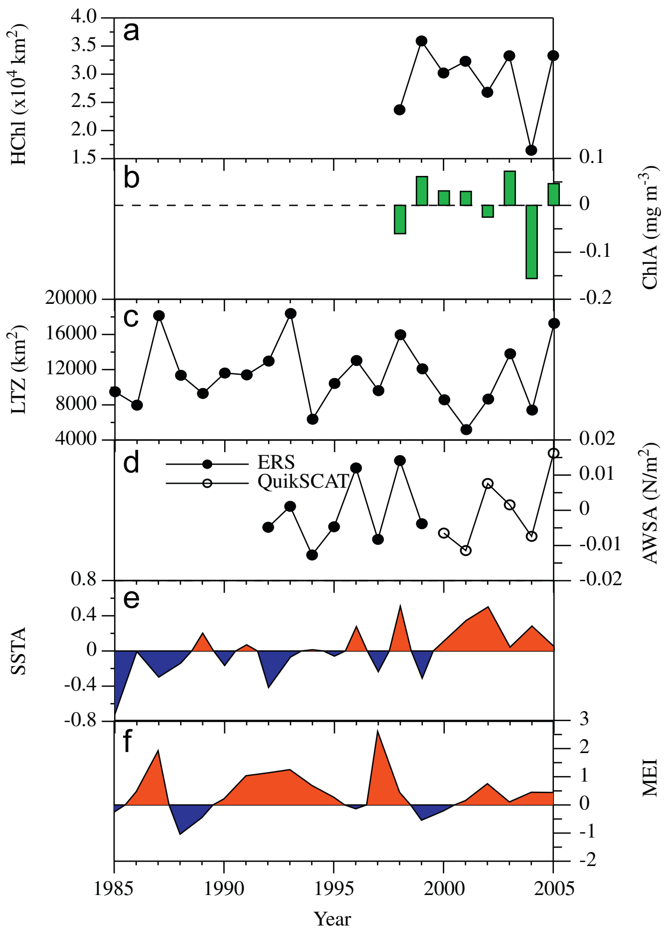

Fig. 5. The interannual variability of summer coastal upwelling in the Taiwan Strait. (a) Time series of the area of chlorophyll ≥ 1 mg/m^3 (HChl), (b) Chlorophyll Anomaly (ChlA), (c) Low Temperature Zone (LTZ), (d) alongshore wind stress anomaly (AWSA), (e) Sea Surface Temperature Anomaly (SSTA) and (f) overlapping biweekly mean Multivariate ENSO Index (MEI) during various time periods between 1985 and 2005.

with a correlation coefficient of 0.72 for 95% significance. Interannual variability of chlorophyll *a* and HChl was also evident between 1998 and 2005, the lowest HChl in the summer of 2004 was only about half of that in 2003 and 2005 (Fig. 5).

The interannual variation of summer coastal upwelling in the TWS was further studied based on Empirical Orthogonal Function (EOF) analysis of the monthly mean SST data derived from AVHRR products for 1985–2005 (Hong et al., 2009b). The results showed that the first mode (85.3%) of the spatial variance indicates a persistent front with strong temperature gradients near the four upwelling regions discussed previously. The temporal variation of this front is closely correlated with the alongshore wind stress anomaly from 1992 to 2005, indicating the wind-driven nature of coastal upwelling. The results also indicated that the summer coastal upwelling on the western side of the TWS was stronger in 1987, 1993 and 1998, and weaker in 1986, 1994, 2001 and 2004, which is also confirmed by hydrographical records at the Dongshan and Pingtan stations (Hong et al., 2009b). Hong et al., 2009b also note that the intensity of coastal upwelling is highly correlated with multivariate ENSO index at a time lag of 3–6 months (see Fig. 6 in Hong et al., 2009b), suggesting that a delayed ENSO effect was likely a major mechanism for the interannual variability of TWS coastal upwelling.

The 1997–1998 ENSO events was one of the strongest in the 20th century. The combined hydrographic and satellite-derived information provides evidence for the teleconnection between the TWS upwelling and the ENSO events. Weakening of the upwelling was observed during the summer of 1997, while the area of low temperature and high salinity was much larger in the summer of 1998. Estimated from composite images, the scale of the SW-upwelling zone or the TB-upwelling zone was about 100 km in August 1996, and increased to 100–150 km in August 1998. In August 1997, the scale of both SW- and NW-upwellings decreased and the low temperature zone had a length scale of only 10–50 km (Hong et al., 2005). Besides weakening of the coastal upwelling in 1997, the amount of Yuedong (the eastern Guangdong) coastal water and Zhujiang diluted water entering the TWS were also reduced significantly (Hong and Wang, 2001).

Comparison of the species composition and distribution of pelagic copepod between a non-ENSO year (1994) and an ENSO year (1997) also provides evidence of the effect of this ENSO event (Huang et al., 2000b; Hong et al., 2005). The fresh water indicator species such as *Labidocera euchaeta* and *L. bipinnata* did not appear in this area during the summer of 1997, indicating reduction of the Zhujiang diluted water; and the deep water species such as *Neocalnus gracilis* and *Actideus armatus* did not appear in the nearshore in summer of 1997 as they usually do during normal upwelling events. The yield of the pelagic fish *Sardinella Anritas* and the composition of the fish species also showed clear changes during 1997–1998. It seems that ENSO events can influence the intensity of the summer monsoon, which is closely related to the upwelling processes in the TWS, and in turn, affect the upper trophic level species composition and abundances (Kuo and Ho, 2004; Hong et al., 2005).

During the winter of the 1997–1998 El Nino event, the TWS water was significantly warmer and more depleted in nutrient resulting in lower biological productivity as compared to other years between 1986 and 2003 (Shang et al., 2005). Furthermore, the pico-phytoplankton dominated both the phytoplankton biomass and productivity in the northern TWS, whereas the nano-phytoplankton dominated in the winter of 1995, a normal year (Hong et al., 2005). It provides yet another indication for stronger intrusion of Kuroshio water into the TWS during the winter of 1997–1998. These observations suggest that El Nino events have potentially significant ecological impacts on the TWS (Hong et al., 2005; Shang et al., 2005).

5. Ecosystem responses to the interannual variation of upwelling

Upwelling has a tremendous impact on biogeochemical processes, biological productivity and ecosystem structure. The timing and location of pelagic fishing grounds are coincident with these upwelling events (Hong et al., 1991; Tang et al., 2002). The Taiwan Bank fishing ground was the first identified as an upwelling fishing ground in 1991 (Hong et al., 1991).

By comparing remote sensing SST and field chemical and biological data collected since 1985, the evidence of ecosystem changes in response to interannual environmental variation was found in the TWS. The nutrient distribution, phytoplankton and zooplankton abundances showed anomaly and the community structure altered. For example, the summer upwelling was weakened in 1997, and the observed surface NO_3 concentration and chlorophyll *a* value were only 0.60 μmol/dm^3 and 0.4 mg/m^3, respectively, whereas they were 3.0 μmol/dm^3, 2.5 mg/m^3 in the summer of 1988. In the winter of 1998, the Zhe–Min coastal water weakened and northward intrusion of warm water was strengthened, either biomass or productivity were dominated by the pico-plankton while in 1995, the micro-plankton dominated the contributions (Hong et al., 2005).

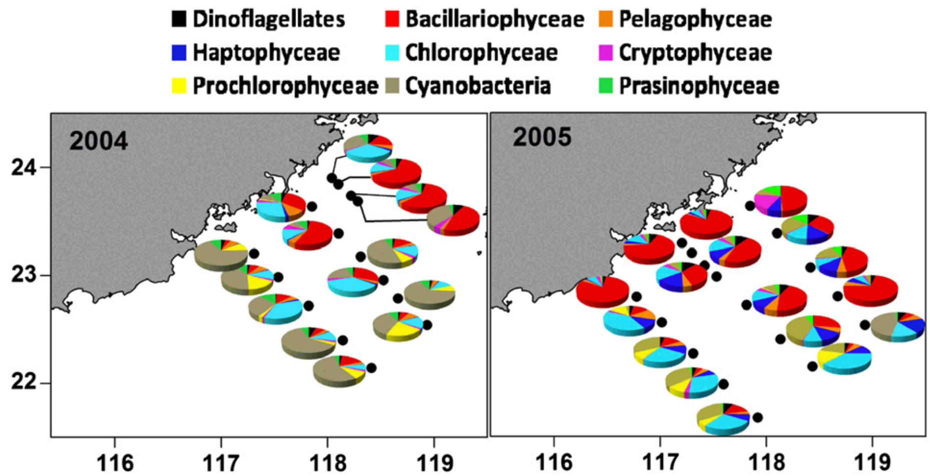

Fig. 6. Response of phytoplankton group composition to upwelling events between the summer of 2004 (left panel) and 2005 (right panel) using photosynthetic pigment analysis.

During 2004–2007, we conducted four summer cruises in the southern part of the TWS in order to investigate the detailed responses of the ecosystem to upwelling events. Our results again show significant year-to-year variations of physical and biological processes. For example, comparing 2004 and 2005, the monthly mean SST derived from AVHRR reveals that the area of low temperature zone ($<=1$ °C below the regional mean) is 1.6 times larger in 2005 than that in 2004, while the area of higher phytoplankton biomass (SeaWiFS/MODIS chlorophyll $a \geq 1$ mg/m^3) increased by about 55% in 2005 over that in 2004. The alongshore wind stress derived from QuikSCAT in 2004 was 0.0026 N/m^2, and this increased to the much higher value of 0.024 N/m^2 in 2005. Field observations also indicated that the water column-integrated chlorophyll *a* during the sampling periods was 38 mg/m^2 in 2004, which was about half the value during 2005 (63 mg/m^2). This suggests that strong coastal upwelling events occurred in 2005, leading to a broader area of cold, nutrient-rich and productive water.

Based on photosynthetic pigment analysis, it was discovered that phytoplankton group changes occurred in response to upwelling events. Diatoms were predominant in the upwelling area near Aotou (SW-upwelling) in 2005 and accounted for 72% of the total phytoplankton biomass. At the same location in 2004, when upwelling was reduced, cyanobacteria overwhelmed the diatoms and contributed up to 63% of the total phytoplankton biomass (Fig. 6). *Skeletonema costatum, Pseudo-nitzschia delicatissima, Asterionellopsis glacialis* and *Thalassionema nitzschioides* were dominant species in summer, while *Melosira sulcata and Coscinodiscus* spp. in winter in coastal area in the southern TWS.

Upwelling events usually develop and decay over a short period (a week to 10 days) responding to changes of wind patterns. It was reported that both phytoplankton biomass and community structure change rapidly at different stages of upwelling. Diatoms were dominant in the community as being induced by upwelling events, but were progressively replaced by picoplanktonic cyanobacteria during the decline of upwelling, while diatoms increased and cyanobacteria decreased during the developing stage of the upwelling event (Hu, 2009). Overall, diatoms were more sensitive to the nutrient input caused by upwelling, and usually with blooms following onset of upwelling, but it then diminished and was replaced by other smaller phytoplankton (e.g. cyanobacteria) as the upwelling declined.

The variations of hydrographical processes largely control the seasonal variations of nutrient distribution and fluxes, and thus cause dramatic changes in phytoplankton community structure. In general, the region is characterized by low phosphate, as discussed previously (Huang and Hong, 1999; Huang et al., 2000a). Measurements of bulk alkaline phosphatase activity and single-cell alkaline phosphatase activity assay in July–August 2004 and March 2005 showed that the phytoplankton community in the TWS was generally under phosphate stress, but this shortage might be abated with the external input of phosphate during upwelling events (Ou et al., 2006). Moreover, *Asterionellopsis glacialis* (centric diatom) often became the dominant species during the upwelling period. The mechanism of formation of this diatom bloom was investigated in terms of nutrient physiology, and the *in situ* measurements. Incubation experiments indicated that the nitrate reductase and glutamine synthetase composition of *Asterionellopsis glacialis* was different from those of other species. The specific proteins found during proteomic analysis explained the fast response of *Asterionellopsis glacialis* to nitrogen supplementation from the upwelling water. These results suggested that *in situ* physiological adaptation could be an important mechanism in determining the dominant species changes under different nutrients conditions related to upwelling events (Hong et al., this issue).

During the 2005 and 2006 cruises, 157 species of copepods were identified, and the lateral distribution of copepods was closely related to variations in chlorophyll *a* concentration. Higher chlorophyll *a* and copepod abundance were observed in the coastal area due to coastal upwelling with an SST less than 23.0 °C and sea surface salinity greater than 34.0. *Calanus sinicus* is a temperate species with an optimal temperature range of 9–20 °C. In summer, when the seawater was warmer, *Calanus sinicus* was restricted to the upwelling region with low temperature and high salinity water. Thus, *Calanus sinicus* could be considered a biological indicator of upwelled cold water in the southern TWS (Guo et al., this issue).

6. Summary

In summary, the dramatic temporal and spatial variability in physical and biogeochemical processes in the TWS are modulated by strong monsoon forcing, complex topography and conjunction of several current systems including the intrusion of Kuroshio water. The interannual variation in these processes show teleconnection with impact of ENSO events. During the winter of the 1997–1998 El Nino, the TWS water was significantly warmer and depleted in nutrients, which resulted in lower biological productivity as compared to other years between 1986 and 2003.

There are four upwelling areas in the TWS. Upwelling near the coast occurs during the summer and depends on the prevailing southwesterly winds. Upwelling around the Taiwan Bank and the Penghu Islands occurs throughout the year, which is due to the interaction between the bottom topography and the northward flow. It is estimated that the summertime upwelling could contribute up to 16% of phosphate of the total phosphate needed for the primary production in the TWS. In these upwelling areas, the ocean acts as source and sink of CO_2 to the atmosphere that depends on the stage and the intensity of the upwelling events.

The primary producers in the Taiwan Strait are dominated by nano- and pico-phytoplankton, and the contribution of the microbial food web to the traditional food web is estimated to be about 30%, implying the fundamental significance of the microbial food web in this subtropical region. The phytoplankton biomasses and community structure differ considerably between the northern and southern TWS, indicating the importance of phytoplankton structure transition from SCS to ECS in the TWS. The intrusion of Zhujiang (Pearl River) diluted water could extend to the southern part of the Taiwan Strait, which was confirmed by the numerical model results and *in situ* observations. However, the impact of this Zhujiang diluted water on physical processes and nutrient dynamics in the TWS are still unclear.

The Taiwan Strait is an important channel in the west Pacific Ocean transporting water and chemical constituents between the East China Sea and the South China Sea. We have made some progress in advancing our understanding on physical and biogeochemical processes in the TWS. However, we still need better spatial and temporal observations, along with modeling and remote sensing, to address the complex physical and biogeochemical processes and ecosystem dynamics in the TWS.

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