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Evolution of a coastal upwelling event during summer 2004 in the southern Taiwan Strait

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Abstract
A coastal upwelling event in the southern Taiwan Strait (STWS) was investigated using intensive cruise surveys (four repeated transects in a month) and satellite data in July and early August 2004. The extensive upwelling-associated surface cold water was first observed in early July ($\sim 2.0\times10^4$ km^2) along the STWS coast. Then, the cold surface water reduced in size by ~50% with decreased chlorophyll concentrations after 15 days, indicating the weakening of the upwelling event. At the end of July, the cold surface water disappeared. The temporal variations of the surface cold water and the 3-D hydrography around Dongshan Island are thought to be mainly attributed to the weakened upwelling-favorable southwestern wind, the asymmetric spatial structure of the wind field and the intrusion of warm water from the northern South China Sea.

Key words: coastal upwelling, evolution, SST, ocean color, remote sensing, Taiwan Strait

1 Introduction

Upwelling is an important process in the ocean, by which deep, cold, nutrient-rich water is brought to the surface, stimulating new production and phytoplankton biomass. However, there is great variability in the coastal upwelling processes, mainly related to changes in wind strength and direction (Brink, 1983; Mann and Lazier, 1996; Chavez et al., 2002; Ramp et al., 2005). For example, within the 6-month season of upwelling off Oregon, there are four or five periods of strong upwelling separated by periods of little or no upwelling (Mann and Lazier, 1996).

The Taiwan Strait (TWS) is located between the South China Sea (SCS) and the East China Sea (ECS) (Fig.1). During summer, southwest monsoon prevails. Following the wind pattern, the horizontal advection in the TWS mainly originates from the SCS, normally referred to as Yuedong coastal water and/or South China Sea shelf water. Meanwhile, such a wind pattern is favorable for inducing coastal upwelling along the mainland coast (see review by Hu et al., 2003; Shang et al., 2004; Tang et al., 2002; Gan et al., 2009). The coastal upwelling in the southern TWS has been investigated since the 70's (Chen et al., 1982; Hong, et al., 1991; Xiao et al., 1988). It occurs in the shallow channel (~40 m average water depth) between the Taiwan Bank and the East Guangdong-South Fujian coast, which has a complicated dynamic and frontal structure (Li et al., 2000; Wang et al., 2001) and thus becomes one of the main summer fishing grounds in China Sea. Furthermore, this upwelling was suggested to contain two sub-systems, Yuedong and Minnan upwelling, separated in the vicinity of Dongshan Island with different temporal patterns within the three-month season of upwelling (June to August) (Li and

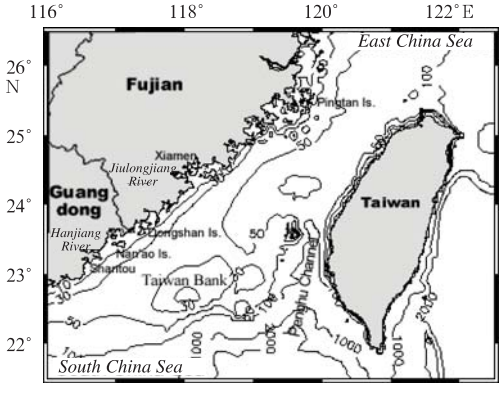

Fig.1. Map of the Taiwan Strait, overlaid with the bathymetry contours in meters.

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Li, 1989). There have also been limited reports (e.g., Hong et al., 1991) that the upwelling center might be shifted between the vicinity of Dongshan Island and offshore Shantou from June to August. However, the details of the short-term transitions have never been reported in the literature.

In this paper, based on intensive in situ surveys and synoptic satellite mapping, we document the short-term evolution of a coastal upwelling event in this region from 6 July to 2 August in 2004.

2 Data sources

In situ data were collected along four cruise transects in the southern TWS from 6 to 23 July 2004 and from 26 July to 2 August 2004, respectively (Figs 2 and 3). These data include surface temperature, salinity, and chlorophyll fluorescence measured using a SeaBird SBE21 thermosalinographer and a WETLabs WETStar fluorometer. The flow-through in vivo fluorescence was calibrated to chlorophyll-a concentration (Chl, mg m^{-3}) using water samples from the discrete stations (Zhang et al., 2006). In addition, CTD data were collected using a SeaBird SBE 19 CTD profiler during the last two transects. Sample locations are shown in Fig. 2.

Daily MODIS (Moderate Resolution Imaging Spectroradiometer)/Aqua Level-2 sea surface temperature (SST, °C) and Chl data were obtained from the US NASA Goddard Space Flight Center (GSFC), and then mapped to a cylindrical equidistant projection at ~1 km/pixel resolution. MODIS Chl data over <30 m waters were excluded due to satellite algorithm artifacts (Zhang et al., 2006). Daily wind field from QuikSCAT were obtained from the US NASA PO-DAAC. Daily wind vectors of the first 5 pixels close to the mainland coast on each scan line were averaged. Three-day mean latitudinal distribution of wind vectors were thus produced by averaging the daily wind vectors for each three-day period.

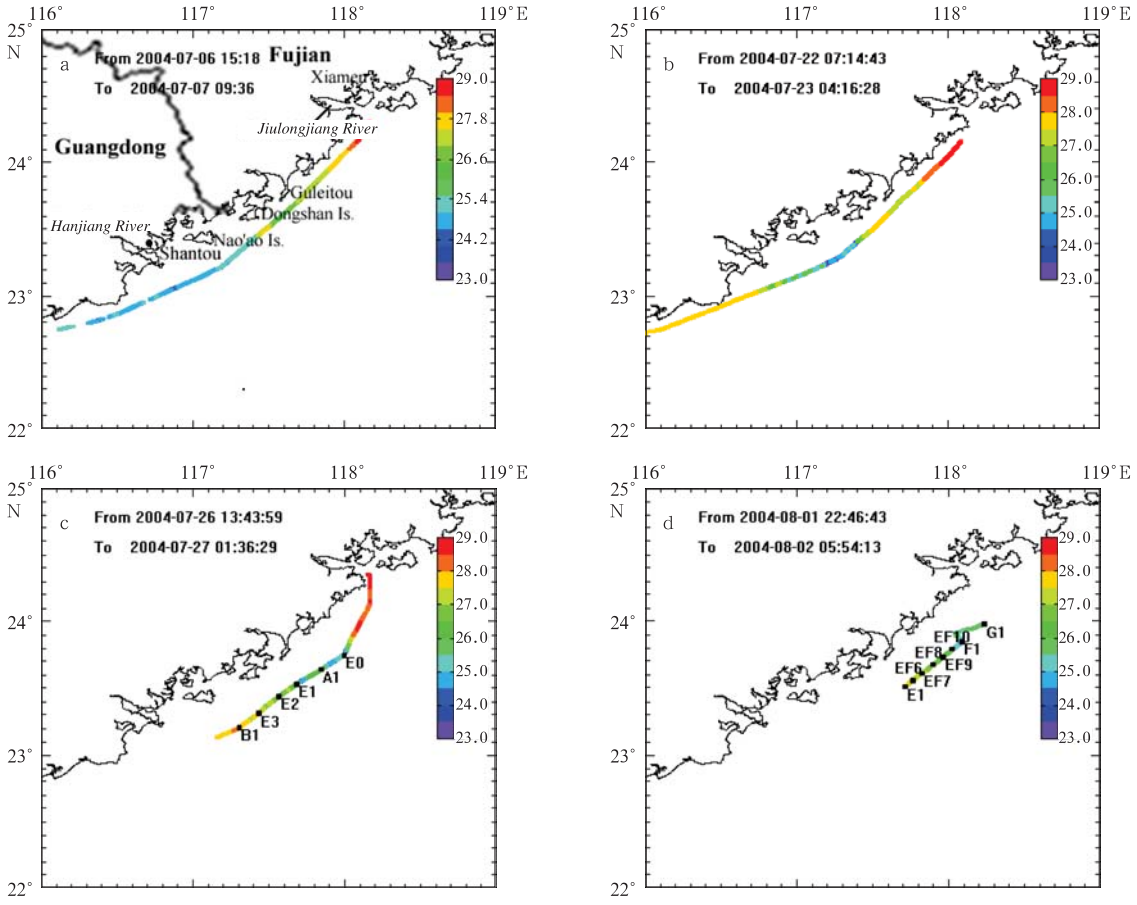

Fig.2. Surface temperature along the cruise transects during July and August 2004, overlaid with CTD stations.

3 Results and discussion

Figures 2 and 3 show the surface temperature, salinity, and Chl along the four cruise transects. During 6 to 7 July, a distinct cold belt with surface temperature <26 °C and salinity ~34.4 was observed along the eastern Guangdong and southern Fujian coast, where upwelling has been most frequently observed (Li and Li, 1989; Hong et al., 1991; Hu et al., 2003). The cold belt extended northward to 23.45°N where it encountered a strong front that might be influenced by the Hangjiang River plume (Fig. 3a). SST increased by about 2 °C and surface salinity decreased by 0.6 across the front. By 22–23 July, the length of the surface cold water (temperature <26 °C and salinity >34.2) decreased to about 40 km (Figs 2b and 3b) and was limited to between ~23°N and 23.45°N. South and north of this zone, the upper layer was occupied by warm (~28 °C) and less saline (~33.6) water. By

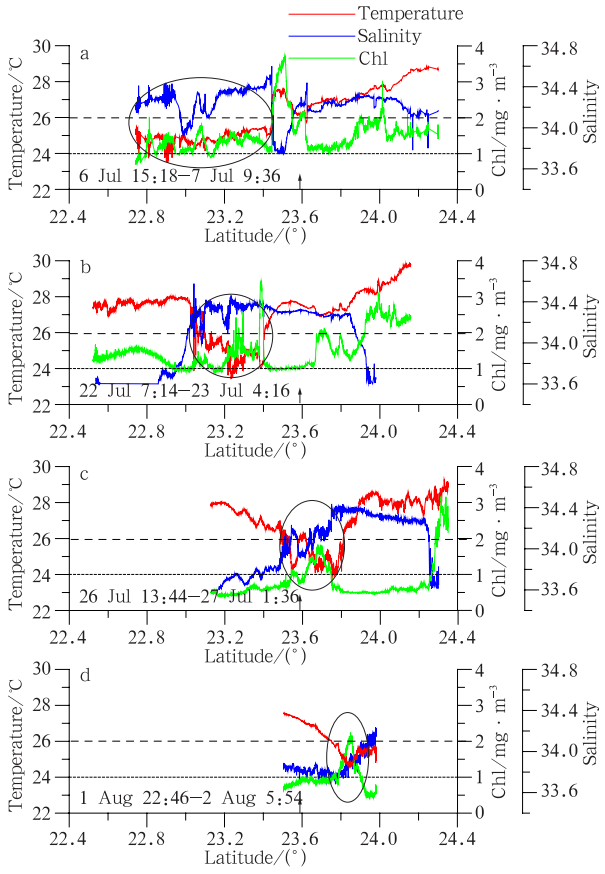

Fig.3. Surface temperature, salinity, and Chl along the four cruise transects (locations shown in Fig. 2). The dashed lines denote 26 °C. The dot lines denote Chl of 1.0 mg·m^{-3}. The arrows denote the southern tip of Dongshan Island.

26–27 July, cold surface water (SST <26 °C) was found north of Dongshan Island (~23.75°N), and by 1–2 August it slightly shifted to the north around 23.86°N.

MODIS SST images provided more synoptic view of the surface cold patches (Fig. 4). Because of the RMS difference of 1.39 °C between in situ and MODIS SST in the Taiwan Strait and cloud contamination on MODIS SST, a threshold of 28 °C was chosen to delineate cold from warm waters (white outlines in Fig. 4). On 29 June, no surface cold patch occurred off the southwestern coast. Later on 11 July, a large area (~2.0×10^4 km^2) of cold water (<28 °C) appeared, covering the region both north and south of Dongshan Island. On 24 July, the size of the surface cold water north of Dongshan Island reduced to ~8.8×10^3 km^2 (Fig. 4c). Due to cloud contamination, it was difficult to judge if there was any cold patches south of Dongshan Island solely based on MODIS SST data. One week later and on 31 July, while surface cold water appeared to have shifted further north to cover most of the Zone B, south of Dongshan Island (Fig. 4d) the cold water was replaced by surface warm water. Consequently, over the 20-day period from 11 July to 31 July, the average SST of Zone A (south of Dongshan Island, outlined on Fig. 4a) in the southwestern TWS increased from ~28.1 °C (n=12 309) to ~30.0 °C (n=12 298). In addition, a tongue of warm water (>28 °C) associated with Jiulongjiang River plume was distinct in Zone B, stretching northeastward. Whether it is forced by the upwelling coastal jet, as the Pearl River plume observed over the northern South China Sea shelf (Gan et al., 2009), is beyond the scope of this study.

By integrating the in situ underway mapping and remote sensing observations, we suggest that a coastal upwelling event occurred in the southern TWS during 6 to 11 July, and had reduced its size and intensity during 22 to 24 July. During July 26 to 2 August, the event further weakened or even ceased in the south of Dongshan Island, but the surface cold patch maintained in the north of Dongshan Island with its position shifting northward and offshore.

Consistent with the surface signatures, vertical structures of salinity, temperature and Chl on the two transects also showed a tendency of northward shift of low temperature, high salinity, and high Chl waters during 26 July to 2 August (Fig. 5). During 26 to 27 July, the entire upper 1–8 m layer was dominated by waters of temperature <25 °C between Sta.

A1-E0. The thermocline uplifted sharply to ~3 m at Sta. E0. Later, during August 1 to 2 low temperature (<25 °C) and high salinity (>34.3) water was missing at Sta. E0, but shifted ~20 km northward to Sta. F1–G1. The thermocline was deepened with the vertical temperature gradient decreased.

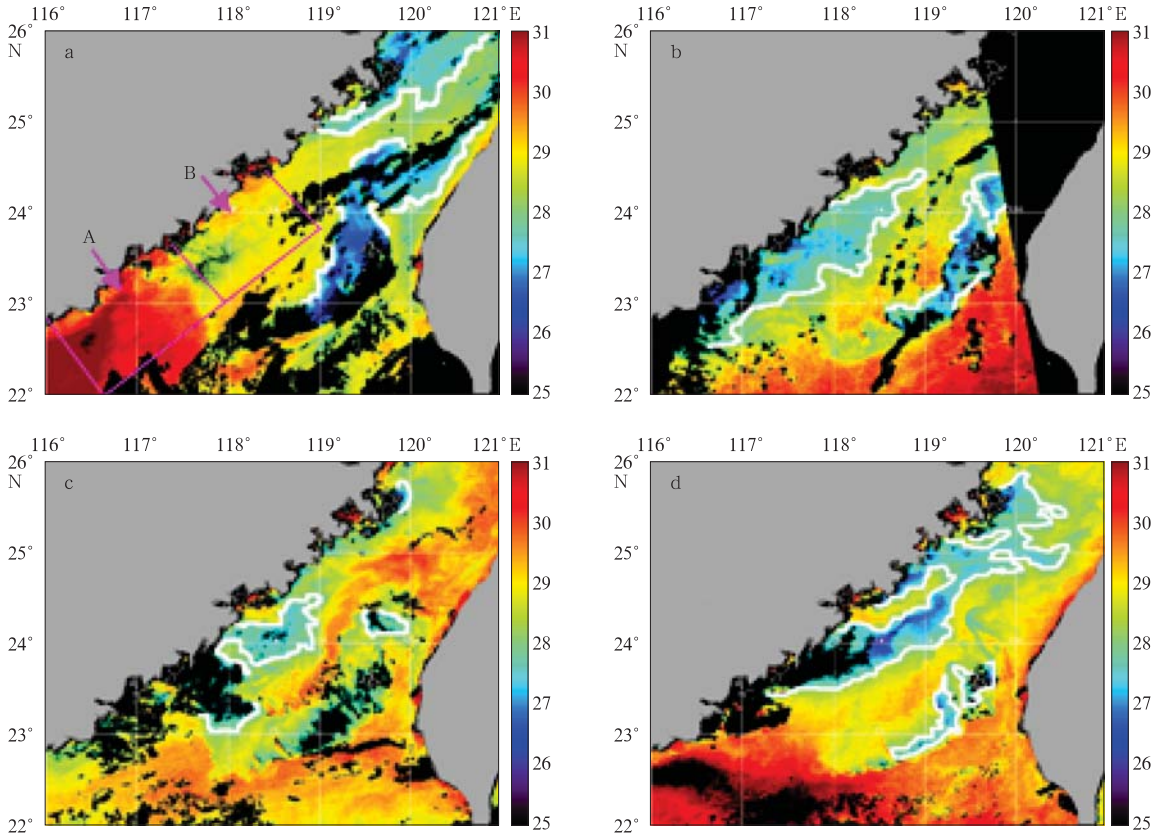

Fig.4. MODIS sea surface temperature (SST) images on 29 June (a), 11 July (b), 24 July (c) and 31 July (d) 2004. The 28 °C isotherm is outlined in white.

In response to the upwelling event, high Chl anomaly was observed (Figs 3 and 5). During 6 to 7 and 22 to 23 July, surface Chl in the cold water was >1.0 mg·m^{-3}, while higher concentration (>2.0 mg·m^{-3}) was found near the upwelling/plume front (Figs. 3a and 3b). Then, on 26 to 27 July, Chl decreased to <1.0 mg·m^{-3} for most of the ship transects, especially south of Dongshan Island where the cold surface water had disappeared (Fig. 3c). Only one narrow band (<20 km) of high surface Chl was found around 23.7°N. Vertical profiles of Chl showed similar features where a high Chl front was found between Sta. A1 and E0 (23.6–23.72°N) (Fig. 5c). On 1 to 2 August, a narrow high Chl band appeared further to the north at 23.85°N, co-located with the cold water (Fig. 3d); and the Chl was high through the entire water column around Sta. F1 (Fig. 5f). As a consequence of the weakened or ceased upwelling event south of Dongshan Island, the average MODIS Chl for Zone A (south of Dongshan Island, see Fig. 4a for the location) decreased from 0.49 mg·m^{-3} on 11 July to 0.34 mg·m^{-3} on 25 July, while average Chl for Zone B (north of Dongshan Island, see Fig. 4a for the location) remained unchanged.

These observed variations from 6 July to 2 August may be related to the temporal changes of the upwelling favorable wind. The southwesterly wind prevailed in early July as revealed by QuikSCAT (Fig. 6), which would lead to the offshore Ekman transport (Brink, 1983) and therefore induce extensive and cold surface water (~2.0×10^4 km^2) on 11 July, leading to subsequent high phytoplankton biomass in the southwestern TWS. During mid July and early August, the wind became weak and variable in direction. On 15 and 26 to 27 July, two cyclones passing by the northern SCS (images not shown) produced a spatially asymmetric wind pattern in the TWS (Fig. 6). This, combined with the advection of warm water

from the northern SCS (Figs 4d and 5a), may have greatly weakened the surface transport and upwelling, which in turn led to increased SST and decreased Chl. Nevertheless, other processes such as tidal mixing

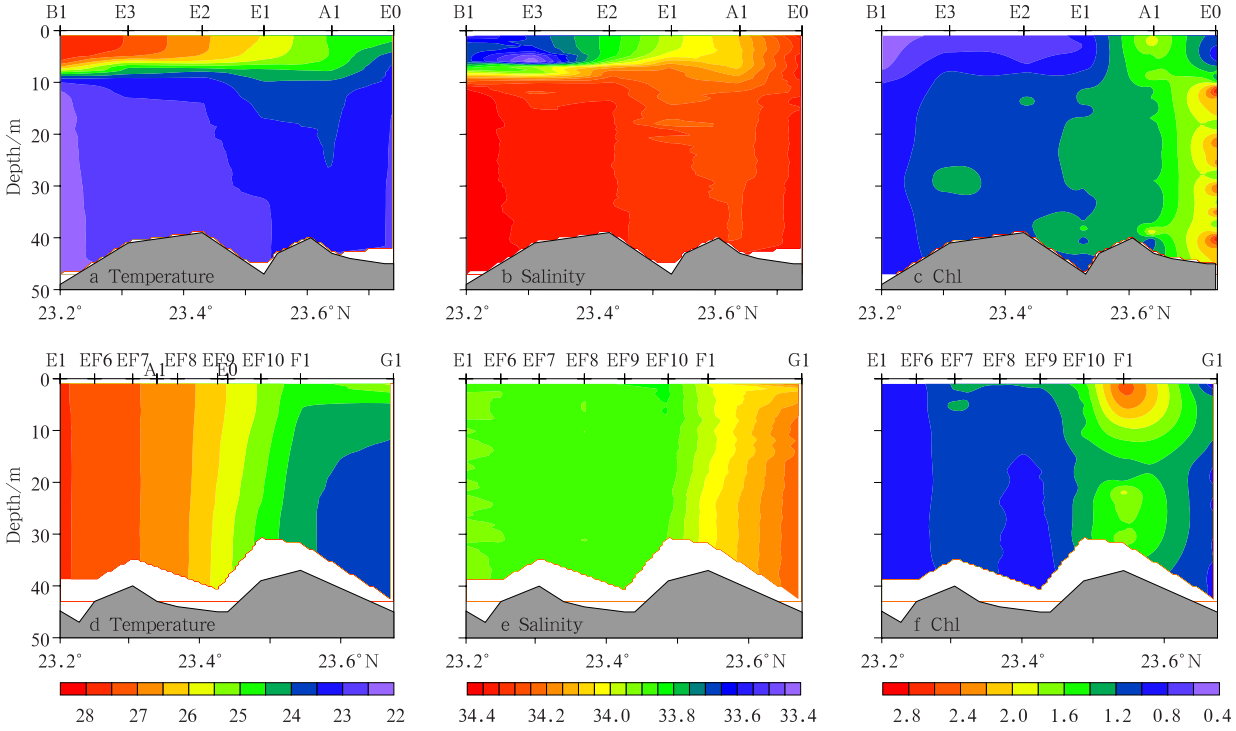

Fig.5. Vertical distributions of temperature, salinity and WetStar Chl along the southwestern TWS coast on 26–27 July (upper panel) and 1–2 August 2004 (lower panel).

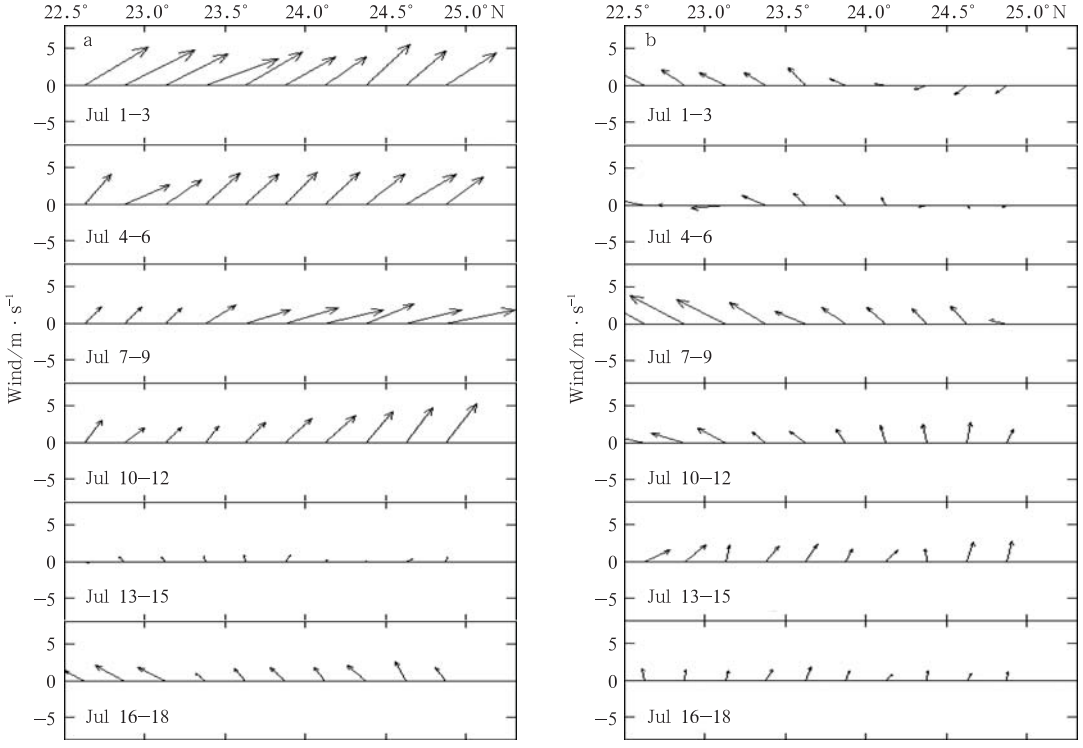

Fig.6. Latitudinal variation of wind vector for 3-day composite during 1 July and 5 August in the southern TWS.

and river plume may couple together with the upwelling, leading to the observed patterns. An interdisciplinary investigation with buoy, ADCP and numerical modeling will be required to improve our understanding of the upwelling processes in this complex region.

4 Conclusions

For a long time the initiation and evolution of coastal upwelling events in the TWS have remained largely a mystery. Here, short-term evolution of a coastal upwelling event in the southern TWS was studied using intensive cruise surveys (four repeated transects in a month) and satellite data in July and early August 2004. Strong coastal upwelling occurred along the southwestern TWS coast in early July, which induced extensive cold surface water ($\sim 2.0\times10^4$ km^2) with high Chl concentrations. Then, the cold water reduced by $\sim$50% in size with decreased Chl, indicating the weakening of the upwelling by early August. Although the exact mechanism for such variations needs to be further investigated with inter-disciplinary studies (e.g., current measurement and numerical modeling), according to the 3-D hydrography and satellite data we believe that the weakened upwelling-favorable wind, the asymmetric spatial structure of the wind field and the intrusion of warm water from the northern SCS might explain this phenomenon to some extent. The detailed time-series of synoptic satellite and 3D field observations helped reveal the dynamic structure of the upwelling that has not been documented before. Such observations will further our knowledge in understanding the cause, initiation, variation, and consequence of upwelling events in this region.

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