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Intrusion of the Pearl River plume into the main channel of the Taiwan Strait in summer

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ABSTRACT

The Penghu Channel is the main channel connecting the East and South China Seas, two of the largest marginal seas in the world. Located in the southeast of Taiwan Strait, the Penghu Channel is usually covered by the high salinity water from the South China Sea and the Kuroshio. However, we observed abnormal low-salinity water in the Penghu Channel during a cruise through the southern Taiwan Strait and northern South China Sea in August 2008. We argue that the normalized alkalinity is a good indicator for the identification of a river plume as it is not affected by rainwater. Using satellite-derived water transparency and chlorophyll images and field-measured alkalinity, the source of this low salinity water was found to be the intrusion of the Pearl River plume. A significant phytoplankton bloom across the entire Taiwan Strait occurred with the intrusion event. The intrusion was not a unique event, as we also found a strong jet-shaped Pearl River plume intruding into the Penghu Channel in the summer of 2009 from cloud-free satellite-derived images. Time series satellite data reveal that the Pearl River plume intrudes into the Penghu Channel in the summer of most years. Multiple data analysis and modeling simulation indicate that a large river discharge and strong southwesterly winds on the shelf may be responsible for the significant intrusion of the Pearl River plume into the Penghu Channel in summer. As the Pearl River plume has a high nutrient and dissolved inorganic carbon content, combined with the strong northward flows through the Penghu Channel, such intrusions may contribute to the nutrient dynamics and carbon budget of the East and northern South China Seas.

1. Introduction

The South China Sea (SCS) and the East China Sea (ECS) are the two main marginal seas in the western Pacific Ocean, and are ranked as the second and eleventh largest marginal seas in the world, respectively. The SCS and ECS are connected by the Taiwan Strait (TWS), which is about 180 km wide and 350 km long, with an average depth of about 60 m (Jan et al., 2002), as shown in Fig. 1. The current through the TWS has a direct impact on the circulation and biogeochemical processes in the SCS, the ECS and even the Japan Sea (Chen and Wang, 1999; Hong et al., 2011a; Isobe, 1999; Katoh et al., 2000; Liu et al., 2000).

Circulation in the TWS is mainly controlled by the strong East Asia monsoon and the complex topography of the Strait (Hong et al., 2011a; Naik and Chen, 2008; Tseng and Shen, 2003). In winter, the Zhejiang–Fujian Coastal Current flows southward along the eastern coast of China, but the direction of the current on the eastern side of the TWS is still not well defined (Chen and Sheu, 2006; Chen and Wang, 1999; Wu and Hsin, 2005). In summer, it is generally accepted that the entire TWS is dominated by a northward current driven by southwesterly winds, except during typhoon events (Chen et al., 2003; He et al., 2014; Hsin et al., 2010). Separated by the shallow Taiwan Bank located in the middle of the southern TWS, the northward currents in the southern TWS are divided into a two-pronged flow. The eastern prong flows through the Penghu Channel and is made up of oligotrophic waters from the SCS and the Kuroshio, whereas the western prong flows through the channel between mainland China and the Taiwan Bank and derives from the upwelling of the SCS subsurface water and coastal water (Hong et al., 2009, 2011b). It is well known that the deep Penghu Channel is the main pathway for volume transport through the Strait in summer because of the topography of the TWS (Jan and Chao, 2003; Jan et al., 2002; Wu et al., 2007).

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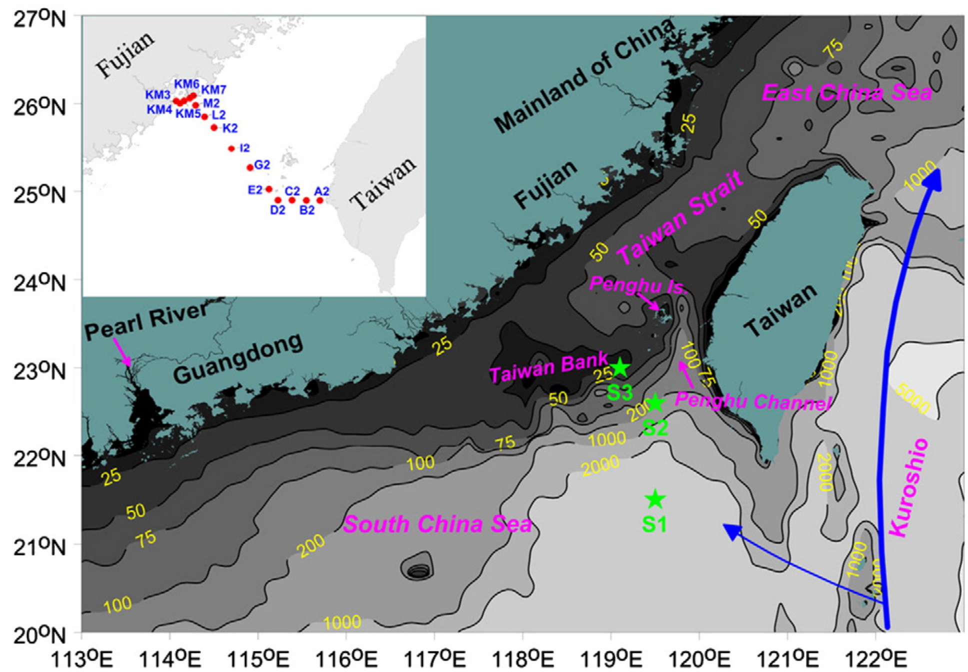

Fig. 1. Location and bathymetry (isobaths in meters) of the study area. Also shown are the sampling stations along the southern Taiwan Strait transect of the ORI-873 cruise in 2008 (upper left panel). Star symbols of S1, S2, and S3 are the locations of three selected points to show the variation of time series satellite data during 2000–2010 (shown in Fig. 9).

Flowing into the northern SCS, the Pearl River is the largest river which inputs into the northward currents in TWS. As the largest river in China after the Yangtze River and the 13th largest river in the world in terms of freshwater discharge (Yin et al., 2004), the Pearl River delivers 3.5×10^{11} m^3/yr of freshwater and 85×10^6 tons/yr of sediment load into the SCS. The Pearl River has about 80% of the discharge occurring during the wet season of April–September and only 20% during the dry season of October–March (Yin et al., 2004; Zhang et al., 1999). The annual-mean discharge of the Pearl River is 10,524 m^3/s, and the maximum river discharge occurs in July (Yin et al., 2004). The water comes from three main branches – the Dong Jiang (East River), Xi Jiang (West River) and Bei Jiang (North River) – before entering the SCS. The general pathway of the Pearl River plume (PRP) is well defined, and is mainly driven by the East Asia Monsoon (Dong et al., 2004). During the dry season, with strong northeasterly winds and low river discharge, the plume is advected westward by coastal current induced by the northeasterly wind, and the horizontal extent of the plume is much smaller. However, during the wet season with relative weak southerly winds and a large river discharge, the plume is advected eastward and offshore by the coastal current induced by the upwelling favorable winds (Dong et al., 2004).

Previous studies have found that the PRP could intrude into the southern TWS in summer. Based on the underway measured temperature and salinity at the surface, Chen et al. (2002) observed a 20 km zone with a high temperature (up to 28.6 °C) and low salinity (about 33) extending to the south of the Taiwan Bank. This phenomenon was also found in the summer of 2005, and was confirmed by numerical modeling (Hong et al., 2009). These studies indicate that the PRP and the Yuedong (the eastern Guangdong) Coastal Current, which has a high temperature and a low salinity and density in the upper layer, flow northeastwards through the channel west of the Taiwan Bank (the western prong defined by Hong et al., 2011b). More recently, modeling studies by Gan et al. (2009) and Shu et al. (2011) revealed that the PRP also extends northeastwards to the southern TWS and as far as the southern part of the Penghu Channel. However, these modeling results require validation by satellite and field observations.

During a cruise through the southern TWS and northern SCS in August 2008, we observed water of abnormally low salinity in the Penghu Channel. At the same time, a phytoplankton bloom was observed in the middle and northern TWS from satellite ocean color images. This study aims to trace the source of this low-salinity water to the Pearl River, and to reveal the biological responses to this event through both in-situ measurements and satellite data. To the best of our knowledge, this is the first time that the intrusion of the PRP into the Penghu Channel has been observed by satellite images and confirmed by both modeled results and field data.

2. Data and methods

2.1. In situ data

The ORI-873 cruise onboard the R/V Ocean Researcher I traversed the northern SCS and the southern TWS from 30 July to 6 August in 2008. The underway salinity and temperature were obtained by a self-recording CTD instrument. The temperature and salinity profiles at each station (Fig. 1) were determined with a shipboard SBE-911-plus conductivity–temperature–depth (CTD) unit manufactured by the Sea-bird Corporation. The temperature was recorded on the 1990 International Temperature Scale and the salinity on the 1978 Practical Salinity Scale. Discrete samples were collected at various depths with a Rosette sampler fitted with 2.5 L Niskin bottles that were mounted on the CTD unit to determine the salinity, pH and titration alkalinity (TA). Data from the sensors on the CTD unit were obtained during both the downcast and the upcast periods. The CTD unit was lowered as well as raised at a rate of about 1.0 m/s. Discrete water samples were taken during the upcast. Salinity in the discrete samples was determined by measuring conductivity with an AUTOSAL salinometer, which was calibrated with IAPSO standard seawater with a precision of 0.003. Values of pH were measured to a precision of ± 0.002 at 25 ± 0.05 °C with spectrophotometric seawater pH measurement of m-cresol purple on total scale (Clayton and Byrne, 1993). Total alkalinity was measured using Gran titration (Gran, 1952) composed of an Orion 81-02 pH meter, an Orion 3-Star pH benchtop meter, an 18-ml titration cell and a temperature-controlled water bath set at 25 ± 0.05 °C. The precision of the TA values was ± 2–3 μmol/kg, and corrected using Dickson seawater standard as reference. More detailed method descriptions of pH and TA measurements can be referred to Chen and Wang (2006).