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Particle dynamics of the surface, intermediate, and benthic nepheloid layers under contrasting conditions of summer monsoon and typhoon winds on the boundary between the Taiwan Strait and East China Sea

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ABSTRACT

Two shipboard surveys of hydrographics and sediment dynamics were conducted off the mouth of Minjiang (the Min River) in July 2012, under contrasting summer monsoon and typhoon wind conditions. Observations included profiles of conductivity, temperature, depth, fluorescence, and suspended-particle volume concentration and current velocity. In addition, water samples were taken for the analyses of mass concentration, POC, and chlorophyll of suspended sediment. Seafloor sediment samples were also taken for grain-size analysis. Nepheloid layers (NLs) were observed at surface, intermediate, and benthic depths (SNL, INL, BNL, respectively). The NL dynamics under the two wind conditions were mainly controlled by (1) the presence of the Minjiang river plume and terrigenous material it carries; (2) water-column stability affected by wind, current, and waves; (3) current-induced resuspension of seafloor sediment; and (4) physically coupled biological activities. The wind field was the major forcing controlling the observed flow field and the upper water column stability. In the typical summer condition, southerly winds induced offshore-directed currents, enhancing the seaward dispersal of the Minjiang river plume, facilitating water-column stratification, thereby forming 3 NLs in the water column. Phytoplankton growth was enhanced by terrigenous material and sunlight. The suspension of the seafloor sediment was the one of the major sources for suspended particles in these NLs. Furthermore, the C/N ratio of POC in the three NLs is 5.72, almost identical to the Redfield ratio, indicating their predominant marine origin. Conversely, under typhoon-related northerly winds, the offshore spread of the river plume was restricted. The reduced riverine input and enhanced mixing resulted in the disappearance of the SNL. Elevated turbidity in the INL was largely due to the presence of phytoplankton, while the BNL was comprised of sediment resuspended off the seafloor and from horizontal advection. Our results suggest that the presence of the river plume from the Minjiang at the study site sets the condition for the SNL dynamics. The dynamics of INL and BNL were dominated by the wind field, and to a lesser degree, the wave field and tidal current.

1. Introduction

Nepheloid layers (NLs) are defined as layers with high suspended-particle concentrations in the water column, of which the vertical variability is higher than the regional and temporal variability (McCave, 1986). The NLs are characterized as the major pathways for the transfer of suspended particles on continental shelves and at the land-ocean interface (Naudin and Cauwet, 1997). Therefore, it is vital to understand the particle dynamics of the NLs that affect particle transport and the marine environment.

The bottom nepheloid layers were first detected in the lower water column of the deep ocean (Baker, 1976; Betzer and Pilson, 1971; Biscaye and Eittreim, 1977; Dickson and McCave, 1986). They also have been observed in a wide range of marine environments including submarine canyons (Canals et al., 2006; Durrieu de Madron, 1994; Liu et al., 2010; Puig et al., 2004), on continental shelves (Oliveira et al., 2002; Shideler, 1981), in coastal zones (Bourgault et al., 2014; Naudin and Cauwet, 1997) and in lakes (Baker et al., 1985; Sandilands and Mudroch, 1983). Their genesis is attributed to resuspension of sediment by currents and swell, and by biological activities (Naudin and Cauwet, 1997; Shideler,

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1981). Thus, the BNLs tend to form in regions where there are high variability in bottom currents caused by the dissipation of eddy energy from the surface (McCave, 1986). Furthermore, Bassin (1974) summarized two factors for the maintenance of BNLs: a source for suspended particles and a layer of low diffusivity above the bottom layer that prevents upward diffusion, implying stratification in the water column.

The surface nepheloid layers (SNL) appear in the surface or subsurface water over the shelf and slope (Lorenzoni et al., 2009; Ribó et al., 2013). The SNLs are generally related to river plumes that extend across the coastal zone (Naudin and Cauwet, 1997), being an important mechanism for delivery of terrigenous sediment from the coastal environment to deep waters (Lorenzoni et al., 2009). In addition, biological particles contribute to the SNLs (Biscaye and Eittreim, 1977; Oliveira et al., 2002). Satellite imagery and in-situ observations show that the river plume responds rapidly to alongshore wind, moving predominantly in the wind direction with a weak Ekman drift (Stumpf et al., 1993). The dispersal of river plume is also determined by the turbulent mixing by the wind field in the upper part of the water column and by tidal forces in the lower part (Kakoulaki et al., 2014; Liu et al., 1999, 2002a; Rong et al., 2014; Warrick et al., 2004).

The intermediate nepheloid layers (INLs) are usually found near continental shelves and slopes, being associated with strong density gradients (Lorenzoni et al., 2009). They mostly originate either from the detachment or from lateral spreading of the BNL near the shelf-break (Azetsu-Scott et al., 1995; Dickson and McCave, 1986; McCave, 1986; Oliveira et al., 2002; Ribó et al., 2013), and effectively transport terrigenous material laterally from the shelf to the deep sea. Additionally, the INLs also form from accumulation of living organisms at the density interface (Naudin and Cauwet, 1997).

NLs sourced from living organisms, which are controlled by complex bio-physical coupling that includes physical processes (mixing and stabilization), and the light and nutrient conditions for phytoplankton growth (O'Boyle and Silke, 2009; Pingree et al., 1978; Sambrotto et al., 1986). For example, the degree of vertical mixing in water column determines the availability of light and inorganic nutrients in the water column (Pingree et al., 1978). The thermocline in the stratified water and the frontal boundaries between the mixed and the stratified waters are suitable for the rapid growth of plant cells (Pingree et al., 1978). Conversely, layers of phytoplankton patches could not occur in well-mixed waters (Dekshenieks et al., 2001). In brief, theese layers can only persist in regions where stratification is sufficient to suppress the turbulence (Dekshenieks et al., 2001).

In this study, we had the rare opportunity to observe these three types of NLs occurring simultaneously on the shallow shelf (~40 m) under the conditions of typical summer monsoon winds. At the same study site, we also came across a contrasting wind condition influenced by a distal typhoon under which only two NLs were observed. The goal of this paper is to answer the following questions: (1) where are the suspended particles in the NLs sourced from; (2) what mechanisms control the NL dynamics; and (3) what factors limit the vertical extents of the NLs?

2. Study area and field experiment

2.1. Study area

The Taiwan Strait (TS) connects the two largest Chinese marginal seas, and is subject to seasonal monsoons. It has complex bottom topography, covering an area of ~63,000 km^2 with a mean water depth of 60 m. Over the year, the prevailing winds of the TS show strong seasonality: northwesterly winds dominate in winter and southwesterly winds prevail in summer. The seasonal variability of winds, freshwater discharge, and oceanic forcing controls similar seasonality in several current systems, including the Zhe-Min/China Coastal Current, the Kuroshio Current intrusion, and the extension of the South China Sea Warm Current (Hong et al., 2011; Jan et al., 2002; Wu et al., 2013). Generally speaking, the South China Sea Warm Current and the Kuroshio Current branch carry Taiwan-derived terrigenous sediment northwestward in summer (Chen and Sheu, 2006). Conversely, in winter, the Zhe-Min Coastal Current carries Changjiang-derived terrigenous sediment southward to mix with Taiwan-derived sediment (Liu et al., 2007). Tidal currents add additional complexity to the circulation patterns.

The TS also receives a large amount of terrigenous sediment from distal major rivers of Changjiang (the Yangtze River) and Zhujiang (the Pearl River) and proximal small rivers on the Zhe-Min coast on the mainland side, and small mountainous rivers on the west coast of Taiwan, which have among the highest sediment yields in the world (Horng and Huh, 2011; Kao and Milliman, 2008; Liu et al., 2013; Milliman and Syvitski, 1992; Xu et al., 2009). Furthermore, they contribute 2.6×10^8 ton of sediment, about one-third of the total input, to East China Sea (ECS) (Huh and Su, 2004). The TS is a pivotal conduit for the exchange of material of terrestrial and marine origin between the two China Seas.

Typhoons, though stochastic, frequently bring heavy rainfall resulting in increased sediment and water discharge to the TS. Each year, on average about 30 tropical cyclones formed in the western North Pacific and 4.5 typhoons make landfall on Taiwan (Lee et al., 2006). During a four-year observation, 35 typhoons affected the TS, 30 of which generated local wind stress and/or along-shore water level gradient that induced strong southward transport in the TS (Zhang et al., 2009, 2013, 2014; Chang et al., 2010).

Being the 4th largest river in China and located at the northern opening of the TS, Minjiang discharges on average 7.5 Mt/yr of sediment into the TS and the peak discharge occurs in June–August (Liu et al., 2008). Previous studies show that most sediment is trapped inside or near the estuary (Chen et al., 1998; Liu et al., 2008; Xu et al., 2009). However, not many studies have been focused on the effect of the Minjiang river effluent and the terrigenous sediment it carries from the source-to-sink perspective on the boundary between the TS and the East China Sea. Therefore, we chose the site off the Minjiang river mouth to accomplish this goal.

2.2. Field experiments

In the flood season of 2012, shipboard experiments were carried out on two research-cruises using R/V Ocean Researcher II (OR2)-1886 (1:00 July 6–5:00 July 7, during spring tide) and OR2-1892 (1:00 July 24–1:00 July 25, during spring tide) at a location (MJ) NE of the mouth of Minjiang and SE of Mazu Island (Fig. 1a). The experiment consisted of measuring the wind field using the onboard anemometer and the flow field using shipboard-ADCP (TRDI 300 kHz), which has a 4-m bin size. CTD (SBE 911plus) profiling was conducted at 2-h intervals including the measurements of fluorescence, and the use of a LISST-100 (Laser In-situ Scatting and Transmissometry, type C) to record the volume concentration (VC, in µl/l) of 32 size-classes from 0.25 to 500 µm (on a logarithmic scale) of suspended particles (Agrawal and Pottsmith, 2000). The CTD was lowered at approximately 1 m/s and the LISST-100 sampled at 1 s intervals (taking an average of 10 measurements), resulting in VC profiles of suspended sediment with 1 m resolution in the vertical. Accordingly, the CTD data were averaged into 1-m vertical segments. In addition, water samples were collected at the surface, mid-depth and near-bottom using Niskin bottles and surfacial sediment samples on the seabed were taken at 2-h intervals. During the second cruise, a severe typhoon Vicente hit South-