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Tropical storm-induced turbulent mixing and chlorophyll-*a* enhancement in the continental shelf southeast of Hainan Island

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ABSTRACT

Based on moored observations and remote sensing data in July and August 2005, energy sources for enhancing turbulent mixing and possible mechanisms of phytoplankton bloom in the continental shelf southeast of Hainan Island under the influence of Washi, a fast-moving and weak tropical storm, are analyzed in this paper. Observations show that strong near-inertial internal waves were generated by the rapidly changing wind stress and the near-inertial energy was dissipated quickly across the thermocline. The strong turbulent mixing associated with the near-inertial baroclinic shear instability occurred with maximum eddy diffusivity above 3.2×10^{-4} m^2 s^{-1}, and the surface chlorophyll-*a* (Chl-*a*) concentration after the storm increased by 22.2%. The Chl-*a* concentration augment was inferred to be an upper ocean biophysical response to the enhanced near-inertial turbulent mixing which could increase the upward nutrient flux into the surface low eutrophic zone during the passage of Washi.

1. Introduction

The upper ocean response to a moving storm or hurricane has been an important topic in the physical oceanography study (D'Asaro, 2003; Price, 1981; Sanford et al., 2011; Shay et al., 1992; Zedler et al., 2002; Zheng et al., 2006) and drawn more and more attention for recent years (Black and Dickey, 2008; Dohan and Davis, 2011; Lee and Brink, 2010; Lin et al., 2003; Wada et al., 2009; Walker, 2005; Wang et al., 2012). The response of the upper ocean to a storm or hurricane is shown by sea surface temperature cooling and near-inertial oscillations that are strong on the right of the storm track. The storm-induced near-inertial oscillations play an important role in mass, heat and energy exchanges between the upper mixed-layer and deep layer below the pycnocline. Near-inertial internal waves are not only a carrier for the kinetic energy being transported to the ocean interior (Zhou et al., 2005) but also a driving force for heat being fluxed down to the low layer of ocean water (Sriver and Huber, 2007). The influence of tropical storms on the nutrient flux from the water below thermocline to the mixed-layer is insignificant for the deep ocean area. In the continental shelf sea, however, the situation changes because the near-inertial internal waves induced by tropical storms may directly affect the ocean water below thermocline and enhance shear and turbulent mixing (Burchard and Rippeth, 2009; Rippth et al., 2002; Shearman, 2005), leading to the increase of the vertical nutrient flux. Consequently, high primary production appears in euphotic zones. Thus, studies on the near-inertial internal waves and phytoplankton blooms caused by tropical storms are crucial in understanding the mixing dynamics and biogeochemical processes in continental shelf seas.

The South China Sea (SCS) with an area of about 34,500 km^2 is the largest marginal sea in the western Pacific. It is susceptible to tropical storms averaging up to 15 occurrences per year according to historical records (Lin et al., 2003; Wu et al., 2005; Zhao et al., 2008). As a tropical storm passes by, the upper ocean has significant response to the strong wind forcing (J. Chang et al., 2008, Y. Chang et al., 2008; Lin et al., 2008; Shang et al., 2008), with nutrients efficiently replenished in euphotic layer and phytoplankton biomass rapidly enhanced (Lin et al., 2003; Shiah et al., 2000; Zhao et al., 2009). Most of the area of the SCS has sufficient sunshine but is short of nutrients, and the nutrient supply becomes a main factor sustaining the primary production (Tang et al., 2004a, 2004b). Recent studies show that tropical storms or typhoons are very important in forcing the promotion of phytoplankton biomass and primary production (Lin et al., 2003; Zheng and Tang, 2007). However, previous studies mainly focus on the influence of strong typhoons on primary production in the SCS (Lin et al., 2003; Sun et al., 2010; Zhao et al., 2008; Zheng and Tang, 2007). Little work has been done on the influence of weak tropical storms, especially on the correlation between the turbulent mixing induced by storm-generated near-inertial oscillations and the biological process of phytoplankton blooming.

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In fact, it is not easy to make in-situ observations on the ocean responses to tropical storms. Satellite remote sensing of sea surface temperature, wind speed, and ocean color has been proven to be a key measure for understanding the ocean response to tropical storms. However, the remote sensing only provides ocean surface data and in-situ profile observations are necessary to disclose the detailed storm-related oceanic variability. Up to now, few existing datasets are appropriate for unveiling the upper ocean physical processes under the tropical storm influence in the continental shelf region of the SCS (Cui et al., 2009; Sun et al., 2011), especially in the area off the Hainan Island.

This study presents moored observations of ocean responses to a weak tropical storm in the continental shelf region off Hainan Island. The in-situ observations combining with multi-sensor remote sensing data during the tropical storm are used to investigate the influence of the tropical storm on phytoplankton distribution and the dynamical mechanism of the phytoplankton bloom. These investigations help to better understand upper ocean physical and biological processes in response to the tropical storm Washi which passed the northwestern shelf of the SCS in 2005.

2. Data and method

2.1. Remote sensing data

The typhoon track data used in this study are obtained from the Unisys Weather website (http://weather.unisys.com/hurricane/w_pacific/), which is based on the best hurricane track data issued by the Joint Typhoon Warning Center (JTWC). The data include maximum sustained surface wind speeds and the storm center locations every 6 h. The moving speed of a storm was thus estimated based on the positions of its center every 6 h in our analysis. The tropical storm Washi was formed as a cyclone in the northwestern SCS (18.4°N, 112.6°E) at 18:00 on July 28, 2005. It became a tropical storm on July 29 and reached its maximum wind speed of 23.1 m s^{-1} on July 30. Then, Washi reduced to a cyclone and made the landfall in the coast of northeast Vietnam (20.5°N, 104.5°E) on July 31 (Fig. 1). The storm with wind speed less than 18 m s^{-1} moved slowly in its first 18 h (<2.5 m s^{-1}) and then fast with a high speed (>3.7 m s^{-1}). Generally, the tropical storm Washi was a fast-moving, weak storm.

Daily sea surface temperature (SST) data are derived from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) with a spatial resolution of 0.25° by 0.25°. Because of the cloud-penetration capability of TMI, the measurements can overcome the cloudiness influence (Wentz et al., 2000). Surface wind data were obtained from the South China Sea Ocean Data Base (SCSDB, http://www.ocdb.csdb.cn/), which is an reanalysis product of the National Ocean and Meteorology Administration (NOAA) Earth System Research Laboratory (ESRL) survey data. The spatial resolution of the wind data is 0.25° by 0.25° and the temporal resolution is 6 h. The chlorophyll data are derived from MODIS-Aqua data (http://gdata1.sci.gsfc.nasa.gov) with the spatial resolution of 9 km × 9 km.

2.2. Moored observations

A moored observation system had been deployed at (19°35′N, 112°E) in the northwest SCS for 6 days from July 28 to August 2, 2005 by the Institute of Oceanology, Chinese Academy of Sciences. The depth of the mooring site is 130 m, about 130 km away from the nearest center of

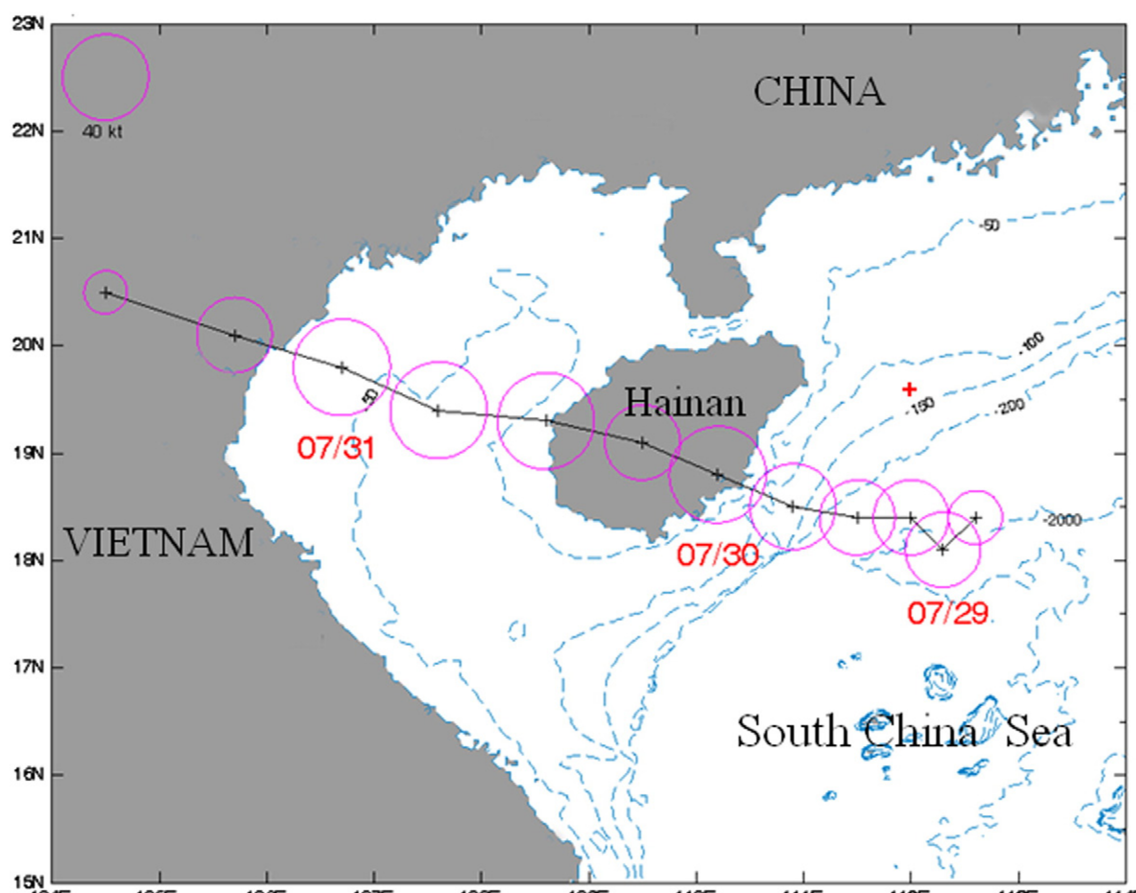

Fig. 1. Map of the study area, where the plus sign indicates the mooring position, and the red circles denote the track locations of the tropical storm Washi.