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Summer circulation variability in the South China Sea during 2006–2010

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ABSTRACT

Satellite observations of sea surface height (SSH) from 1993 to 2010 reveal a decadal variability of summer circulation in the South China Sea (SCS) with three phase changes in 1998, 2001 and 2006, respectively. There appears to be a large rise during 2006–2010 contributing to unprecedented anomalous high sea levels in 2010. The first leading empirical orthogonal function (EOF) mode of SSH exhibits an anomalous anticyclonic circulation pattern in the western central SCS north of 11°N, thus weakening the northern cyclone of the summer dipole during 2006–2010. The negative phase of the Pacific decadal oscillation (PDO) may have contributed to the anomalous high sea levels and disappearance of the summer dipole pattern. These variations reflect a linkage between the circulations of the SCS and Pacific Ocean.

1. Introduction

The South China Sea (SCS) current system is characterized by strong seasonality in wind forcing. The dominant basin-wide circulation in the upper layer is anticyclonic (cyclonic), driven by the southwesterly (northeasterly) summer (winter) monsoon winds. In summer, in the western SCS off central Vietnam there exists a dipole structure of a southern anticyclone and a northern cyclone with the Vietnam offshore current around 11°N between these two eddies (G. Wang et al., 2006; W. Fang et al., 2006). G. Wang et al. (2006) suggested that the southern anticyclonic eddy and the northern cyclonic one were concomitant features, and called them a dipole structure, which begins in June and peaks in August or September. The southern anticyclonic eddy in the southern SCS is stable and well recognized (Bayler and Liu, 2008; Fang et al., 2002), whereas the northern cyclonic one is modulated by local and basin-scale wind forcing (Bayler and Liu, 2008; Xie et al., 2007; Zhuang et al., 2010).

Superimposed on seasonality is the significant interannual variability, especially with weakened circulation gyres and upwelling under the condition of weakened monsoon winds during El Niño (G. Fang et al., 2006; Xie et al., 2003). The strong influences of El Niño on the SCS oceanic circulation have been previously described (e.g., C. Wang et al., 2006). The summer dipole displays both interdecadal variability (Wang et al., 2010) and interannual variability (Chen et al., 2010). During the El Nino developing phase, the western SCS summer dipole was apparent (Chang et al., 2008), whereas during the El Nino decaying phase, the dipole structure almost disappeared (Xie et al., 2003). The varying dipole occurring during 1993–2005 can be displayed by two composites of summer (JAS) sea surface height (SSH) anomalies (i) during the El Nino developing phase (1994, 1997, 2002, 2004) and (ii) during the El Nino decaying phase (1995, 1998, 2003, 2005) (Fig. 1).

The SSH anomaly is often interpreted as the change in oceanic circulation given that the dynamic sea level variations balance geostrophic velocity anomalies (e.g., Hakkinen and Rhines, 2004); it also can be interpreted as upper ocean heat storage based on a simple linear relationship (Cheng and Qi, 2007; Swapna et al., 2009). To date, few previous studies focused on the decadal phase change of the SCS summer oceanic circulation although SCS variability on interannual scales linked to the large scale forcing of the tropical Pacific has been reported (e.g., G. Wang et al., 2006; Qiu et al., 2012; W. Fang et al., 2006; Xie et al., 2003). The time series of the abovementioned studies were also mostly limited to before the year of 2006. Furthermore, the decadal phase change and linear trends of SSH and the circulation anomaly were not presented. In this study, we demonstrate summer circulation variability in the South China Sea during 2006–2010 and modulation by large scale forcing.

2. Data and method

Data used for this study include satellite altimeter observations of SSH, measurements of surface wind, as well as the Pacific decadal oscillation (PDO) index. The monthly SSH anomaly data is the merged product from T/P, ERS-1, Jason-1 and ERS-1/2, provided by AVISO, with a 1/3° spatial resolution (see http://www.aviso.oceanobs.com/duacs/). All the altimetry data were corrected at AVISO, using standard techniques for instrumental noise, orbit error, atmospheric attenuation, sea state bias, etc. To study the interannual to decadal variability, the seasonal cycle is removed: the climatological monthly means from January to December during 1993–2010 are subtracted from monthly values to obtain monthly anomalies from the climatology. Empirical orthogonal function

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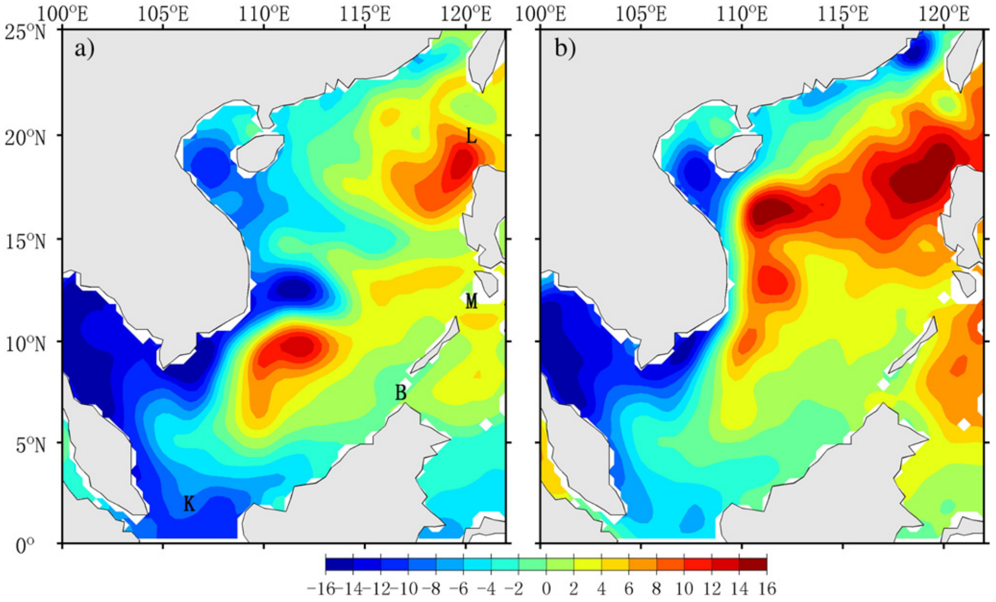

Fig. 1. Composites of summer (JAS) SSH anomalies (unit in cm) for the El Nino events (1994–1995, 1997–1998, 2002–2003, 2004–2005). a) SSH anomalies composite by summers of 1994, 1997, 2002 and 2004 for the El Nino developing phase. b) SSH anomalies composite by summers of 1995, 1998, 2003, and 2005 for the El Nino decaying phase. L, M, B and K denote Luzon Strait, Mindoro, Balabac and Kalimata Straits, respectively.

(EOF) analysis (Emery and Thomson, 1998) is used to obtain the dominant spatial patterns and temporal variations of summer (JAS) SSH. The monthly anomalies of surface geostrophic velocity is computed from SSH anomalies. i.e., the zonal (u) and meridional (v) components of the geostrophic velocity anomalies are derived from SSH anomaly (η) by $u = -g\eta_y/f$ and $v = g\eta_x/f$ and where g is gravity, f is the Coriolis parameter; and the derivatives η_x and η_y are computed using finite differences, where x and y are the distances in longitude and latitude, respectively.

To present the linear trends of large scale wind forcing, we use monthly surface wind data with a 2.5° spatial resolution from the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global atmospheric reanalysis data (http://www.esrl.noaa.gov/psd/). Surface wind stress and wind stress curl were calculated by the monthly surface wind velocity. The PDO is defined by the leading principal component of the North Pacific sea surface temperature variability poleward of 20°N (Mantua et al., 1997), which represents large scale interannual to decadal climate variability in the North Pacific (available on http://jisao.washington.edu/pdo/PDO.latest). The PDO has a significant imprint in the surface winds both in subtropical and tropical Pacific oceans (Qiu and Chen, 2010).

3. Summer SSH and geostrophic velocity anomalies during 2006–2010

3.1. SSH anomalies

Fig. 2 shows the climatological summer (JAS) mean of SSH anomalies for 1993–2010 and the annual summer means of SSH anomalies for 2006–2010. During summers of 2006–2010, there existed an anomalous high summer sea level in the deep basin with an increasing trend from 2006 to 2010 in most of the deeper central and northern basin, with the maximum exceeding 30 cm. Another notable feature of SSH anomalies is the weakening or disappearance of the dipole structure in the western SCS for the five consecutive summers of 2006–2010, including for the two El Nino developing summers (2006 and 2009), which are different from the occurrence of the dipole pattern in the summers of El Nino developing phase in 1993–2005 (see Fig. 1a). Previous studies indicated that the summer circulation in the western SCS has a dipole structure with the anticyclonic eddy in the south and the cyclonic one in the north (e.g., G. Wang et al., 2006). However, in the summers of 2006–2010 the dipole structure was replaced by positive SSH anomalies off the central western SCS coast. Fig. 2g displays the time-latitude distribution of June-to-September SSH anomalies at 111°E during 1993–2010. This indicates that the summer dipole around 11°N in the western SCS displayed interannual to decadal variations. Note that the summer dipole (the northern cyclone denoted by negative SSH anomalies with blue color around 12°N and the southern anticyclone with red color in Fig. 2g) was more apparent during 1994, 1996, 1997 and 2002–2005, but disappeared or was replaced by a single anticyclone during 2006–2010. The highest SSH anomalies along 111°E in summer of 2010 extended to south of Hainan Island (Fig. 2f and g).

3.2. Surface geostrophic velocity anomalies

Fig. 3 displays the climatological summer (JAS) mean of surface geostrophic velocity anomalies for 1993–2010 and the annual summer means of surface geostrophic velocity anomalies for 2006–2010. It can be seen that for the climatological summer (JAS) mean (Fig. 3a) there was a prominent anticyclonic circulation in the southwestern SCS with stronger western boundary current off the coast of southeastern Vietnam. In contrast, during 2006–2010, the annual summer means of geostrophic velocity anomalies in the northwestern SCS become more energetic, with strong northward western boundary currents and a strong anticyclonic circulation occurring in the northwestern SCS in 2010 summer (Fig. 3f), which could not be seen in the climatological summer mean (Fig. 3a).

3.3. Seasonal evolution of SSH anomalies in 2010

Fig. 4 shows the seasonal evolution of SSH anomalies from April to September in 2010. In April and May 2010, there were positive SSH anomalies occurring off the coast of central Vietnam in the western SCS (Fig. 4a and b). From June to September 2010, the anomalous high sea levels extended to the deep basin of the central and northern SCS (Fig. 4c–f) and began to fall in October. This large area positive SSH anomalies, especially over the northwestern basin of the SCS, were not observed before 2010, even in another strong La Nina summer of 1998. Corresponding to the large positive SSH anomalies, in April to June there was an anticyclonic eddy occurring off the coast of central Vietnam in the western SCS. From June to September 2010, an energetic