Deep-Sea Research II 117 (2015) 41–52

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

A modeling study of the formation, maintenance, and relaxation of upwelling circulation on the Northeastern South China Sea shelf

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ARTICLE INFO

Available online 15 January 2014

Keywords:
Wind-driven upwelling dynamics
Geostrophic cross-isobath transport
Circulation over variable shelf

ABSTRACT

We investigated persistent summer upwelling circulation, in response to upwelling and downwelling favorable winds, in the Northeastern South China Sea (NSCS). We used a validated three-dimensional ocean circulation model that was forced by realistic atmospheric fluxes and downscaled coupling of real-time lateral fluxes. We found that upwelling in the NSCS was formed and maintained by the presence of an intensified westward along-isobath pressure gradient force (PGF_m) and bottom frictional effect that led to cross-isobath currents over the unique NSCS widened shelf. The upwelling favorable PGF_m and the frictional effect arose from the interaction between the eastward shelf current and the shelf topography. These intrinsic upwelling dynamics in the NSCS were largely sustained during episodic downwelling winds in the upwelling season because the retreat of the eastward shelf current from pre-existing upwelling was significantly slowed by the unique widened shelf topography. Furthermore, the upwelling dynamics could also be maintained and, even developed, during downwelling favorable winds, when the eastward shelf current was sustained by the pumping of downstream outflow.

1. Introduction

Spatiotemporal variation of upwelling circulation over a continental shelf can be induced by various forcing mechanisms. It is well known that the presence of alongshore topographic variations on an otherwise relatively straight continental shelf has a profound influence on coastal upwelling circulation (Lentz et al., 1999; Gan and Allen, 2005a; Barth et al., 2005; Weisberg et al., 2005; Gan et al., 2009a, 2010). These studies showed that interaction between the upwelling flow and variable shelf topography alters both alongshore and cross-shore momentum balances and leads to strong variability in upwelling circulation. A variable wind field can also form highly variable coastal upwelling circulation. For example, it occurs when an upwind current is formed by the relaxation of upwelling winds (Send et al., 1987; Gan and Allen, 2002) or when enhanced spatial variability of the upwelling intensity is caused by a spatially variable wind stress field (Gan et al., 2005; Castelao and Barth, 2007). Meanwhile, remote currents and wave intrusion from the region beyond the shelf also exert additional variance and forcing on the upwelling circulation over the shelf (e.g. Chapman, 1987; Denbo and Allen, 1987; Pringle and Dever, 2009).

The topography of the Northeastern South China Sea (NSCS) is characterized by a complex variable coastline in the nearshore region and by a prominent eastward widened shelf. The widened shelf is formed by an abrupt offshore extension of isobaths east of the Pearl River Estuary and is bounded by the 50 m isobath at its southern edge (Fig. 1). Gan et al. (2009a) examined the response of the monsoon-driven coastal upwelling circulation effected by this unique topography and found that the upwelling intensified over the widened shelf because of a strengthened bottom Ekman transport and shoreward cross-isobath geostrophic transport. This kind of topographic control of shelf upwelling was also reported in many other studies (e.g. Lentz et al., 1999; Janowitz and Pietrafesa, 1982; Oke and Middleton, 2000; Weisberg et al., 2000; Gan and Allen, 2002, 2005a; Pringle, 2002). While the apparent source for the intensified bottom frictional transport was the strengthened shelf current over the converging isobaths at the head of the widened shelf, the source for intensified geostrophic transport was provided by the along-isobath pressure gradient due to net stress curl in the water column (Gan et al., 2013.)

In general, under the influence of the East Asian monsoon, southwesterly upwelling favorable winds prevail over the NSCS during the summer in June, July, and August (Li, 1993). However, in the summer of 2000, this upwelling favorable wind was not remarkable over the NSCS (Fig. 2). The average magnitude of the upwelling favorable wind stress was weakened by episodic downwelling favorable winds (Fig. 3). The time series of alongshore

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0967-0645/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.dsr2.2013.12.009

wind stress at locations P1–P6 (Fig. 1) from June 5 to August 24, 2000 (Fig. 3) demonstrate the spatial differences of wind stress and show that all series correlate well. The figure also reveals that the upwelling favorable wind seldom occurred from June 20 to July 22, 2000. From June 5 to August 24, the total number of days with upwelling favorable and downwelling favorable winds was roughly the same, yet the coastal upwelling phenomenon dominated over the shelf in the NSCS for the entire period. The average upwelling feature over this period is demonstrated by the existence of cold sea surface temperature (SST) as seen from the remotely sensed data (Fig. 2), similar to the upwelling feature when winds were persistently upwelling favorable shown in Gan et al. (2009a). In spite of the stronger southwesterly winds existed over the western part of the shelf, the colder upwelled water occurred over the eastern part. Similarly, the standard deviation of wind stress in Fig. 2 shows the existence of highly variable wind stress near the head of the widened shelf, while the higher variance of SST appeared near the coastal promontory off Shantou. These statistics suggest that the upwelling occurred persistently in the NSCS during summer; and that the upwelling circulation in the NSCS was not formed and sustained by upwelling-favorable wind forcing alone. Other unknown forcing mechanisms, such as the flow-topography dynamics of the widened shelf and remote inflow/outflow, may also play important controlling roles, as was pointed out by Gan et al. (2009a,b).

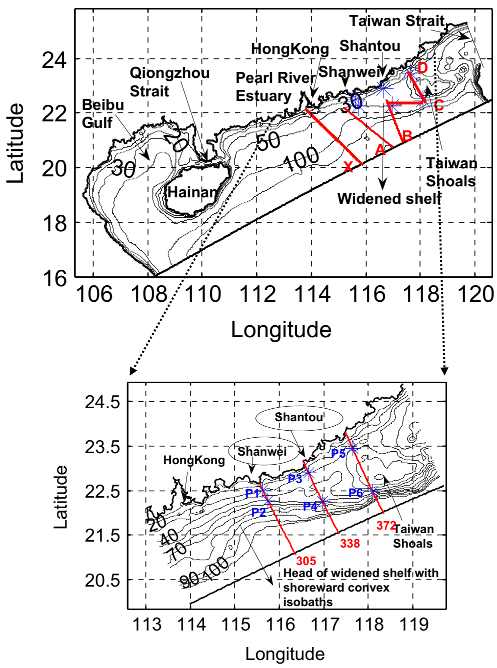

Fig. 1. The topography (m) in the NSCS with the zoomed area at the widened shelf. The five transects marked with X, A, B, C, and D represent the locations of observed data transects during summer cruises in 2000. The selected cross-shelf sections (dashed lines) are marked by their grid numbers 305, 338, and 372. The shoreward convex isobaths are at the head of the widened shelf about one half degree southwest of Shanwei. Six locations selected for this study are P1, P3, and P5 along the 30 m isobath with the corresponding grid numbers 305, 338, and 372 as well as P2, P4, and P6 along the 50 m isobath with the same grid numbers.

In this study, we used a three-dimensional numerical ocean model, with realistic atmospheric fluxes and real-time lateral fluxes produced by downscaled coupling, to investigate the unknown forcing processes that sustained the persistent summer upwelling circulation in the NSCS during both upwelling and downwelling favorable winds.

2. Ocean model

The NSCS ocean model (Gan et al., 2009a,b, 2010) is based on the Regional Ocean Model System (ROMS) (Shchepetkin and McWilliams, 2005) for three-dimensional, time-dependent oceanographic flows that are governed by hydrostatic primitive equations. A local closure scheme based on the level-2.5 turbulent kinetic energy equations by Mellor and Yamada (1982) was adopted in the vertical mixing parameterization. The model domain extends from 15.99°N, 108.17°E in the southwest corner to about 25.81°N, 119.54°E in the northeast corner with its central axis directed 23° anticlockwise from true east (Fig. 1). We used a curvilinear grid (x,y) with an average 3 km horizontal grid size. Thirty levels of stretched, generalized, terrain-following coordinates (s) form minimum and maximum grid spacing in the water column with less than 1 m over the inner shelf and

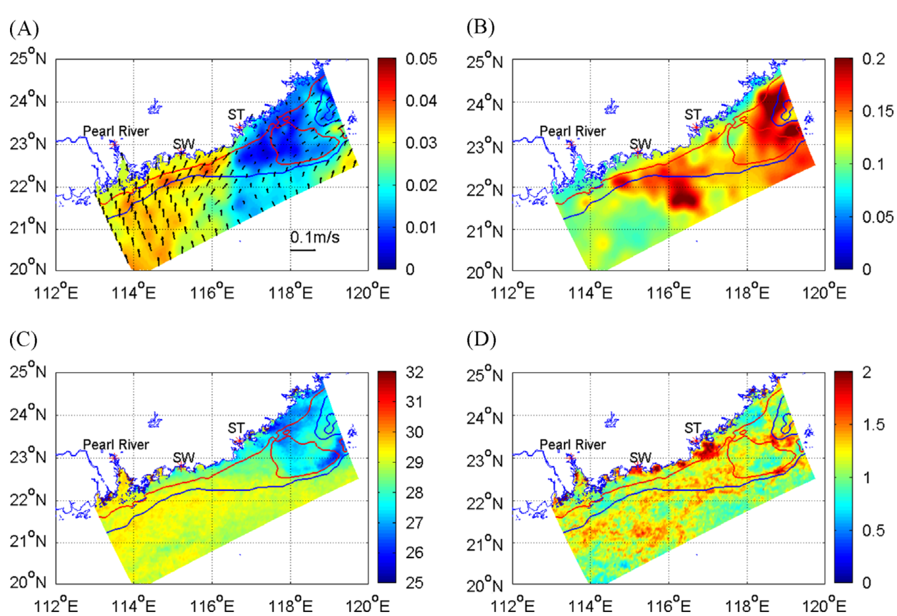

Fig. 2. (a) Averaged QuikScat wind stress vectors (Pa) and magnitude (color contours); (b) standard deviation of wind stress vector magnitude, (c) averaged MODIS SST (°C) and (d) its standard deviation of SST for days 20–100 (June 5–August 24) in the NSCS. The 30 m and 50 m isobaths are shown as red and blue contour lines, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)