Spring mesoscale high in the western South China Sea

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Abstract

A recurring spring mesoscale eddy in the western South China Sea (SCS) is studied using remote sensing data and historical in situ observations. The feature first appears east of the central Vietnam coast in February as a high sea-level anomaly, grows rapidly to a well-developed anticyclonic eddy by March, matures in April, and decays in May. Besides the warm-core feature, it also has an inherent low-salinity property, so it is named "spring mesoscale high (SMH)". Though with clear interannual variation in terms of intensity and spatial coverage, the SMH always emerges in the region between 110°E and 114°E and between 12°N and 16°N. The formation of SMH is ascribed to the combined effects of wind forcing and releasing of potential energy set up by winter monsoon. In particular, the wind-stress curl plays an important role in its development, maintenance, and dissipation.

Key words: spring, western South China Sea, warm eddy


1 Introduction

The South China Sea (SCS) is subjected to extreme seasonal variations in atmospheric forcing of the northeasterly and southwesterly monsoons. In response to the seasonally reversing wind over the SCS, the upper layer of the SCS undergoes dramatic seasonal variation. For example, a basin-wide cyclonic gyre exists over the northern SCS basin in winter, and a prevailing northeastward flow with a narrow western boundary current (in the opposite direction of the southwest monsoon) along the continental slope south of China in summer (Qiu, 2000).

Spring is the transition season for the upper ocean from its winter pattern to its summer pattern. Based on monthly sea surface temperature (SST) data, Chu and Chang (1997) and Chu et al. (1997) found that the SCS in spring was characterized by a small warm pool from April to May and proposed that the warm pool was developed from a warm eddy near the west coast of Luzon Island in early April. However, the temperature anomaly at 50 m depth from a numerical model driven by climatological wind showed a warm pool formation at the western part of the SCS deep basin in April (Chu, Chen et al., 1998). This warm pool can also be seen in the survey conducted in May 1995 and was named Xisha Warm Pool (Chu, Fan et al., 1998).

In this paper, we show that a warm eddy in the vicinity of the Xisha Islands is a recurring seasonal signal in spring, using the altimeter data and the historical hydrographic observations. Since the eddy is more striking in the sea level anomaly (SLA) than in the SST anomaly (SSTA), we name it "spring mesoscale high (SMH)". The paper is organized as follows. Section 2 introduces the data used. Section 3 describes the features of the SMH. Interannual variations of the SMH and a preliminary result about the response of the rainfall to this semi-stationary eddy are reported in Section 4. The role of wind field in the evolution of the SMH is discussed in Section 5. Finally, summary and discussion are presented in Section 6.

2 Data

2.1 Climatological temperature and salinity data

The climatological temperature and salinity data used here are calculated from the historical in situ observations from 1920 to 2005 collected by the South China Sea Institute of Oceanology, as well as ocean station data (OSD) and CTD data of the World Ocean Database 2001. Readers can refer to the work of Liu et al. (2008) for details about quality control, interpolation and smoothness.

2.2 Altimetry data

Gridded SLAs are provided by the Ssalto/Duacs mission altimeter products of archiving, validation and interpretation of satellite oceanographic data (AVISO). The data are weekly from 1993 to 2006 and have spatial resolution of (1/3°) by (1/3°). The climatological maps of SLAs are obtained over each month, and the seasonal mean maps are averaged season by season from 1993 to 2006. Spring includes March, April, and May.

2.3 QuikSCAT wind field

The daily QuikSCAT wind products from 2000 to 2006 are
used to show the relationship between the wind field and the SMH. The QuikSCAT data are produced by remote sensing systems sponsored by the NASA Ocean Vector Winds Science Team. The products are global, and on grids of (0.25°) × (0.25°). The climatological wind field is computed over the monthly mean, averaged month by month.

2.4 Remote sensing SST

In order to have the same time span as the altimeter data, we use the monthly advanced very high resolution radiometer (AVHRR) Pathfinder SST v5 (spatial resolution of 4 km) from 1993 to 2006. The SST observations with quality flags higher than four (with seven being the highest quality) are averaged over each month to give monthly climatological SST. As we know the infrared sensor is affected by cloud and aerosols seriously, to avoid poor coverage in the climatological SST, we calculate the climatological SST only over those data points with observations no less than 10 a.

2.5 Precipitation data

The monthly rainfall products, TRMM. PR level-3 3A12, are based on the precipitation radar (PR) sensors on board the tropical rainfall measuring mission (TRMM) satellite. The variables of this data set include a convective rainfall rate, a stratiform rainfall rate, and a surface rainfall rate, among others. The geographic coverage is from 40°S to 40°N with a spatial resolution of 0.5°. Only the monthly rainfall data of March and April in each year from 1998 to 2005 are selected for analyzing because much rainfall in May is induced by the southwest monsoon onset.

These data have been processed to monthly climatological, seasonal or monthly mean for the qualitative analysis about the SMH. Although these data have different time spans and diverse temporal and spatial resolutions, the seasonal signals including the SMH can be well kept in the processing.

3 Evolution of the SMH

Altimeter data and SST data from 1993 to 2006 are processed to produce the climatological monthly-mean SLA and SST fields. The SMH can be easily seen in the SLA field in the western SCS (12°–16°N, 110°–114°E) from March to April (Fig. 1). It satisfies the two crucial criteria, out of the five proposed by Wang et al. (2003) to identify the mesoscale eddy, namely, the SLA contours are closed and the SLA difference between its center and its outermost enclosed contour is greater than 7.5 cm. In January, the SST map shows no obvious warm and high SLA signals. In February, a small high SLA stretches from the Vietnam coast toward the center of the basin and the enclosed SLA contour of 5 cm begins to appear. In March, the high SLA contour is enclosed and accompanied by northward stretching isotherms, which indicates the formation of the SMH. April is the mature stage of the SMH. In this month, the area of SMH expands, and the SLA field shows two high cores with a higher one to the west. In May, the SMH can still be identified, but the high SLA has covered the deep basin from the west to the east. Since it has become a basin-scale feature in the SCS, we can call it a warm pool as literatures have done. Then in June the high SLA reaches the west coast of Luzon Island and is combined with the high SLA in the Pacific through the Luzon Strait. The climatological features of SLA are consistent with the results of Ho et al. (2000) and Li et al. (2003) derived from much shorter time series of SLA.

Since the SMH centers around 14.5°N (Fig. 1), we select the climatological transect of temperature and salinity along 14.5°N (Fig. 2) to examine its vertical structure. There are few

![Fig.1. Climatology of SLA (cm) and SST anomaly fields from January to May. Contours are SLA isolines. The SLAs over the area shallower than 200 m are left blank.](image-url)
warm signals though high SLA signal has appeared in February in the western SCS, while the relatively low salinity water has existed in the depth range above 60 m. In March, isotherms deepen from 50 m to 120 m around 112°E, which is nearly coincided with the location of the high SLA in Fig. 1, while the low-salinity water exists in the depth range shallower than 50 m around 114°E. The isotherms deepen around 113°E in April, which is to the east of the core shown in the SLA map, while the salinity contours manifest two low-salinity cores, which is similar to the SLA map, though the east core in this transect is to the east of the east core in the SLA map. The west core is fresher than the east core, and its deepened contours can reach the depth of 120 m, also deeper than the east core. The two low-salinity cores explain the existence of the two high cores in the SLA map. The upper layer of the whole SCS basin has warmed up in May, and the salinity also becomes saltier. No distinct eddy-like structure can be seen anymore. The evolution of the vertical structure shows us the emergence of the SMH in February, the development in March, the peak in April and the fading in May, which agrees with the SLA maps. As for the discrepancies between the remote sensing SLA and the SCSIO hydrographic data, it may be due to different time spans of the two data sets.

4 Interannual variation and rainfall rate associated with the SMH

4.1 Interannual variation

When the SLA field from 1993 to 2006 is examined, we find that the high SLA recurs in each spring mainly in the region bounded by 12°N and 16°N and 110°E and 114°E (Fig. 3, left panel), though the maximum strength and area coverage vary.

Fig. 2. Climatology of temperature (°C; upper panels) and salinity (lower panels) along 14.5°N from February to May, constructed from the SCSIO hydrographic data. Contour intervals are 1°C and 0.1.

Fig. 3. Coverage of the SMH in each year from 1993 to 2006 (left), and distribution of surface rainfall rate along with SLA (right). The boundaries are determined by the SLA of 5 cm in 1994 and 1996 for the weaker SMHs and 7.5 cm in other years.
greatly from year to year. The SMH was weak during the period from 1993 to 1996, especially in 1994 and 1996, when the maximal SLA was less than 7.5 cm. Then it intensified in terms of area coverage and strength after 1997, and weakened again in 2004 and 2005.

4.2 Rainfall rate
To investigate the impact imposed by the SMH on the atmospheric boundary layer, we analyze the monthly rainfall data and SLA in March and April jointly. The rainfall rate in May is excluded because more rainfall results from summer monsoon onset during May. The SLA data in the region covering the SMH (10°–18°N, 110°–120°E) are interpolated to the grid of the rainfall data to explore the relation between them. The result shows that most of high rainfall appears over positive SLA (Fig. 3, right panel). The peak of rainfall locates between 0 cm and 5 cm of the SLA, but this part of the high rainfall does not result from the SMH. Instead, it may be a result of high SST itself. Comparing the rainfall over the SLA higher than 5 cm, which can be considered as the SMH coverage, with that over the SLA lower than −5 cm, we find that though the maximum is nearly the same, much more precipitation distributes over the SMH. This distribution pattern means the SMH intensifies local convection and thereby leads to unstable atmospheric stratification.

5 Wind field matching the SMH
As a transition season of the monsoons, the wind field in each month of spring has its own characteristics (Fig. 4). The northeasterly monsoon dominates the whole SCS in March. A belt of negative wind-stress curl exists from the Luzon Strait to the Vietnam coast, which covers most area of the SMH shown in Fig. 1. Compared with the wind field in February (not shown), the negative wind-stress curl belt expands southeastward to the central basin. The northeasterly monsoon weakens in April, a sign of which is the northeasterly controlling in the northwestern SCS in March turns to the southeasterly controlling. Accordingly, the region occupied by the negative wind-stress curl expands to most parts of the central and northern SCS and covers the whole SMH. The southerly prevails in May, and much of the central and northern SCS has become a region of the positive wind-stress curl.

The evolution of the climatological wind in spring implies that the wind-stress curl likely plays an important role in the generation and dissipation of the SMH. The negative wind-stress curl in March and April favors the genesis and development of the SMH, while the positive wind-stress curl in May weakens the SMH. In response to the positive wind-stress curl, the SMH begins to decay.

6 Summary and discussion
We have shown that a mesoscale high SLA signal recurs in the western SCS in spring. It is gestated in February, develops in March, matures in April, and fades away in May. The wind-stress curl plays an important role in its development, mainte-
nance, and dissipation. In addition to the corresponding relatively-higher SSTAs as a warm-core eddy, we also find its inherent low-salinity feature in the historical in situ observations, which explains the two cores seen in the SLA map but not in the temperature field. In view of this, we term it spring mesoscale high instead of spring warm-core eddy. Though with distinct interannual variations in terms of intensity and coverage, the mesoscale eddy tends to appear in the region bounded by 12°N and 16°N and 110°E and 114°E. In addition, the SMH can increase local rainfall by intensifying the convection in the atmosphere above it.

As to the mechanism for the formation of SMH, Chu, Chen et al. (1998) showed the importance of wind in generating the warm-core eddy in the spring-to-summer transition season through numerical experiments. We wish to note that in their temperature anomaly map of April for the no-wind test run, the warm-core eddy still exists though much weaker than those in the control run and no-lateral-transport test run (Fig. 5). These results of sensitive experiments also suggest that the lateral transport contributes to the generation of SMH. Nevertheless, questions remain. Why does the high SLA signal stretch out at the central Vietnam coast, not anywhere else, and then shed as an eddy? Where does the SMH obtain its low-salinity feature from? Is it from the local precipitation or from the Vietnamese coastal water? It seems that the high SLA signal stretching out from the Vietnam coast in February supports the latter (Fig. 1), while the low-salinity water cannot be seen in the climatology of salinity along 14.5°N in February (Fig. 2). We hope to provide some answers to these questions through our future work.

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