Effect of Cylindrically Shaped Atoll on Westward-Propagating Anticyclonic Eddy—A Case Study

Yu-Chia Chang, Guan-Yu Chen, Ruo-Shan Tseng, and Peter C. Chu

Abstract—**Mesoscale anticyclonic eddies occasionally propagate westward across the Dongsha atoll situated on the continental slope in the northern South China Sea (SCS). Satellite observations of this phenomenon are used to identify eddy weakening and deforming. Stronger anticyclonic eddies are weakening within a distance of 30–120 km from the atoll. A weaker anticyclone with an eddy diameter of 120 km, a sea-level slope of 8.3×10^{-8}, a Reynolds number of 17, and a slow moving speed (2.5 km/d) in the SCS can be split into two smaller eddies.**

Index Terms—**Deformation, Dongsha atoll, eddy, split.**

I. Introduction

The South China Sea (SCS) is a marginal sea in the western Pacific Ocean and is one of the largest seas (around 3 500 000 km^2) in the world. Mesoscale eddies occur frequently in the SCS and have been detected using satellite altimetry data [7], [15] and hydrographic measurements [3], [6], [8]. Most of the SCS eddies originate from the eastern SCS in winter [17] while off central Vietnam and other places in summer [16], [19]. In winter, orographic wind jets along the eastern boundary of the SCS spin up cyclonic and anticyclonic eddies [17]. A synoptic cool-core cyclonic eddy northeast of the Dongsha Island in July 1997 using the Airborne Expendable Bathythermograph and Conductivity–Temperature–Depth sensors was identified [3]. Annual occurrence of a mesoscale eddy south or southwest of Dongsha, with 6 cm as the sea-level difference between the edge and center of the eddy $(\Delta\eta)$, was indicated [2]. This eddy is called the Dongsha Cyclonic Eddy. It moves with a typical speed of 8 km/d (9 cm/s), which is comparable to the propagation speed of Rossby waves.

Collision of the mesoscale eddy with topography can cause its destruction [12], [13]. Such a topographic effect was confirmed by a 3-D numerical simulation for destruction of the warm core ring after its interaction with the continental shelf and slope [20]. However, the topographic-caused eddy weakening and destruction have not been studied in the SCS, particularly near the Dongsha atoll area, which is located in the northeastern SCS. The Dongsha atoll has a diameter of 25 km, covers an area of 500 km^2, and consists of the Dongsha Island (116.73° E, 20.70° N), lagoons, and reef platforms (Fig. 1). In this study, satellite altimetry data are used to investigate the effect of Dongsha atoll (or more generally, a cylindrically shaped atoll) on the mesoscale eddy weakening, deformation (possible splitting), and destruction as the eddy approaches the atoll.

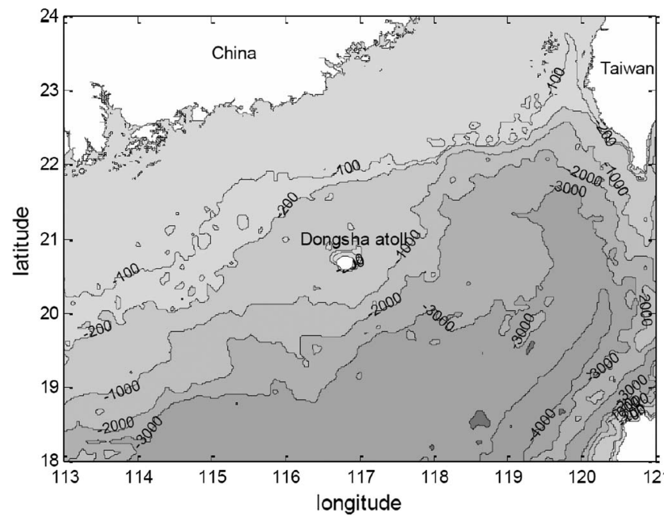

Fig. 1. Location of the Dongsha atoll and bathymetry (unit: m) in the northeastern SCS.

II. Data

A multiple-altimeter data set of $1/3^\circ \times 1/3^\circ$ grids from the Archiving, Validation, and Interpretation of Satellite data in Oceanography (AVISO) was used. It consists of the sea-level anomaly (SLA) of four satellites (TOPEX/Poseidon, ERS-1/2, Jason-1, and Geosat Follow-On) recorded every week during 2000–2005. The sea surface height (SSH) is composed of a variable oceanic part, the mean sea surface (MSS), and an SLA part. The MSS data are a six-year along-track mean, computed exclusively from the TOPEX/Poseidon data (1993–1998).

Since the along-track satellite measurements do not pass through all the grid points, the objective analysis causes error in the SLA data, which depends on the number of available satellites at the given time period. The error of the gridded

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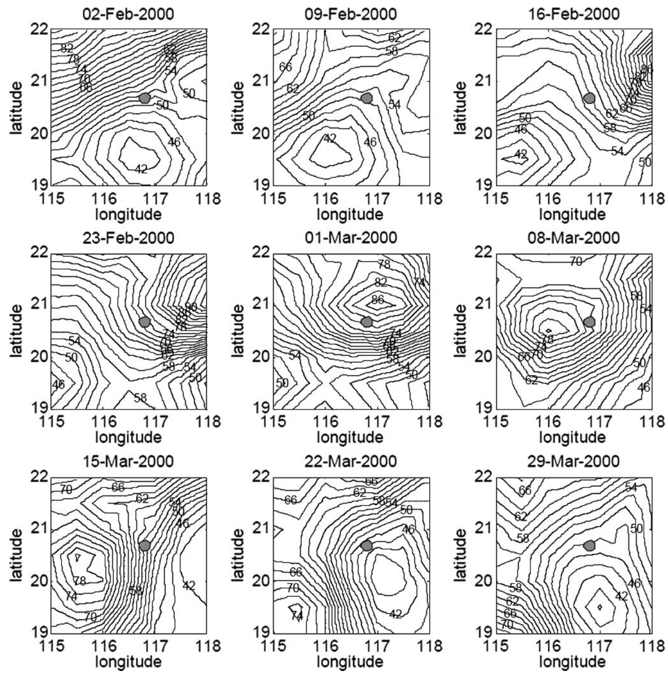

Fig. 2. Weekly SSH fields in February–March 2000. The shaded circle is the Dongsha atoll.

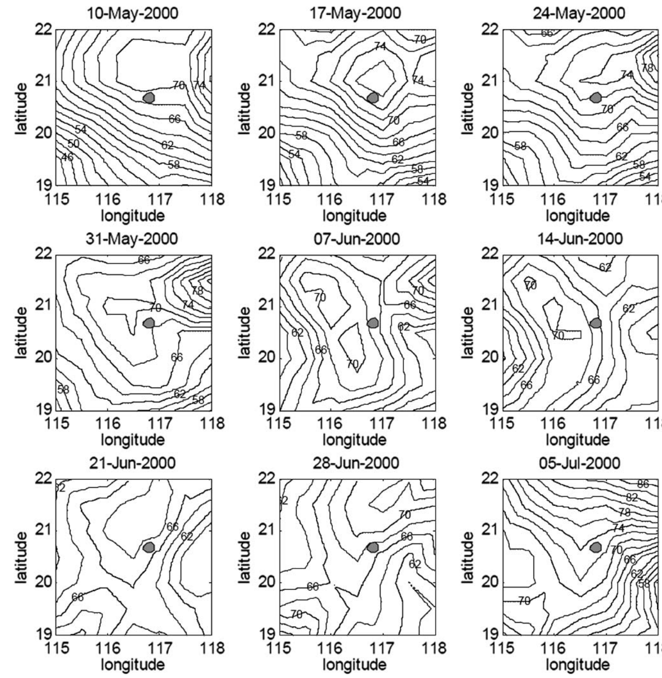

Fig. 3. Weekly SSH fields in May–June 2000. The shaded circle is the Dongsha atoll.

SLA data was 1.3%–57.8% around the Dongsha waters deeper than 200 m [2]. To identify and trace mesoscale eddies from a weekly SSH contour map, the following criteria are used for identifying an eddy and its characteristics [2], [18]: 1) the existence of closed SSH contours; 2) nearly elliptic enclosed contours; 3) the eddy center defined as the center of the innermost contour; and 4) the eddy diameter defined as the diameter of the outermost contour.

III. Effect of Atoll on Westward-Propagating Anticyclonic Eddy

Nine weekly consecutive SSH fields from February 2 to March 29, 2000 (Fig. 2), show the evolution of an anticyclonic eddy. On February 23, an anticyclonic eddy with a high SSH center of 95 cm (sea-level difference $\Delta\eta = 13$ cm) appeared east of the Dongsha atoll and moved westward. A week later (March 1), the anticyclonic eddy moved westward closer to Dongsha and was weakened to $\Delta\eta = 11$ cm with a high SSH center of 87 cm. After March 1, the anticyclonic eddy moved westward further to pass the atoll and continued to be weakened.

Nine weekly consecutive SSH fields from May 10 to July 5, 2000 (Fig. 3), show the deformation of a southwestward-moving anticyclonic eddy and persistence around the Dongsha atoll for two weeks (June 4–17, 2000). An anticyclonic eddy with an SSH of 77 cm ($\Delta\eta = 5$ cm) existed north of the atoll on May 17, 2000. On May 24, it touched the atoll and changed into a long and narrow eddy. After a week (May 31), the deformed eddy moved along the atoll, and a second eddy was developed. The rest of the eddy moved along the original direction. Finally, after colliding with the Dongsha atoll, it seems to be split into two smaller eddies with an enclosed contour of 70 cm on June 7, 2000. This is the only eddy-splitting case ever observed during the entire period of 2000–2005. Fig. 5(a) shows the tracks of the centers of six anticyclonic eddies moving westward or southwestward across the Dongsha atoll during 2000–2005 with nearby starting locations. Most of them were just gradually weakened. Only one eddy (shown as the dashed curve) was split into two smaller eddies.

In the open ocean, previous studies have shown that anticyclones cannot split alone due to limitations imposed by the conservation of angular momentum [9], [10]. This limitation is applicable only for barotropic processes, and anticyclones can be split by baroclinic instability [5]. A zero-potential-vorticity lens with radius R_1 can also be split into two offspring with the existence of a wall if the wall length is longer than $1.19R_1$ [14]. Different from [14], the eddy splitting here was caused by touching the atoll, not by being cut by the wall.

IV. Discussion

Aside from the general discussion in the previous section, more discussions based on nondimensionalized parameters are presented in the following. Generally, eddy flows are depicted by the gradient wind equation

$$fv + \frac{v^2}{R} = -g\frac{\partial \eta}{\partial x} \qquad (1)$$

where f is the Coriolis parameter, g is the gravitational acceleration, v is the tangential velocity, R is the radius of the eddy, v^2/R is the centrifugal force, and $-g\partial\eta/\partial x$ is the pressure gradient force. For a typical eddy, the tangential velocity is $v = 0.3$ m/s, and the mean radius of the eddy is $R = 100$ km. At 21° N latitude, the local Coriolis parameter

$$f = 5.21 \times 10^{-5}\ \mathrm{s}^{-1} \qquad (2)$$

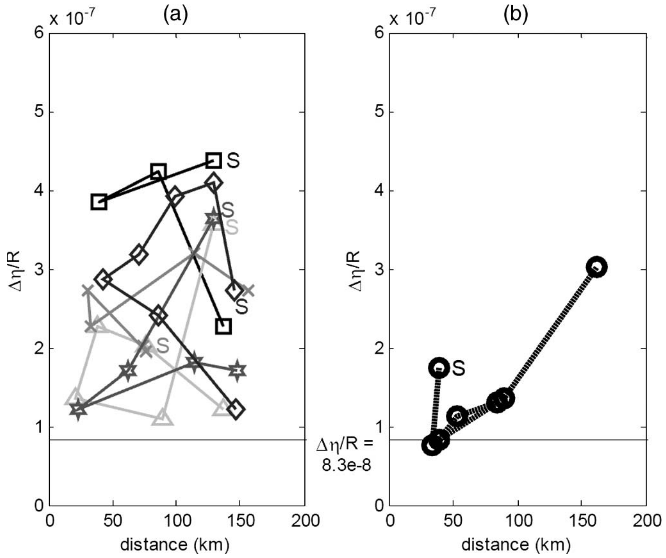

Fig. 4. Eddy sea surface slope $(\Delta\eta/R)$ versus distance between the eddy center and the Dongsha atoll (δ) for (left) five nonsplitting and (right) one splitting eddies. The starting location of the eddy is marked by the character "S."

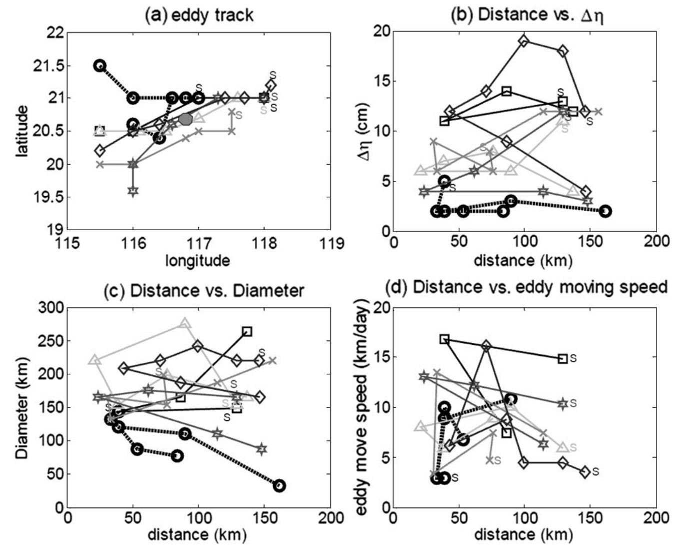

Fig. 5. (a) Tracks, (b) height differences $\Delta\eta$, (c) diameters, and (d) moving speeds of six eddies versus the distance δ. The starting location of the eddy is marked by the character "S." The dashed curves represent the splitting eddy.

and the Coriolis force term $(fv = 1.56 \times 10^{-5}\ \mathrm{m/s^2})$ is much larger than the centrifugal force term $(v^2/R = 9 \times 10^{-7}\ \mathrm{m/s^2})$. Thus, the centrifugal force v^2/R can be neglected in (1), which leads to

$$v = -\frac{g}{f}\frac{\partial \eta}{\partial x} \cong -\frac{g}{f}\frac{\Delta\eta}{R}. \tag{3}$$

Since g and f are constants, the eddy tangential velocity is proportional to $\Delta\eta/R$. Fig. 4 shows the dependence of the eddy sea surface slope $(\Delta\eta/R)$ on the distance from the eddy center to the Dongsha atoll (δ) for the nonsplitting eddies [Fig. 4(a)] and the splitting eddy [Fig. 4(b)]. From the starting location (marked by "S"), $\Delta\eta/R$ generally reduces with decreasing δ. The eddy splitting occurs as $\Delta\eta/R$ is smaller than 8.3×10^{-8} [Fig. 4(b)].

Viscosity plays a very important role in the dissipation of an eddy; hence, the Reynolds number Re is also included in the analysis of eddy behavior. The Reynolds number is defined by

$$Re = \frac{vR}{K_E} \tag{4}$$

where K_E is the eddy viscosity. Substitution of (3) into (4) gives

$$Re \cong \frac{g}{f}\frac{\Delta\eta}{R}\frac{R}{K_E} \cong \frac{g\Delta\eta}{fK_E}. \tag{5}$$

Here,

$$K_E = 220\ \mathrm{m^2/s}\ \text{(ref. [1])} \qquad g = 9.8\ \mathrm{m/s^2}. \tag{6}$$

Thus, the Reynolds number is proportional to $\Delta\eta$. The strongest eddy with $\Delta\eta$ of 19 cm was weakened to 7 cm for δ within 100 km [Fig. 5(b)]. Four weaker eddies with $\Delta\eta$ of 12–14 cm were weaken to 3–8 cm for δ of 80–130 km. The weakest eddy with $\Delta\eta$ of 5 cm passed across the atoll and split into two smaller eddies when it was close to the atoll with $\Delta\eta$ of 2 cm for δ within 30 km. Using the values listed in (2) and (6) for the parameters and 2 cm as the value for $\Delta\eta$, the magnitude of Re for anticyclonic eddy splitting is 17 (Fig. 6).

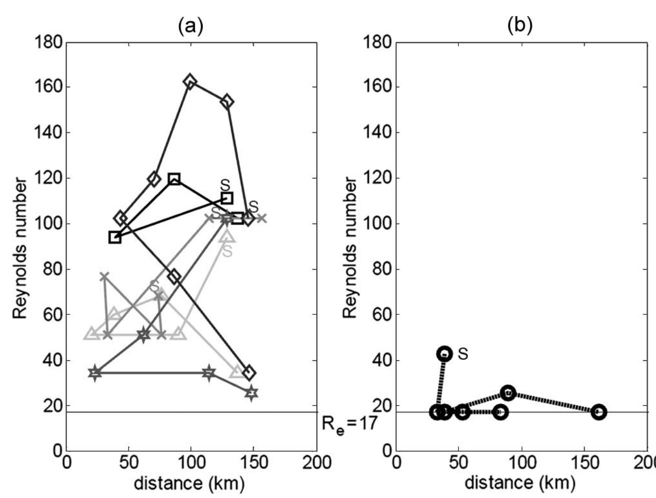

Fig. 6. Reynolds numbers (Re) versus distance δ for (left) five nonsplitting and (right) one splitting eddies. The starting location of the eddy is marked by the character "S."

The relationship between the eddy diameter and the distance to the atoll [Fig. 5(c)] shows the existence of a value of the eddy diameter (120 km): 1) weak eddies with diameter equal to 120 km being split and 2) stronger eddies with diameter larger than 120 km (170–220 km) being weakened when they are approaching to the atoll. Since the diameter of the atoll is about 25 km, the ratio between the eddy diameter and the atoll diameter (γ) is 4.8.

The relationship between the moving speed of the eddy (s) and the distance to the atoll [Fig. 5(d)] shows that the splitting eddy (shown by the dashed curve) has slow moving speed. This implies that an eddy with a slower s may be easily affected by the atoll. For the distance less than 50 km, the splitting eddy has the minimum s of 2.5 km/d. Based on these observations, the conditions for eddy splitting at the Dongsha atoll are given by

$$Re = 17 \qquad \gamma = 4.8 \qquad s = 2.5 \text{ km/d}. \tag{7}$$

Since there is only one eddy which was found to be split into two smaller eddies, there is no statistical significance for the thresholds of eddy splitting. However, it provides rare conditions for the eddy splitting in the study area. It is also noted that the root-mean-square error of the gridded SLA data is around 2 cm (http://www.aviso.oceanobs.com/en/altimetry/multi-satellites/index.html). The eddy seems to be split into two parts (June 7, 2000 in Fig. 3) with a difference between the two parts of less than 2 cm. Whether the two parts in the eddy are caused by SLA errors or by existence of the atoll needs further investigation (may use a modeling approach).

V. Summary

A multiple-altimeter data set of $1/3^\circ \times 1/3^\circ$ grids from the AVISO during 2000–2005 was used to identify the weakening/destruction and splitting of anticyclonic eddies as they approached the Dongsha atoll. It is found that the observed eddies can be weakened within distances of 30–120 km from the eddy center to the atoll. The data in May 2000 indicated that a weaker anticyclone with an eddy diameter of 120 km, a Reynolds number of 17, and slow moving speed (2.5 km/d) in the SCS is possible to be split into two smaller eddies.

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References

[1] R. A. Barkley, "Johnston Atoll's wake," *J. Mar. Res.*, vol. 30, pp. 201–216, 1972.

[2] C. H. Chow, J. H. Hu, L. R. Centurioni, and P. P. Niiler, "Mesoscale Dongsha Cyclonic Eddy in the northern South China Sea by drifter and satellite observations," *J. Geophy. Res.*, vol. 113, no. C4, p. C04018, Apr. 2008.

[3] P. C. Chu, C. W. Fan, C. J. Lozano, and J. Kerling, "An airborne expandable bathythermograph survey of the South China Sea, May 1995," *J. Geophys. Res.*, vol. 103, no. C10, pp. 21 637–21 652, Sep. 1998.

[4] P. C. Chu and C. W. Fan, "A low salinity cool-core cyclonic eddy detected northwest of Luzon during the South China Sea Monsoon Experiment (SCSMEX) in July 1998," *J. Oceanogr.*, vol. 57, no. 5, pp. 549–563, 2001.

[5] S. S. Drijhfout, "Why anticyclones can split," *J. Phys. Oceanogr.*, vol. 33, no. 8, pp. 1579–1591, Aug. 2003.

[6] W. Fang, G. Fang, P. Shi, Q. Huang, and Q. Xie, "Seasonal structures of upper layer circulation in the southern South China Sea from *in situ* observations," *J. Geophys. Res.*, vol. 107, no. C11, p. 3202, Nov. 2002.

[7] C. Hwang and S. A. Chen, "Circulations and eddies over the South China Sea derived from TOPEX/Poseidon altimetry," *J. Geophys. Res.*, vol. 105, no. C10, pp. 23 943–23 965, 2000.

[8] L. Li, W. D. Nowlin, and S. Jilan, "Anticyclonic rings from the Kuroshio in the South China Sea," *Deep Sea Res., Part I*, vol. 45, no. 9, pp. 1469–1482, Sep. 1998.

[9] D. Nof, "The role of angular momentum in the splitting of isolated eddies," *Tellus*, vol. 42, no. 4, pp. 469–481, Aug. 1990.

[10] D. Nof, "Fission of single and multiple eddies," *J. Phys. Oceanogr.*, vol. 21, no. 1, pp. 40–52, Jan. 1991.

[11] Open University, *Ocean Circulation*, Oxford, U.K.: Pergamon, 1989.

[12] P. L. Richardson and A. Tychensky, "Meddy trajectories in the Canary basin measured during the semaphore experiment 1993–1995," *J. Geophys. Res.*, vol. 103, no. C11, pp. 25 029–25 045, 1998.

[13] P. L. Richardson, D. Walsh, L. Armi, M. Schröder, and J. F. Price, "Tracking three meddies with SOFAR floats," *J. Phys. Oceanogr.*, vol. 19, no. 3, pp. 371–383, Mar. 1989.

[14] H. L. Simmons and D. Nof, "Islands as eddy splitters," *J. Mar. Res.*, vol. 58, no. 6, pp. 919–956, Nov. 2000.

[15] Y. S. Soong, J. H. Hu, C. R. Ho, and P. P. Niiler, "Cold-core eddy detected in South China Sea," *Eos Trans. AGU*, vol. 76, no. 35, pp. 345–347, 1995.

[16] G. H. Wang, D. Chen, and J. L. Su, "Generation and life cycle of the dipole in summer South China Sea circulation," *J. Geophys. Res.*, vol. 111, no. C6, p. C06002, 2006.

[17] G. H. Wang, D. Chen, and J. L. Su, "Winter eddy genesis in the eastern South China Sea due to orographic wind jets," *J. Phys. Oceanogr.*, vol. 38, no. 3, pp. 726–732, Mar. 2008.

[18] G. H. Wang, J. L. Su, and P. C. Chu, "Mesoscale eddies in the South China Sea observed from altimeter data," *Geophys. Res. Lett.*, vol. 30, p. 2121, Nov. 2003.

[19] G. H. Wang, J. L. Su, and R. F. Li, "Mesoscale eddies in the South China Sea and their impact on temperature profiles," *Acta Oceanol. Sin.*, vol. 24, no. 1, pp. 39–45, 2005.

[20] J. Wei and D. P. Wang, "A three-dimensional model study of warm core ring interaction with continental shelf and slope," *Cont. Shelf Res.*, vol. 29, no. 13, pp. 1635–1642, Jun. 2009.