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Migration of mesoscale eddies across a leaping or penetrating western boundary current in the vicinity of a gap*

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Abstract A 1.5-layer quasi-geostrophic reduced gravity ocean circulation model is used to study the propagation of mesoscale eddies across a western boundary current (WBC) either leaping across or penetrating in an anti-cyclonic path through the gap. The steady leaping WBC nearly blocks all eddies from propagating across it through the gap completely. However, both cyclonic and anti-cyclonic eddies can migrate across a penetrating WBC in the vicinity of a gap, while inducing an opposite type of eddies on the cyclonic side of the WBC by weakening or strengthening the intrusion of the WBC. Both type of eddies gained strength from the WBC in the course of the propagation across the WBC in the gap. Eddies approaching the gap from the upstream are found to migrate more easily into the western basin due to the advection of the WBC. The migration speeds of the eddies are almost unchanged by the presence of the WBC in all experiments.

Keyword: mesoscale eddy; Western Boundary Current; gap

1 INTRODUCTION

There are numerous mesoscale eddies in both the South China Sea (SCS) and the Northwest Pacific according to observations (Wang et al., 2003; Chelton et al., 2011). Because of their effects on circulation structure and nutrient distribution, it is important to study eddy propagation and dynamics. Although observed eddy propagation in the Pacific is nearly due west, it is not clear what the fate is of eddies passing through the Luzon Strait into the SCS. This is a complex problem because of the complicated topography in the Luzon Strait and the changeable Kuroshio path.

Barotropic quasi-geostrophic models have long been used to model oceanic eddies (McWilliams and Flierl, 1979), showing a dominantly westward motion, along with a poleward motion. Furthermore, some eddies may encounter walls (with gaps) or a current as they move, which is also an interesting problem that has been studied by some researchers (Nof, 1988; Pedlosky, 1994; Sutyrin et al., 2003). The interaction of mesoscale eddies with WBCs was first studied in a reduced gravity primitive equation model by (Chern and Wang, 2005) and (Johnson and MacDonald, 2005). Van Leeuwen (2007) used a reduced gravity model to study propagation of a vortex on a β plane with a background flow. He concluded that the vortex

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moves at the normal vortex speed, but do not advect with the background flow. The vortex obtains an extra self-propagation due to the tilted thermocline which exactly cancels the advection. These studies describe the general characteristics of the propagation of eddies in the ocean, although questions remain about the propagation of eddies in Luzon Strait influenced by Kuroshio.

It has been shown that the steady state of the WBC flowing by a wide gap has multiple equilibria, the transitions between which depend on the Reynolds number of the WBC and experience a hysteresis loop, and the dynamics has been studied by (Yuan and Wang, 2011), and recently the hysteresis of the WBC flowing by a gap is verified by laboratory rotating table experiments (Kuehl and Sheremet, 2014).

In a numerical study of eddies in the Kuroshio east of the Luzon Strait (Sheu et al., 2010) argues the results fall into either one of two blocked modes or westward passage. Zheng et al. (2011) shows that the probability of eddies penetrating through the Kuroshio is higher than 60% using scale analysis, and presents a case of an anticyclonic eddy passing through the Luzon Strait based on satellite altimeter data. The two blocked modes depend on the two paths of Kuroshio in Luzon Strait.

The possible paths of the Kuroshio in the Luzon Strait are not yet settled. Pu et al. (1992) describe a branch of the Kuroshio passing through the Luzon Strait into the South China Sea (SCS) based on observations. Li et al. (1998) describe the intrusion of the Kuroshio into the SCS as a loop. Using satellite techniques, Yuan et al. (2006) argues the anti-cyclonic Kuroshio intrusion is a transient phenomenon occurring in all seasons but which happens less than 30% of the time. Sheremet (2001) in a 1.5-layer quasi-geostrophic model study of a WBC flowing by a wide gap finds multiple steady solutions as a function of the current strength characterized as either penetrating or leaping states.

In this paper, we study the propagation of mesoscale eddies across a western boundary current in the vicinity of a gappy western boundary. We expand upon the results of (Yuan and Wang, 2011), who built upon the findings of (Sheremet, 2001) of multiple equilibria of a WBC flowing by a gap and studied the interactions of the WBC with mesoscale eddies. They showed that both cyclonic and anticyclonic eddies have significant impacts on the WBC path inside the gap when the WBC is in a critical state. In this paper, we use the same model to study the propagation of eddies influenced by the WBC in steady leaping and penetrating states far away from the critical hysteresis states.

2 THE NUMERICAL MODEL AND METHOD

The model used in this study is the same as (Yuan and Wang, 2011), which is a 1.5 layer quasi-geostrophic (QG) circulation model. The potential vorticity equation of the model is

$$-\frac{1}{{L_R}^2}\psi_t+\zeta_t+J(\psi,\zeta)+\beta\psi_x=A_H\nabla^2\zeta, \tag{1}$$

$$\zeta=\nabla^2\psi, \tag{2}$$

where ψ is the stream function of a depth-averaged flow, and ζ is the relative vorticity. The model coefficients in this study are set up as follows. The Coriolis coefficient gradient $\beta=2\times10^{-11}$ m/s and the baroclinic deformation radius is L_R=50 km, which are the character parameters of the Kuroshio in the Luzon Strait according to Nitani (1972), Also, L_R=50 km is a proper choice for the QG model to reproduce the whole hysteresis cycle of the WBC in the gap (Yuan and Wang, 2011). The viscosity coefficient A_H=300 m^2/s, which is determined based on a set of numerical experiments from A_H=10 m^2/s to A_H=9 000 m^2/s, this is a proper value to adjust the QG model to study the hysteresis of a WBC flowing by a gap and the interactions of the WBCs of different states and eddies in this paper, if A_H is too small, the nonlinear term will be more stronger than the friction term in the Eq.1, leading to unstable submesoscale turbulence; if A_H is too large, the friction term of the Eq.1 is too strong to damp the energy of the model. The details about the 1.5-layer QG model used in this paper is reference to (Li, 2008). The Munk WBC thickness L_M=25 km ($L_M=\sqrt[3]{A_H/\beta}$). The calculation area of model is two basins joined separated partially by a gappy boundary as shown in Fig.1. The zonal western and eastern basins are 1 500 and 1 800 km respectively and the meridional width of the gap in the middle is 240 km, and the grid resolution is 10 km. The northern, southern and eastern boundaries in the eastern basin are open boundaries. The WBC in the model is driven by the stream function gradient between the eastern boundary and western boundary of the eastern basin. The model is set up by the initial WBC of different transports and calculated by the vorticity equation without any other surface forcing. Nonslip boundary conditions are applied along the meridional barrier wall in the middle of the basin.

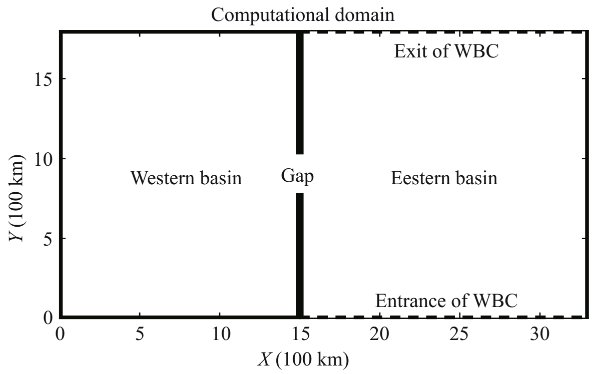

Fig.1 The topography of the model domain

The solid line is the solid boundary, and the dotted line is open boundary.

We first use this model to describe the migration of a lone eddy (in the absence of a WBC). The eddy is inverted into the model with a Gaussian in potential vorticity of sufficient strength that it possesses closed contours:

$$q=\nabla^2\psi-\frac{1}{{L_R}^2}\psi=q_0e^{-\frac{(x-x_0)^2+(y-y_0)^2}{2R^2}}, \tag{3}$$

which R is the radius of eddy, (x_0, y_0) is the initial location of eddy, and q_0 is the initial potential vorticity value in the center of eddy. The eddy is cyclone or anticyclone depending whether ζ_0 is positive or negative. The evolution of eddy is studied by tracking the stream function field and the potential vorticity field, and the maximum (minimum) stream function value of eddy indicates the strength of the eddy. Then we consider the evolution of an eddy passing through a meridional gap. Then we focus on propagation of eddies influenced by the WBC in steady penetrating and leaping states of hysteresis.

The hysteresis of a WBC flowing by a meridional gap has been found and studied by Sheremet (2001), and the impaction on the hysteresis of finite baroclinic deformation radii and time dependence perturbation by mesoscale eddies has been studied by Yuan and Wang (2011). The dynamics of hysteresis refers to the specific circumstances of the relative references above. A brief summary of the hysteresis process of the WBC flowing by a meridional gap is generalized here as a necessary background introduction. Hysteresis here refers to a nonlinear relationship of the path of a WBC flowing by a meridional gap with the transport (Reynolds number) of the WBC. When the transport (Reynolds number) is large, the path of the WBC in the gap is dominated by the inertia effect resulting in a leaping across state. And when the transport (Reynolds number) is small, the advection effect forces the WBC westward into the gap, forming a counter-cyclone penetration state. So when the transport (Reynolds number) of the WBC changes from small to large, there is a critical value of Q_L, the WBC path changes from the anti-cyclone penetrating state through a periodic eddy shedding state and become a gap leaping state. If the transport (Reynolds number) of the WBC reduces, the WBC path will not immediately return to the eddy shedding or anti-cyclonic penetrating state. Only when the transport (Reynolds number) continues to decrease to another threshold value Q_P (Q_P<Q_L), the WBC is restored to the anti-cyclone penetrating state. This is the whole cycle of the hysteresis process, and we reproduce this hysteresis cycle based on the 1.5-layer QG model. The critical value of the Reynolds number when the WBC path shift happens is 27/42 separately in the case of parameters setting above. Then we choose the steady penetrating and leaping sate of the WBC far from the critical state. The penetrating state of the WBC in this study is the steady state when the Reynolds number of the WBC is 20, which is smaller than the critical values 27, and the leaping state of the WBC is the steady state when the Reynolds number of the WBC is 45, which is larger than the critical values 42.

3 RESULT

3.1 Free migration of eddies

The free migration of cyclonic and anti-cyclonic eddies through the gap of a meridional western boundary in absence of a western boundary current are first investigated and compared with the free migration of the eddies in an infinite β-plane. Figure 2 shows the migration of an anti-cyclonic eddy in a basin without the gappy boundary based on the QG model simulation. The eddy is initialized in the eastern basin with the initial potential vorticity at the center of the eddy set at q_0=-1×10^{-5}/s^2 and the maximum azimuthal velocity located at 60 km from the center of the eddy. The stream function fields on the model time Day 0 through Day 400 show that the eddy migrates westward, with a Rossby wave wake of the fishbone shape. This is consistent with the result of (McWilliams and Flierl, 1979) based on the barotrophic mode of a two-layer quasi-geostrophic model, showing the Rossby wave dispersion due to the β effect. The difference from that study is the more centrifugal pattern of the evolving eddy with the center located to the southeast of the eddy, resulting primarily from the stronger Rossby wave dispersion due to stronger β effect in this study than in that of the McWilliams and Flierl.

The eddy loses energy and vorticity rapidly as it

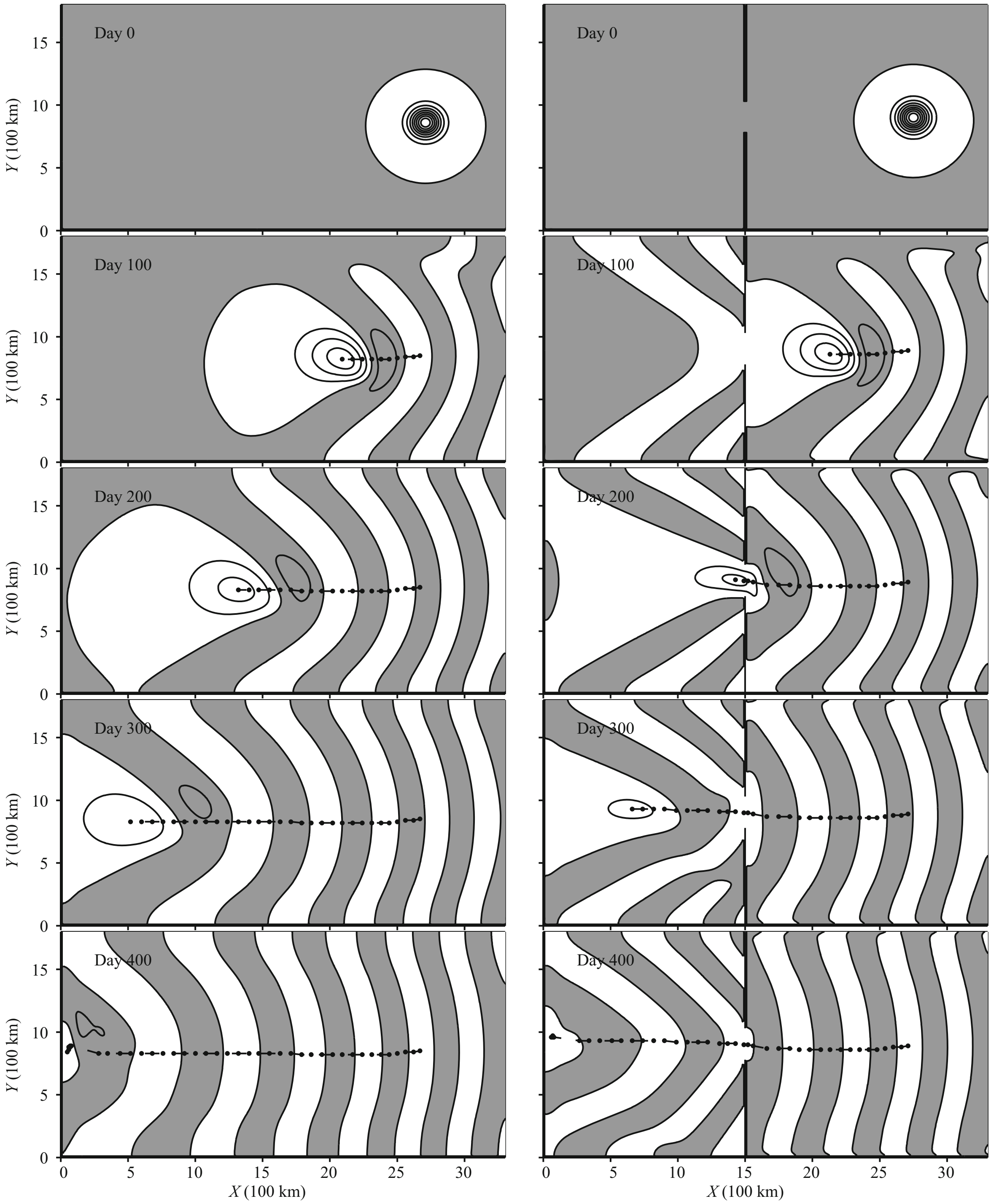

Fig.2 The evolution of the stream function field of an anti-cyclonic eddy of 60 km radius free migrating (left) and passing through a wide gap 240 km (right)

The dot line is the trajectory of eddy center. The white (black) color is for the positive (negative) stream function, and the contour interval is 1 500 m^2/s.

migrates to the west, owing to the "leakage" of the Rossby wave dispersion (McWilliams, 2006). The normalized maximum stream function value of the eddy during the westward migration is shown to decreases to about 40% of its initial value in the first 110 days or so, covering a distance of about 580 km as shown in Fig.2.

Due to the presence of the gappy meridional boundary, the anti-cyclonic eddy loses more energy and vorticity as it migrates westward and through the gap. The panels in the right column of Fig.2 show the continuous evolution of an anti-cyclonic eddy with the same radius and strength as in the left column passing through a wide gap of a meridional boundary in the middle of the basin. The width of the gap is

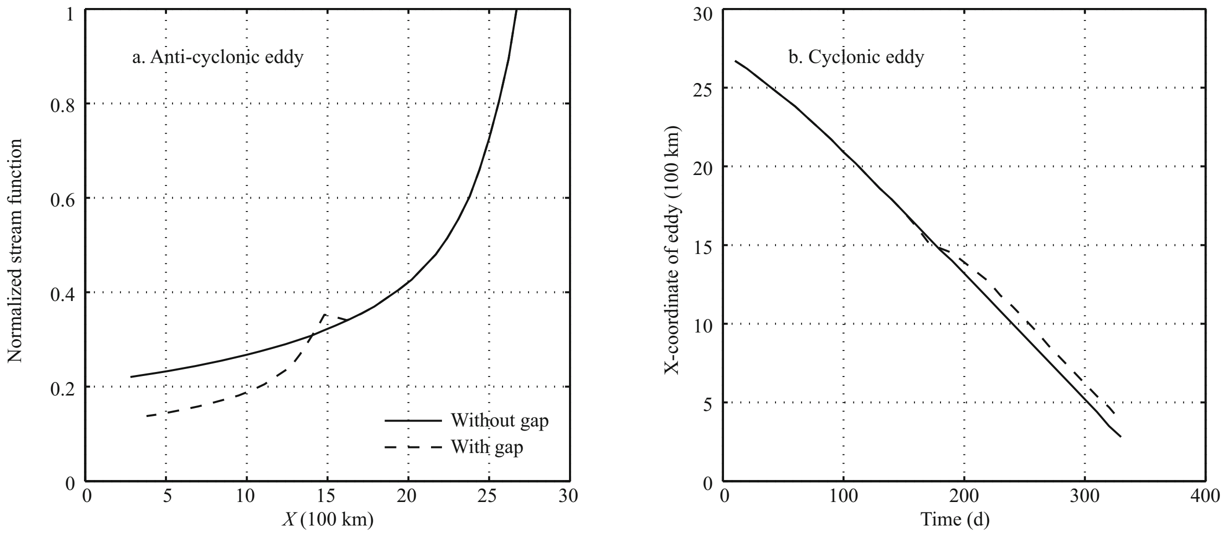

Fig.3 The normalized maximum of the stream function value of an anti-cyclonic eddy of 60 km radius as its location in the *x*-axis direction when it migrates freely (solid line) and passes through a wide gap 240 km (dash line) (a); location of the eddy in *x*-axis direction and the time (b)

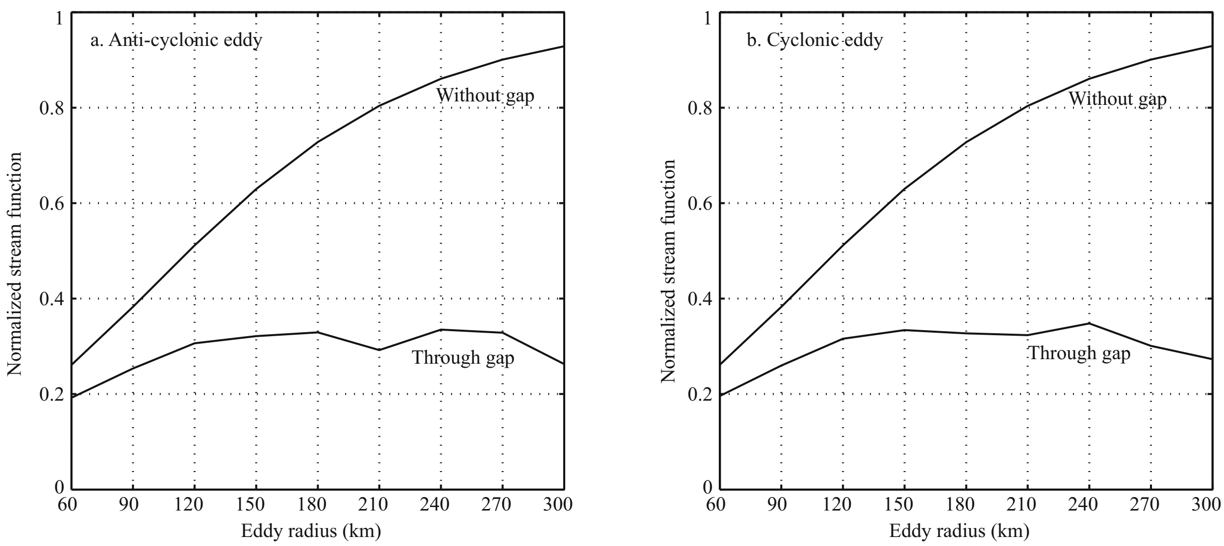

Fig.4 The normalized stream functions of maximum (minimum) value of anti-cyclonic (a) and cyclonic (b) eddies of different radii propagating without and through a gap on Day 250

240 km, much larger than the radius of the maximum azimuthal velocity. More than half of the eddy amplitude has passed through the gap and continue migrating westward (Fig.3). The dash line in Fig.3b shows that, compared to the free eddy migration in an infiniteβ-plane, about 40% more of the eddy amplitude is lost due to the presence of the meridional gap. The westward migration speed of the eddy, however, is nearly unchanged, maintaining at 0.08 m/s westward with or without the meridional boundary (Fig.3b).

The migration of cyclonic eddy is the same as the anti-cyclonic eddy, due to the parity asymmetry of the quasi-geostrophic equation (McWilliams, 2006), except that the centrifugal center shift to the northeast instead of southeast.

The dependence of the amplitude decrease on the eddy vorticity is investigated by comparing the amplitudes of eddies of the same initial vorticity but different radii on Day 250, when the eddies has entered the western basin far away from the gappy boundary (Fig.4). The dependence on the eddy vorticity, hence on the amplitude, is found to be small (figure omitted). The dependence of the amplitude decrease on the eddy radii is also investigated in the same manner and is found to be sensitive to the eddy initial radii. The normalized amplitudes of anti-cyclonic eddies on Day 250 in the left panel show that large eddies decay less than smaller eddies in the absence of the gappy

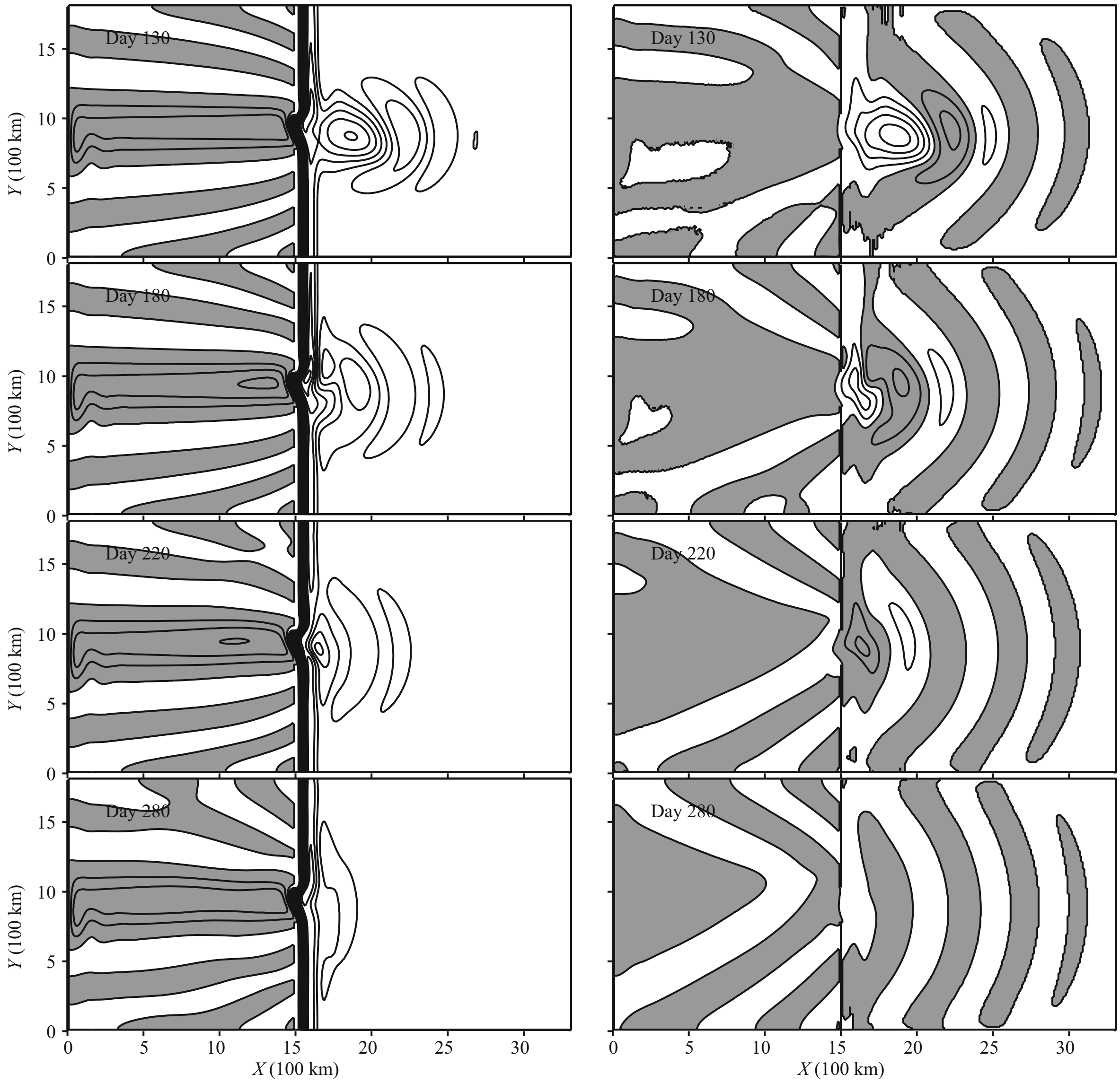

Fig.5 The evolution of an anti-cyclonic eddy of 60 km radius blocked by the WBC in steady leaping state

The total stream fields are in left column, and the anomaly stream fields abstracted the background gap-leaping WBC are in the right column. The white (black) color is for the positive (negative) stream function. The contour interval is 1 000 m^2/s.

boundary, whereas they all decay at about the same rate through the gap notwithstanding the radii. This is understood that large eddies have more energy and decay slowly in free migration, whereas they experience more blockage from the gappy boundary as they migrate through the gap, hence faster decay. For eddies with radii larger than 120 km propagating through the gap, exceed 40% of the eddy amplitudes dissipate owing to the blockage by the gappy barrier, with roughly 25%–35% of the eddy amplitudes migrate into the western basin. The smaller eddies with radii less than 120 km experience less than 40% blockage from the gappy boundary, so they are easier to penetrate into the western basin through the gap width 240 km than the eddies with larger radii. The amplitude decrease of cyclonic eddies has the similar dependence on the eddy radii as the anti-cyclonic eddies do, as shown in the right panel of Fig.4.

3.2 Blocked migration

The WBC in a steady gap-leaping state blocks a wide variety of both cyclonic and anti-cyclonic eddies very effectively, keeping them confined in the eastern basin and moving northward downstream of the WBC along the western boundary. The gap-leaping WBC has a strong potential vorticity (PV) gradient due to the narrow zonal span of the current, so that it acts like an impermeable wall to the eddies. Figure 5 shows an anti-cyclonic eddy of 60 km radius impinging on a gap-leaping WBC at Re=45. The left

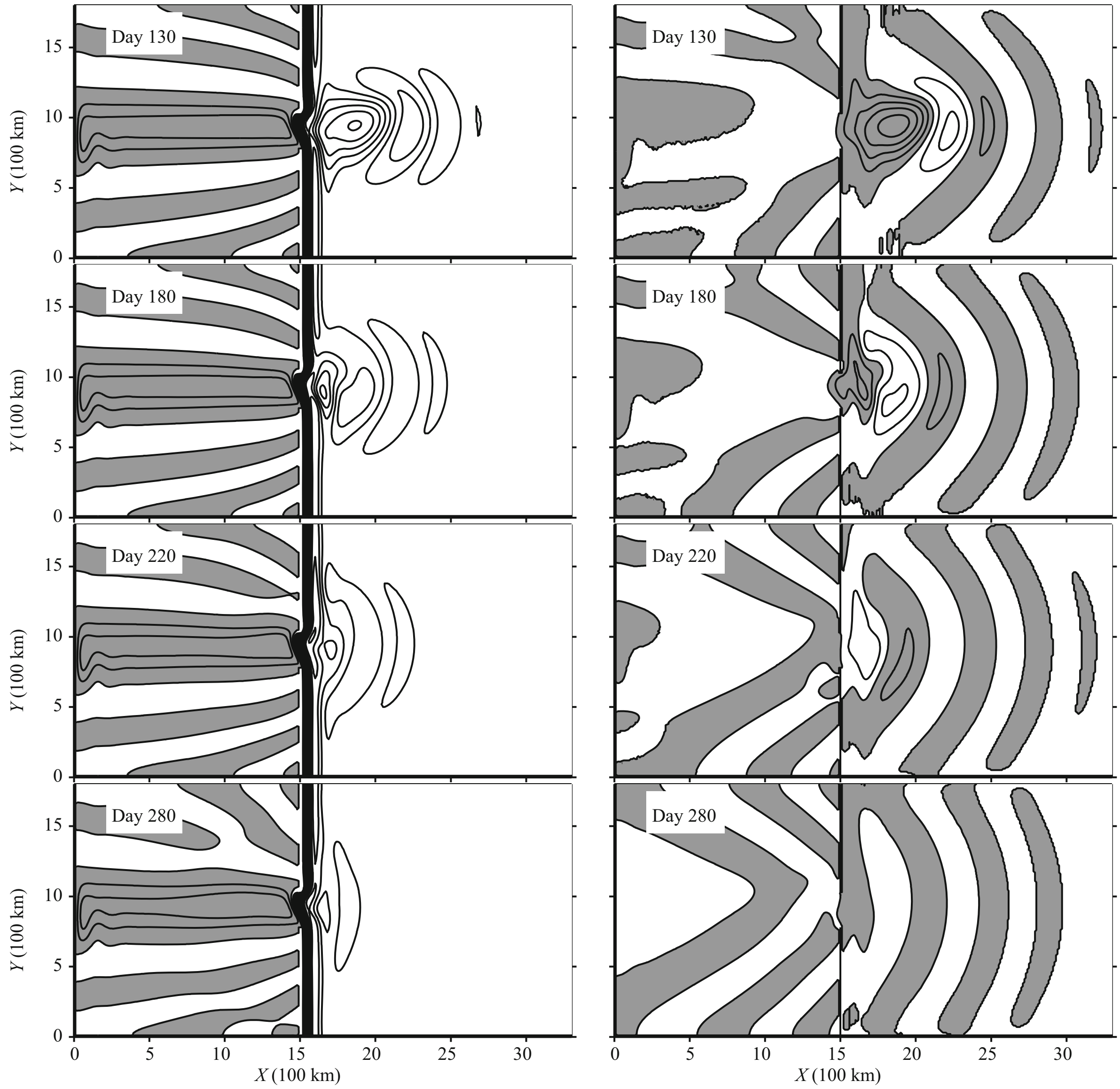

Fig.6 The same as Fig.5, but for a cyclonic eddy

and right columns show the evolution of the total stream function and the eddy stream function with the background stream function of the steady leaping WBC subtracted, respectively. The eddy is located 1 200 km east of the boundary in the eastern basin initially, touches the WBC in the vicinity of the gap on Day 130, and stops propagating to the west on Day 180. The squeezing of the eddy in the zonal direction causes the western and eastern sides of the eddy canceling each other and fades away on Day 280. The wake waves following behind the eddy is also blocked by the WBC. We also notice that very little, negligible, energy has leaked into the western basin across the gap-leaping WBC though the gap. These results are consistent with the numerical simulations of (Sheu et al. 2010) using the primitive equation model of Princeton Ocean Model and the Fourier spectrum analysis of (Lu and Liu, 2013) of both altimeter data and HYCOM reanalysis. The westward migration of the anti-cyclonic eddy is evidently blocked by the gap-leaping WBC.

Because the WBC is far away from its critical state of regime shift, all of the anti-cyclonic eddies of different radii, even as large as 240 km in radius, are blocked by the gap-leaping WBC at Re=45.

Similar to the movement of the anti-cyclonic eddies, all of the cyclonic eddies are also blocked by the gap-leaping WBC. Figure 6 shows a same process as Fig.5, but for a cyclonic eddy. Although the left part of the cyclonic eddies reduces the transport of the WBC when they comes to touches the northward WBC, if the eddy is even too strong to cut off the

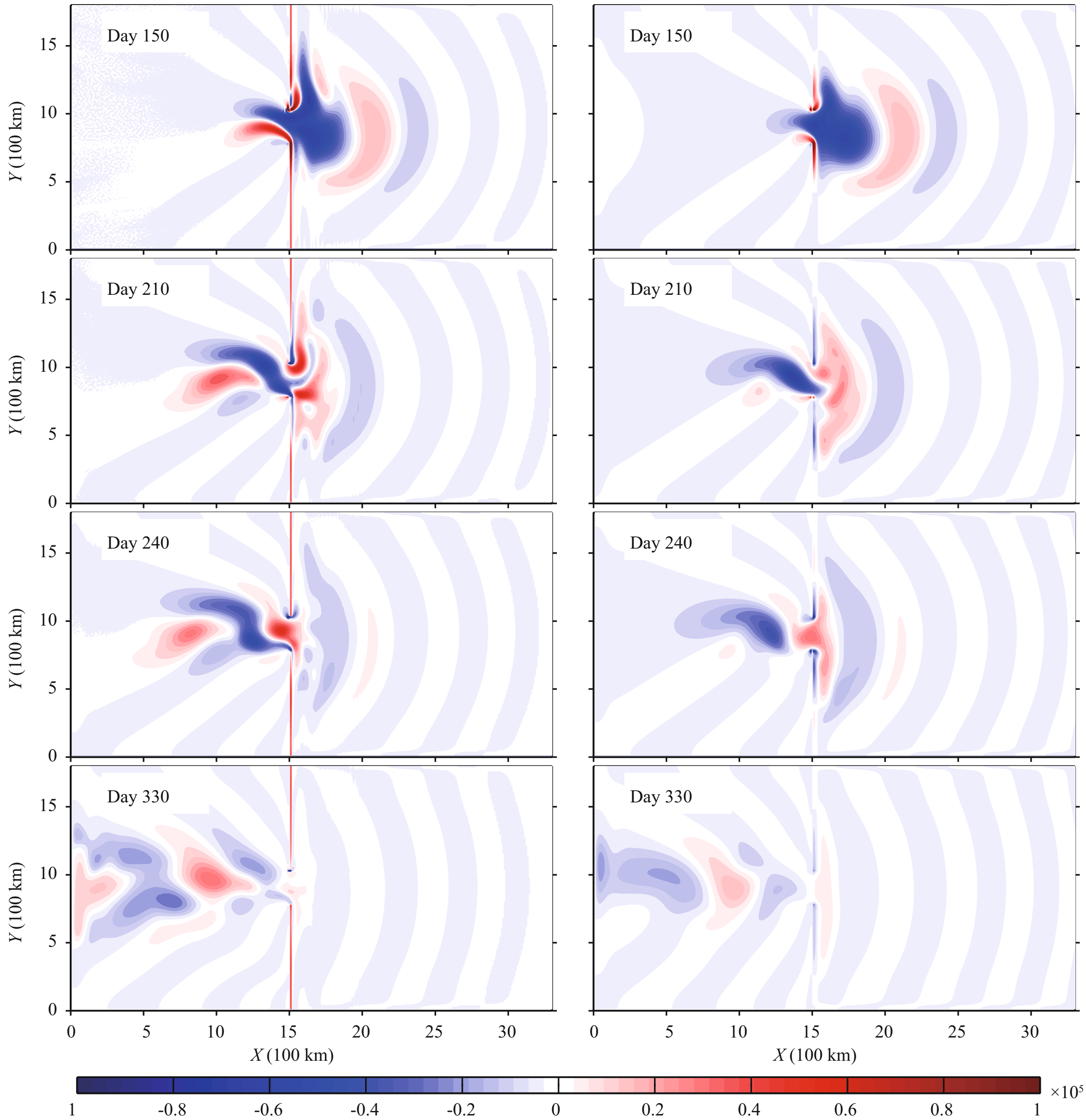

Fig.7 The evolution of anomaly potential vorticity fields of an anti-cyclonic of 120 km radius with (left) and without (right) the WBC in steady penetrating state

WBC temporarily, the right part of cyclonic eddies increase the WBC northward flowing immediately. Whether the eddies are cyclonic or anti-cyclonic, the gap-leaping northward WBC is a sharp and impermeable wall for the impinging eddies and blocks the westward migration of them.

3.3 Migration across a penetrating WBC

When the WBC penetrates into the western basin steadily, the migration of anti-cyclonic and cyclonic eddies meets the intrusion branch of the WBC in the southern gap, which facilitate the partial propagation of eddy vorticity into the western basin. Figure 7 shows the evolution of potential vorticity fields of an anti-cyclonic eddy of 120 km radius and 19 070 m^2/s maximum stream function impinging on a meridional gap of 240 km with (left) and without (right) a penetrating WBC in the gap. The initial potential vorticity of the steady penetrating WBC has been abstracted from the total fields to form the anomaly potential vorticity fields in the left column of Fig.7.

On Day 150, the eddy touches the gap from the eastern side of the gap. Compared to the free migration without the steady penetrating WBC in the right panel, the potential vorticity anomalies in the presence of the penetrating WBC in the left panel feature

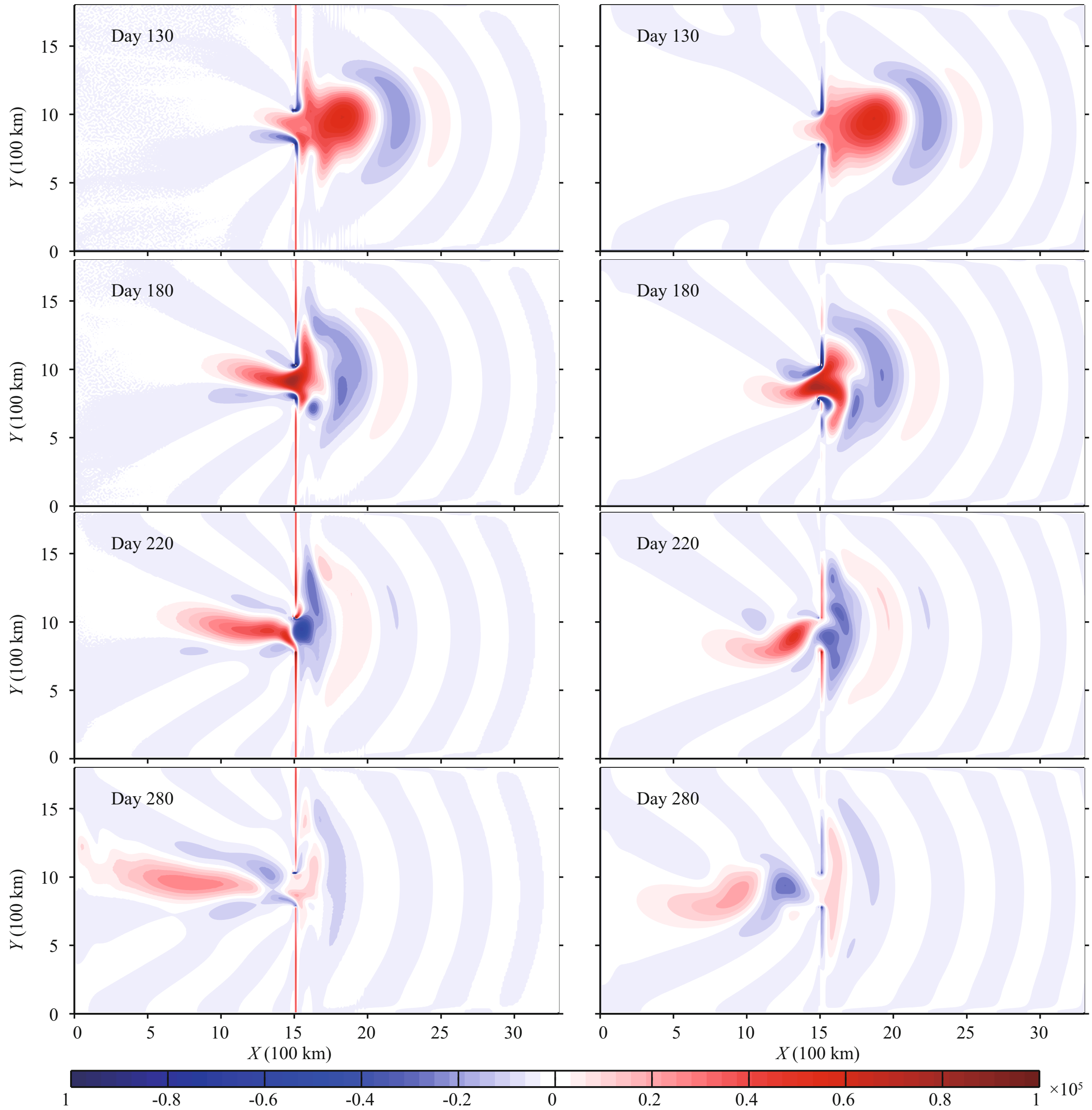

Fig.8 The same as Fig.7, but for a cyclonic eddy

enhanced penetration of the eddy vorticity in the south gap, due to the strengthened intrusion branch of the WBC by the eddy, which in turn induces positive potential vorticity in the western basin immediately to the south of the penetrating eddy vorticity. The pair of potential vortices interacts with each other and migrates to the west together. On Day 240, the impingement eddy from the eastern basin starts to split into two parts, due to the blockage of the induced vorticity in the west of the impingement eddy. Some wakes of the eddy also leak into the western basin through the gap, associated with the propagation of the vortices, and propagate westward.

Cyclonic eddies act to reduce the intrusion branch of the WBC and will produce the mirror reflection anomalies as the anti-cyclonic eddies do. The impingement cyclonic eddy also migrates into the western basin through the gap similar to the anti-cyclonic eddy case, but with no obvious vorticity induced in the western basin due to the reduced intrusion branch of the WBC by the western part of the impingement cyclonic eddy, which is different from the anti-cyclonic eddies case. And then the impingement eddy migrates westward keeping the whole shape. However, if the eddy strength is much larger than the WBC transport, the intrusion branch of the WBC will be cut off temporally, resulting in no further strengthening of the vortices in the western basin. Figure 8 shows such differences from the anti-cyclonic eddy experiment.

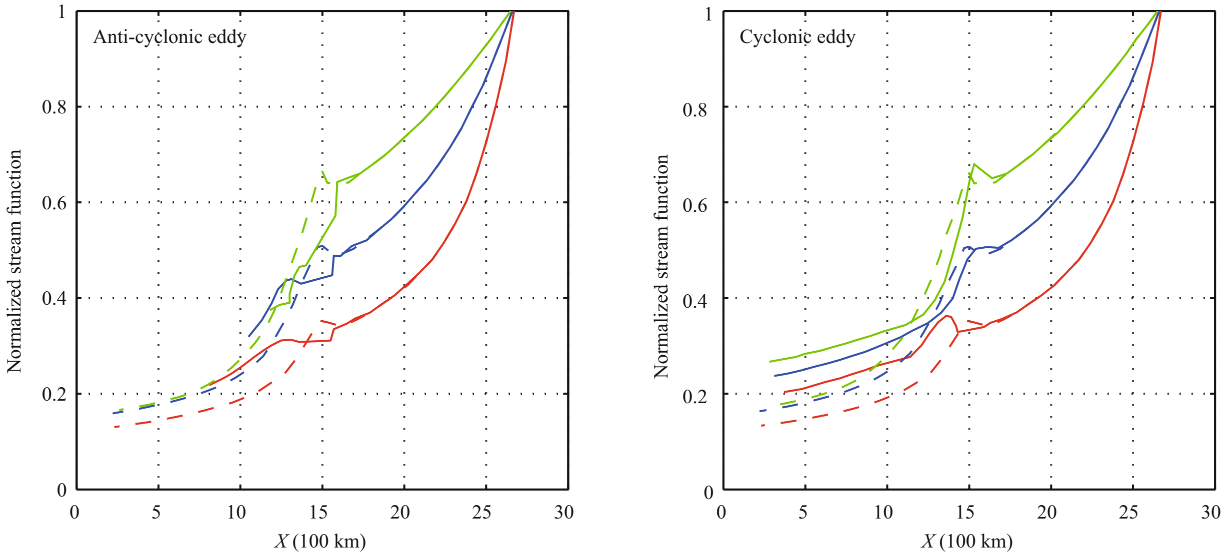

Fig.9 The normalized maximum of the stream function values of anti-cyclonic (left) and cyclonic (right) eddies of different radii 60 km (red), 90 km (blue) and 120 km (green) as their locations in the *x*-axis direction when they migrate across WBC in steady penetrating state

The dash lines stand for the case of eddies pass through the gap without WBC, while the solid lines for those with WBC.

The left panel of Fig.9 shows the amplitude changes of anti-cyclonic eddies of different radii passing through the gap with (solid lines) and without (dash lines) the influence of the penetrating WBC. The maximum amplitude penetration of the anti-cyclonic eddy is significantly enhanced under the influence of the penetrating WBC, suggesting that the eddies are intensified by the anti-cyclonic intrusion of the WBC at the gap. The intensified eddy penetration induces a cyclonic companion eddy, which produces complicated interactions during the propagation of the eddy pair in the western basin. The solid lines are shorter than dashed lines is owing to that the impingement anti-cyclonic eddy splits into two parts due to the blockage of the induced companion eddy.

Similar intensification of the cyclonic eddies are also produced by the penetrating WBC shown in the right panel of Fig.9. But the induced companion eddy is not as strong, probably because the westward advection of the intrusion leg of the WBC is reduced by the cyclonic eddy during the penetrating process.

In the absence of the WBC, eddies initially located north or south of the gap center latitude have smaller rates of penetration through the gap due to the blockage of the gappy boundary (Fig.10). This is true for both cyclonic (right) and anti-cyclonic (left) eddies. Under the influence of the penetrating WBC, eddies initially located at or to the south of the gap center latitude penetrate more easily through the gap than those located in the north, both for cyclonic and anti-cyclonic eddies due to the advection of the penetrating leg of the WBC.

The migration speeds of the cyclonic and anti-cyclonic eddy are not affected significantly by the penetrating WBC in all experiments (figure omitted).

The discussion about a westward propagating anti-cyclonic eddy interacting with the WBC at the critical state is an ongoing research and will be summarized in a separate paper.

4 DISCUSSION AND CONCLUSION

The Kuroshio appears to have existed in two steady states across the Luzon Strait. It either penetrates or leaps across, states that are argued by (Sheremet, 2001) to possess a hysteresis loop as a function of the current strength. It is also observed that this part of the North Pacific is populated with cyclonic and anti-cyclonic eddies that can come into contact with the Kuroshio at the latitude of the Luzon Strait. There are limited, but interesting, observations about the subsequent interaction. We here have studied this problem using a 1.5-layer quasi-geostrophic reduced gravity model that captures the hysteresis discovered by Sheremet.

Both cyclonic and anti-cyclonic eddies migrate westward with amplitude decrease in an infinite β-plane. The amplitude decrease of cyclonic eddies is similar with anti-cyclonic eddies which is dependent with the initial radii of eddies. The eddies of larger initial radii lose less amplitude than the eddies with

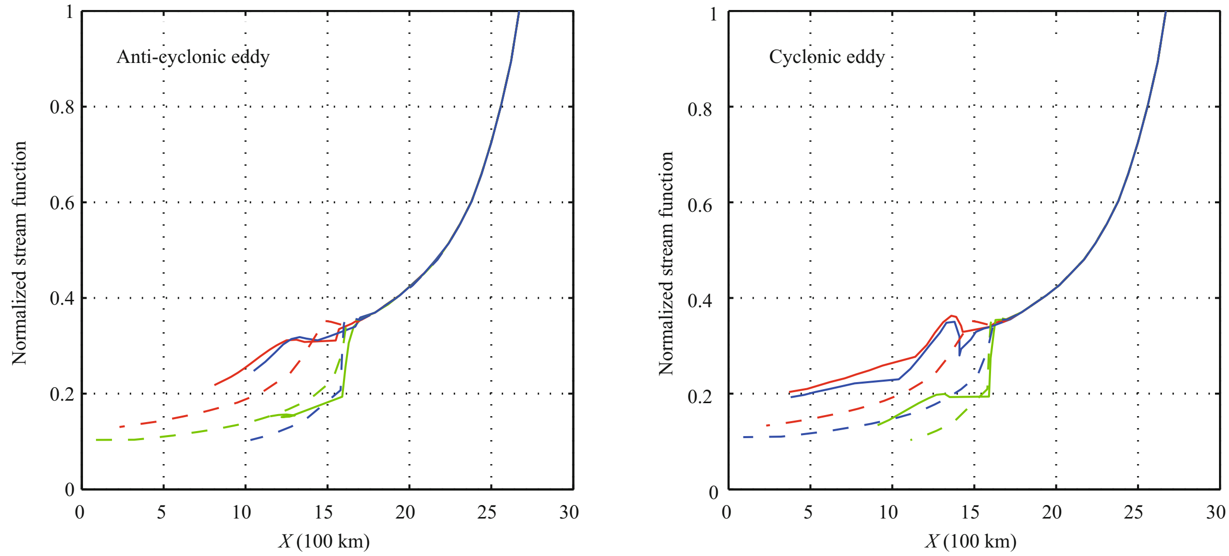

Fig.10 The normalized maximum of the stream function values of anti-cyclonic (left) and cyclonic (right) eddies of different initial location middle (red), 150 km northward (green) and 150 km southward (blue) as their locations in the *x*-axis direction when they migrate across the WBC in steady penetrating state

The dash lines stand for the case of eddies pass through the gap without WBC.

smaller radii. Eddies experience more blockage from the gappy boundary as they migrate through the gap, and roughly 20%–30% of the eddy amplitudes migrate into the western basin for all sizes of the eddies.

The gap-leaping WBC far away from the critical state blocks a wide variety of both cyclonic and anti-cyclonic eddies very effectively, keeping them confined in the eastern basin and moving northward downstream of the WBC along the western boundary.

Both cyclonic and anti-cyclonic eddies migrates across the WBC of penetrating state in a gap accompanying with an opposite type of potential vorticity induced in the western basin due to the weakened (cyclonic) or strengthened (anti-cyclonic) penetration of intrusion branch of the WBC by the eddy. The eddy pair interact with each other and migrates to the west together. Both types of eddies passed into the western basin could be strengthened by the anti-cyclonic intrusion of the WBC at the gap. Eddies initially located at or to the south of the gap center latitude penetrate more easily through the gap than those located in the north, both for cyclonic and anti-cyclonic eddies due to the advection of the penetrating leg of the WBC. The migration speeds of the cyclonic and anti-cyclonic eddies are almost 0.08 m/s in all experiments, which is comparable to long Rossby wave speed at these latitudes.

The similar experiments using a primitive equation model with multiple layers are expected to lead the same conclusions in this manuscript, since the primitive equation also includes the quasi-geostrophic dynamics in the study area. In fact, the blocking and westward passage of eddies in the Luzon Strait have been simulated and investigated by Sheu et al. (2010), showing that the eddies are blocked while the Kuroshio tends to leap directly northward by passing the strait, and eddies are likely to propagate freely through the Luzon Strait while the Kuroshio loops westward into the SCS, corroborates that of our analysis. The advantage of QG model is that it gives the stream function and different vorticity terms directly, thereby providing an easier and clear way to analyze the dynamic and interaction between the WBC and eddies in the Luzon Strait.

One of the limitation of this numerical study is that it has not consider the interaction of eddy with the WBC critical from leaping to penetrating, the dynamic of which is supposed to be more important in the WBC-eddy interactions in the Luzon Strait. Also, these numerical results are needed to compared with the real process of the mesoscale eddies movement in the Luzon Strait, to enhance the dynamical perdition of the fate of the impinging mesoscale eddies from the western Pacific to the Kuroshio in the Luzon Strait.

References

Chelton D B, Schlax M G, Samelson R M. 2011. Global observations of nonlinear mesoscale eddies. *Progress in Oceanography*, **91**(2): 167-216.

Chern C S, Wang J. 2005. Interactions of mesoscale eddy and western boundary current: a reduced-gravity numerical model study. *Journal of Oceanography*, **61**(2): 271-282.

Johnson E R, McDonald N R. 2005. Vortices near barriers with multiple gaps. *Journal of Fluid Mechanics*, **531**: 335-358.

Kuehl J J, Sheremet V A. 2014. Two-layer gap-leaping oceanic boundary currents: experimental investigation. *Journal of Fluid Mechanics*, **740**: 97-113.

Li L, Nowlin Jr W D, Su J. 1998. Anticyclonic rings from the Kuroshio in the South China Sea. *Deep Sea Research Part I*: *Oceanographic Research Papers* **45**(9): 1 469-1 482.

Li R X. 2008. Dynamics of eddy-induced Kuroshio variability in the Luzon Strait. University of Chinese Academy of Sciences, Beijing, China. p.1-44. (in Chinese with English abstract)

Lu J Y, Liu Q Y. 2013. Gap-leaping Kuroshio and blocking westward-propagating Rossby wave and eddy in the Luzon Strait. *Journal of Geophysical Research*: *Oceans*, **118**(3): 1 170-1 181.

McWilliams J C, Flierl G R. 1979. On the evolution of isolated, nonlinear vortices. *Journal of Physical Oceanography*, **9**: 1 155-1 182.

McWilliams J C. 2006. Fundamentals of Geophysical Fluid Dynamics. Cambridge University Press, Cambridge. 283p.

Nitani H. 1972. Beginning of the kuroshio. *In*: Stommel H, Yoshida K eds. Kuroshio: Its Physical Aspects. University of Tokyo Press, Tokyo. p.129-163.

Nof D. 1988. Eddy-wall interactions. *Journal of Marine Research*, **46**(3): 527-555.

Pedlosky J. 1994. Ridges and recirculations: gaps and jets. *Journal of Physical Oceanography*, **24**(2): 2 703.

Pu S Z, Yu H L, Jiang S N. 1992. Branchings of Kuroshio into Bashi Channel and the South China Sea. *Tropic Oceanology*, **11**(2): 1-8. (in Chinese with English abstract)

Sheremet V A. 2001. Hysteresis of a western boundary current leaping across a gap. *Journal of Physical Oceanography*, **31**(5): 1 247-1 259.

Sheu W J, Wu C R, Oey L Y. 2010. Blocking and westward passage of eddies in the Luzon Strait. *Deep Sea Research Part II*: *Topical Studies in Oceanography*, **57**(19-20): 1 783-1 791.

Sutyrin G G, Rowe G D, Rothstein L M, Ginis I. 2003. Baroclinic eddy interactions with continental slopes and shelves. *Journal of Physical Oceanography*, **33**(1): 283-291.

Van Leeuwen P J. 2007. The propagation mechanism of a vortex on the β plane. *Journal of Physical Oceanography*, **37**(9): 2 316-2 330.

Wang G H, Su J L, Chu P C. 2003. Mesoscale eddies in the South China Sea observed with altimeter data. *Geophysical Research Letters*, **30**(21): 2 121.

Yuan D L, Han W Q, Hu D X. 2006. Surface Kuroshio path in the Luzon Strait area derived from satellite remote sensing data. *Journal of Geophysical Research*: *Oceans*, **111**(C11): C11007.

Yuan D L, Wang Z. 2011. Hysteresis and dynamics of a western boundary current flowing by a gap forced by impingement of mesoscale eddies. *Journal of Physical Oceanography*, **41**(5): 878-888.

Zheng Q A, Tai C K, Hu J Y, Lin H Y, Zhang Y H, Su F C, Yang X F. 2011. Satellite altimeter observations of nonlinear Rossby eddy-Kuroshio interaction at the Luzon Strait. *Journal of Oceanography*, **67**(4): 365-376.