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Hysteresis of a periodic or leaking western boundary current flowing by a gap

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Abstract

A 1.5-layer quasi-geostrophic reduced gravity model is used to study the hysteresis of a periodic or leaking western boundary current (WBC) flowing by a gap. When the periods of the WBC variations are much longer than the Rossby adjustment time scales of the circulation in the vicinity of the gap, the Hopf bifurcations during the *Re*-increase and *Re*-decrease loops are delayed to produce a new domain of hysteresis of the Reynolds numbers, and the critical Reynolds numbers of the WBC regime transitions change significantly, with the domain of the hysteresis Reynolds number larger for shorter periodic forcing. When the periods of the WBC variations are comparable to those of the Rossby adjustment time scales of the circulation in the vicinity of the gap, the WBC path inside the gap becomes periodic without hysteresis. The intrusion of the WBC into the western basin generally gets smaller as the period decreases. In addition, the partial leakage of the WBC transport through the gap into the western basin is found to have significant impact on the hysteresis loop of the WBC path when the leaked transport is larger than 1/2 of the WBC. Both the intrusion extent and the critical Reynolds numbers of the WBC regime transition are changed, and the larger the throughflow transport, the larger the change.

Key words: hysteresis, periodic western boundary current, throughflow

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1 Introduction

The path of a western boundary current (WBC) flowing by a meridional gap in the western boundary is dynamically similar to the Kuroshio flowing by the Luzon Strait and the Gulf Stream by the Yucatan Strait. Observations and model studies suggest that the Kuroshio sometimes leaps across the Luzon Strait and sometimes intrudes into the South China Sea (SCS) in a large anti-cyclonic path (Nitani, 1972; Shaw, 1989, 1991; Liu et al., 1996; Li and Liu, 1997; Li et al., 1998; Metzger and Hurlburt, 2001; Yang et al., 2002; Xue et al., 2004; Hsueh and Zhong, 2004; Qu, 2000; Su, 2005; Caruso et al., 2006; Yuan et al., 2006). Although the dynamics of the formation and transition of flow pattern is complicated, there are much work on the physical processes, the main dominant factors of which are WBC transport (Sheremet, 2001; Yuan and Wang, 2011), wind stress curl (Farris and Wimbush, 1996; Wang et al., 2010; Zhong et al., 2013), Rossby eddies (Zheng et al., 2011; Hu et al., 2012; Lu and Liu, 2013; Song et al., 2018), topography and so on (Hou et al., 2017; Guo et al., 2018).

Sheremet (2001) studied the path of a steady WBC in the vicinity of a meridional gap using a 1.5-layer quasi-geostrophic ocean circulation model, showing that the hysteresis of the WBC path in the vicinity of the gap controlled by the transport of the WBC. The transport of the WBC in that study is scaled by a nondimensional number–transport Reynolds number (*Re*). When *Re* of the WBC is small, the steady path of the WBC is an anti-cyclone intrusion through the gap; when *Re* of the WBC is large, the WBC takes a straight leaping path across the gap; when *Re* is in the intermediate range, the WBC takes either a leaping or a penetrating path, depending on the initial state of the WBC. The multiple equilibria of the WBC path are controlled by the multiple bal-

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ances between the inertial, horizontal mixing, and the beta terms of the quasi-geostrophic potential vorticity equation. The existence of the multiple equilibria and the hysteresis of the gap-leaping WBC path have been verified by laboratory rotating table experiments (Sheremet and Kuehl, 2007; Kuehl and Sheremet, 2009, 2014).

The hysteresis of a steady WBC flowing in a gap based on numerical computations inspired some studies on the interactions of the gap-leaping WBC with meso-scale eddies or winds. The regime shift of the WBC path can be induced by perturbations of meso-scale eddies approaching the gap from the east, or by winds (Yuan and Li, 2008; Wang et al., 2010; Yuan and Wang, 2011; Zhong et al., 2013; Song et al., 2018), which explains some of the observed variations of the Kuroshio path in the vicinity of the Luzon Strait.

Latest studies suggest that the existence of a SCS throughflow from the Luzon Strait to the Indonesian seas, and the transport of the SCS throughflow is 2×10^6–3×10^6 m^3/s (Yaremchuk et al., 2009; Qu et al., 2009; Fang et al, 2010). The Kuroshio is also subject to significant intraseasonal-to-interannual forcing of the regional monsoon. How the multiple equilibrium and hysteresis would change under the periodic WBC and throughflow forcing is an open question to study.

In this study, hysteresis of a periodic or leaking WBC flowing by a gap is studied using a 1.5-layer quasi-geostrophic reduced gravity model. The next section is the details about the model and method. Section 3 is the model results and Section 4 is the discussion and conclusion.

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

$$-\frac{1}{L_{\rm R}^2}\psi_t+\zeta_t+J\left(\psi,\zeta\right)+\beta\psi_x=A_{\rm H}\nabla^2\zeta, \tag{1}$$

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

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^{-1}·s^{-1} and the baroclinic deformation radius is $L_{\rm R}$=50 km, which are the character parameters of the Kuroshio in the Luzon Strait according to Nitani (1972), also, $L_{\rm R}$=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 $A_{\rm H}$= 300 m^2/s, which is determined based on a set of numerical experiments from $A_{\rm H}$=10 m^2/s to $A_{\rm H}$=9 000 m^2/s, is a proper value to adjust the QG model to study the hysteresis of a periodic or leaking WBC flowing by a gap in this paper. If $A_{\rm H}$ is too small, the nonlinear term will be stronger than the friction term in Eq. (1), leading to unstable submesoscale turbulence; if $A_{\rm H}$ is too large, the friction term of 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 referenced to Li (2008). The Munk WBC thickness $L_{\rm M}$=25 km ($L_{\rm M}=\sqrt[3]{A_{\rm H}/\beta}$). 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 2 500 and 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 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. For the throughflow experiments, a gap of 300 km width is opened in the southwestern corner of the basin with the transport of the throughflow specified through the gap.

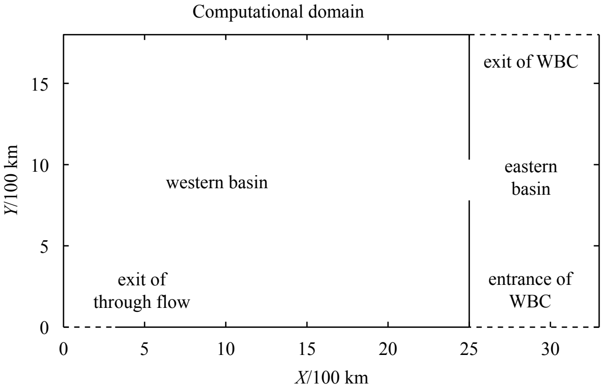

Fig. 1. The computational domain of the model, composed of a rectangular basin separated into two basins by a meridional barrier with a gap of 240 km width in the middle. The dash lines in the eastern basin mark the entrance and exit of the WBC, and the dash line in the western basin the exit of the throughflow.

The WBC in the model is driven by the stream function gradient between the eastern boundary and western boundary of the eastern basin. Specifically, the stream function is set to be 0 along the western boundary of the eastern basin, and it is set to be $Q=Re\times A_{\rm H}$ along the western boundary of the eastern basin. The stream function gradient drives a northward WBC of vertical averaged transport Q in the eastern basin. Throughout this paper, the strength of the WBC is indicated by *Re*.

The hysteresis of a steady WBC flowing in the gap is reproduced based on the QG model. Then the range of *Re* that ensures the hysteresis process can occur is determined, and the detailed calculation and results are showed in Section 3.1.

The periodic WBC is forced by the periodic stream function gradient of the eastern basin. Specifically, the stream function is also set to be 0 along the western boundary of the eastern basin, but it is set to be a sinusoidal function at the eastern boundary of the eastern basin. After long enough integration, the WBC in the eastern basin becomes strictly periodic. By changing the period of *Re* changes in different time scales, we study the hysteresis of the periodic WBCs in the gap, compared with the hysteresis of the steady WBC. The sensitivity of the WBC path on the initial state is examined by setting the WBC initial state as either a stable penetrating or a leaping state, respectively. The detailed calculation and results are showed in Section 3.2.

A throughflow exiting from a zonal opening gap in the southwestern corner of the western basin is forced by the stream function setting along boundaries. The transport of the throughflow is determined by the gradient of the stream functions between the two ends of the zonal opening gap in the western basin. The sensitivity of the hysteresis of the WBC in the vicinity of the meridional gap on the transport of the throughflow is examined by setting the transport of the throughflow equal to 2/15, 1/5, 1/3, 1/2, 4/5 and 9/10 of the WBC, respectively. Then the hysteresis curves of WBC in the vicinity of the meridional gap are calculated, which are compared with the hysteresis curve of a steady

WBC without the throughflow. The conclusions are summarized in Section 3.3.

3 Results

3.1 *Hysteresis of a steady WBC*

The hysteresis map for a WBC, with a baroclinic deformation radius of 50 km, is calculated based on the 1.5-layer QG model (Fig. 2). Following Sheremet (2001), the westward extent of the streamline $\psi=Q/2$ of the WBC defined as $X_{\rm P}$, which is a function of *Re* and the gap width. Here Q is the vertical averaged WBC transport and $Re=Q/A_{\rm H}$.

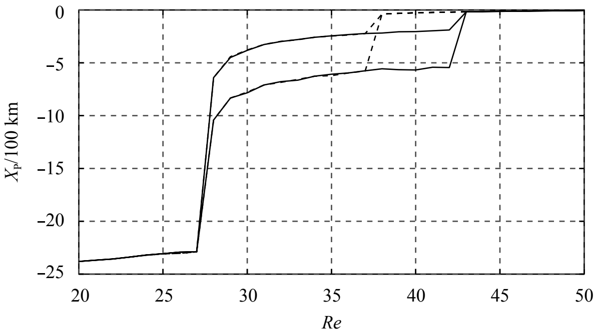

Fig. 2. The hysteresis map of a WBC intrusion into the western basin through the gap. $X_{\rm P}$ means the westward extent of the $\psi=Q/2$ streamline, with 0 standing the position of the gappy barrier. The transport Reynolds number of the WBC is defined as $Re=Q/A_{\rm H}$. Double curves indicate periodic eddy shedding state of the WBC. The solid curves represent the increasing *Re* course, and the dash curves the decreasing *Re* course.

The evolution of the $X_{\rm P}$ of the WBC is computed in the following way. For a set of the open boundary conditions in the eastern basin, starting from a small *Re*, the QG model is integrated into a steady state so that an $X_{\rm P}$ is determined. The steady state is determined if the change of the kinetic energy levels out. Then the open boundary conditions are changed so that *Re* increases, and a new integration is conducted until a new steady or periodic steady state is reached so that a new $X_{\rm P}$ is calculated. For periodic eddy-shedding states, the $X_{\rm P}$ is time dependent. In the following text, only the farthest and closest positions of the first $X_{\rm P}$ from the gap during one period of the eddy-shedding cycle are plotted. The *Re* is gradually increased from a small value to a large enough value and then decreased back to a small value. We call the first procedure the increasing *Re* course and the second procedure the decreasing *Re* course.

Figure 2 shows that there exist two steady (periodic steady) states of the WBC in the range of $37.5\leqslant Re\leqslant 43$ in the vicinity of the gap. The WBC intrudes into the western basin through the gap and reaches the western side of the western basin, forming the β-plume when $Re\leqslant 27$, whereas it leaps across the gap when $Re\geqslant 43$. In the increase case from Re=27 to Re=43, the WBC sheds eddies to the western basin through the gap, as indicated by the double thick curves of the hysteresis loop. The equilibrium of the WBC in the vicinity of the gap when $37.5<Re<43$ depends on the initial condition of the model integration. If the initial condition is a penetrating state, the final equilibrium of the WBC is an eddy-shedding state. If the initial condition is a leaping state, the equilibrium is a leaping state. The final equilibrium depends on the initial state, hence is the hysteresis. There are three critical points of the *Re* in the hysteresis loop, at which the WBC path shifts regimes at small perturbations. Re=42 is the critical value where the WBC is prone to transition from a penetrating state to a gap leaping state. Re=37.5 is the critical value where the WBC is prone to transition to a penetrating state. Re=27 is a Hopf bifurcation, where the WBC transits between steady penetrating to periodical eddy shedding states.

In the following text, we study the hysteresis of the WBC in the gap impacted by the periodic boundary conditions and throughflow separately.

3.2 *Periodic boundary condition*

Based on the discussion of the hysteresis of the steady WBC in the previous section, a steady WBC with *Re* changing in the range of $25\leqslant Re\leqslant 45$ could experience the whole process of hysteresis and cover all the steady and critical states in the gap. In order to force a periodic WBC with *Re* also changing in the range of $25\leqslant Re\leqslant 45$ in the eastern basin, the stream function along the western boundary of the eastern basin is still set to be 0, but it is set to be a sinusoidal function along the eastern boundary of the eastern basin, then *Re* is pecified to be

$$Re = 35+10\sin(\omega t - \pi/2), \tag{3}$$

where $\omega=2\pi/T$, T is the period of the sinusoidally changing WBC transport. Because the integration of the whole hysteresis process of the steady WBC including the increasing and decreasing *Re* course between $25\leqslant Re\leqslant 45$ in Section 3.1 needs more than 30 years, the hysteresis of the periodic WBC changing in various time scales less than 30 years are studies. The Rossby adjustment time scale in the vicinity of the gap is estimated based on the Rossby wave speed and the width of the meridional gap as the following:

$$T_{\rm w} = (240\ {\rm km}) \,/\, (0.08\ {\rm m/s}) = 34.7\ {\rm d}.$$

Model results show that when the transport of the WBC (*Re*) changes in a period much longer than $T_{\rm w}$ (15 years), the western intrusion distance of WBC in the gap ($X_{\rm P}$) follows the hysteresis curve of a steady WBC closely (Fig. 3). The critical values of *Re* of the WBC regime transitions between eddy shedding state and leaping state are coincident with those of the steady WBC. As a

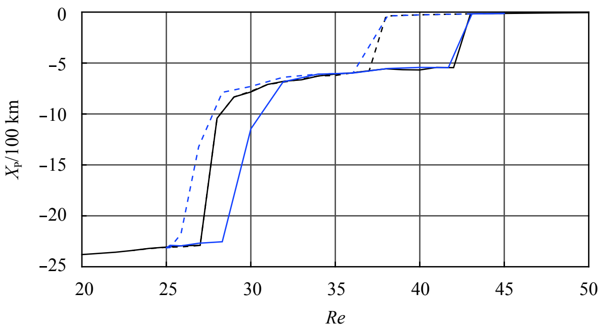

Fig. 3. The westward most intrusion of a 15-year periodic WBC through the gap ($X_{\rm P}$) varying with *Re* (blue curves). The solid curves represent the increasing *Re* course, and the dash curves the decreasing *Re* course. The black curves are the hysteresis of the steady WBC as comparison, which is the same as Fig. 2, but the lines which are not the westward most of X_p are removed for the eddy shedding state ($27\leqslant Re\leqslant 42$).

result, the hysteresis domain is unchanged by the periodic forcing. In comparison, the Hopf bifurcation of the WBC path between steady penetrating and eddy shedding states have been altered by the periodic forcing. The periodic forcing obviously has facilitated eddy shedding in the *Re*-decrease leg of the hysteresis loop so that the transition from the periodic to steady penetrations occurs at a smaller *Re* than that of a steady WBC. In the *Re*-increase leg of the hysteresis loop, however, the increase of the WBC transport takes a long time to reach the WBC loop in the western basin far away from the gap so that the Hopf bifurcation occurs at a larger *Re* due to the periodic forcing. The change of the Hopf bifurcations in the *Re*-increase and *Re*-decrease loop produces a new domain of hysteresis, which is non-existence in the steady WBC experiments.

As the periods of the WBC variation decrease enough, which is still much longer than $T_{\rm w}$, the critical *Re* numbers of the WBC regime transition are no longer in agreement with those of the steady WBC. Figure 4 shows the $X_{\rm P}$-*Re* curve of a WBC oscillating at a 3-year period. The hysteresis domain is larger than that of a steady WBC. The distance of the westward intrusion of the WBC is also reduced. Figure 5 shows the $X_{\rm P}$-*Re* curve of a WBC varying at a 1-year period. It can be seen that the critical *Re* numbers has been changed further, with the hysteresis domain larger than that of a WBC varying at longer periods. The distance of the westward intrusion of the WBC is reduced at shorter periods. Figure 6 shows the variations of $X_{\rm P}$ with time in the above three experiments. The decrease of the western intrusion of the WBC is shown to decrease for shorter periods of the oscillations.

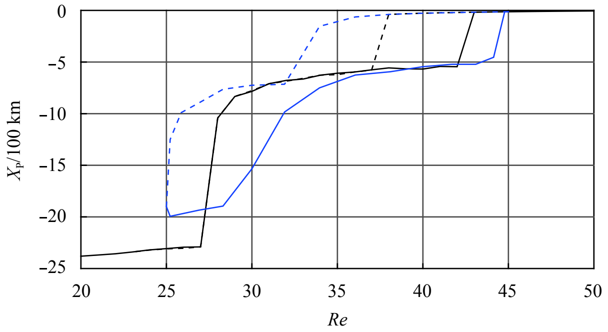

Fig. 4. The westward most intrusion of a 3-year periodic WBC through the gap ($X_{\rm P}$) varying with *Re* (blue curves). The solid curves represent the increasing *Re* course, and the dash curves the decreasing *Re* course. The black curves are the hysteresis of the steady WBC as comparison, which is the same as Fig. 2, but the lines which are not the westward most of X_p are removed for the eddy shedding state ($27\leqslant Re\leqslant 42$).

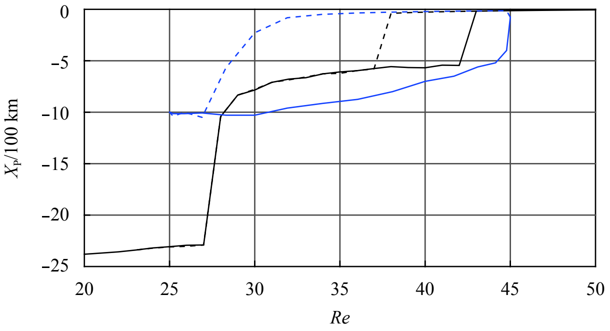

Fig. 5. The westward most intrusion of a 1-year periodic WBC through the gap ($X_{\rm P}$) varying with *Re* (blue curves). The solid curves represent the increasing *Re* course, and the dash curves the decreasing *Re* course. The black curves are the hysteresis of the steady WBC as comparison, which is the same as Fig. 2, but the lines which are not the westward most of X_p are removed for the eddy shedding state ($27\leqslant Re\leqslant 42$).

When the periods of the WBC are comparable with $T_{\rm w}$, the WBC path varies at a much higher frequency, which is quite different with the hysteresis process of the steady WBC. The evolution of $X_{\rm P}$ becomes a zigzag shape and would not stop in any state for a while. The panels in Fig. 7 show the evolution of $X_{\rm P}$ when the WBC changing in periods of 120 d, 90 d, and 60 d, respectively. It shows that $X_{\rm P}$ oscillating in a range of less than 1 000 km most of the time, occasionally reaching a large value. Specifically, the $X_{\rm P}$ evolution of the WBC changing in 120-d period is similar to that of the 90-d period. $X_{\rm P}$ mainly oscillates in a zigzag shape in the range of less than 6 000 km, occasionally reaches a great value over than 10 000 km. When the period of the WBC is 60-d, $X_{\rm P}$ could not reach 10 000 km any more. When the period of the WBC decreases to as short as 10 d, the WBC in the vicinity of the gap could not penetrate deeply into the western basin as shown in Fig. 8. Instead, it stays in a periodic penetration less than 750 km. The most significant difference from the larger period cases is that the periods of $X_{\rm P}$ evolution sometimes doubled that of the WBC transport variations. Because the period of the WBC changing is much shorter than the Rossby adjustment time scale, the evolution of $X_{\rm P}$ cannot keep up with the frequency of *Re* chan-

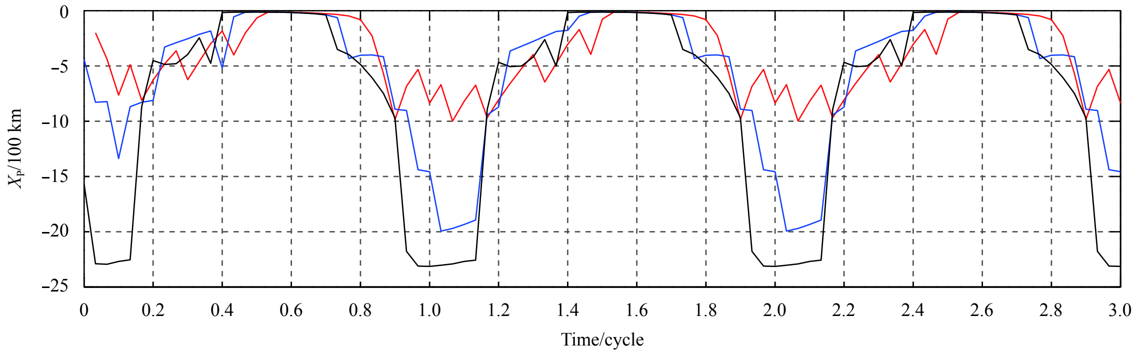

Fig. 6. The evolution of the westward intrusion extent through the gap of the sinusoidally changing WBC ($X_{\rm P}$) over time. The three color curves represent that the period of the WBC is 15 (black), 3 (blue), 1 (red)-year separately, which is the same experiment with response to the $X_{\rm P}$-*Re* curves in Figs 3, 4, 5 respectively. In order to compare the three curves in one picture, the time scale of the *x*-axis is nondimentional cycle.

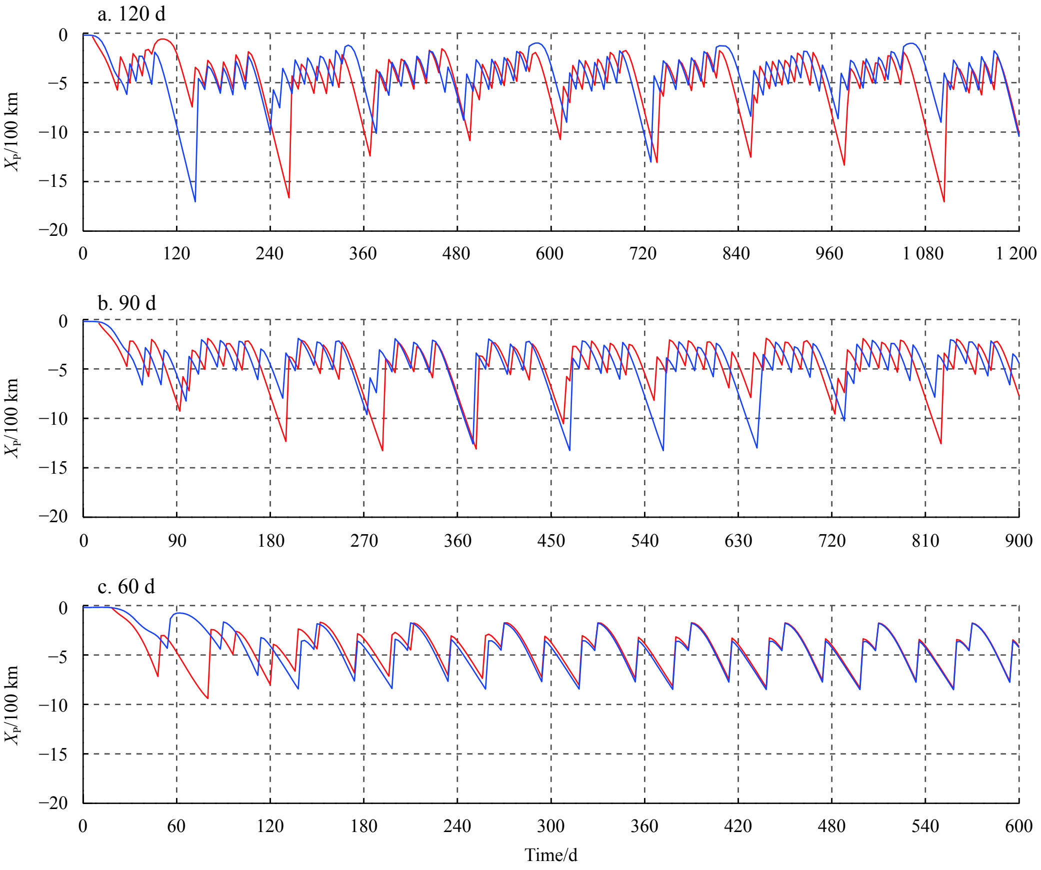

Fig. 7. The evolution of the westward intrusion extent through the gap of the sinusoidally changing WBC (X_p) over time. The period of the WBC is 120 (a), 90 (blue), 60 (red)-d separately. The red line indicates the evolution of the WBC starting from a steady penetrating state, and the blue line is from a gap leaping state.

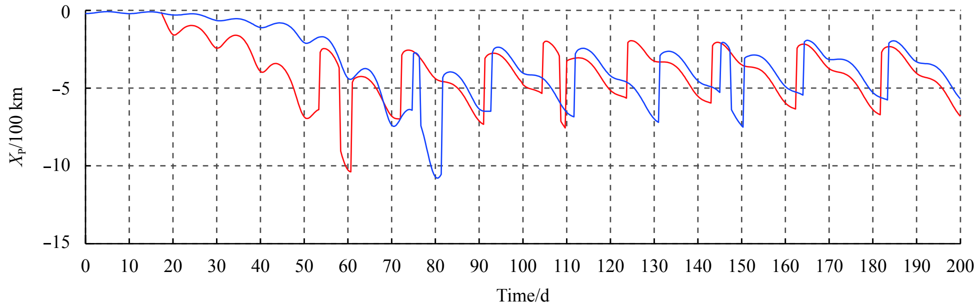

Fig. 8. The evolution of the westward intrusion extent through the gap of the sinusoidally changing WBC (X_p) over time. The period of the WBC is 10 d. The red line indicates the evolution of the WBC starting from a steady penetrating state, and the blue line is from a gap leaping state.

ging, so that the period doubled happens.

The sensitivity of the initial state of the WBC is also studied in all above experiments. Results show that the evolution of the WBC in the gap is not sensitive to the initial state. Figures 7 and 8 show the comparisons of the evolution of the WBC starting from the stable penetrating state (red) and gap leaping state (blue). After a few cycles, the X_P follows nearly the same periodic variations.

3.3 *Effects of a throughflow*

The hysteresis of a leaking WBC flowing by a gap is studied by opening a zonal gap in the southwestern corner of the western basin. The width of the zonal gap is 300 km. The WBC with a throughflow is forced by the gradient of streamfunction along the boundaries. Specifically, the streamfunction along the eastern boundary of the eastern basin is set to be $Q=Re\times A_H$, the streamfunction along the southern boundary of the western basin get rid of opening gap and connected with southern part of gappy barrier in the middle of the computation domain is set to be 0, the streamfunction along both the western and northern boundaries of the western basin, which is also connected with the northern part of the gappy barrier in the middle of computational domain is set to be Q_t. The stream function gradient drives a northward WBC of depth-averaged transport Q in the eastern basin, with a leakage throughflow in the western basin of depth-averaged transport Q_t out of the southwestern zonal gap.

The path of the leaking WBC in the vicinity of the meridional gap is similar to that of the WBC without throughflow, and experience a hysteresis process dominated the transport of the WBC. The steady penetrating state of the WBC with small transport of *Re*=10 is showed in Fig. 9. The WBC penetrates into the western basin through the meridional gap, a throughflow exits out of the zonal openning gap in the southwestern corner of the western basin, and the transport of the throughflow is 1/2 of which of the WBC in the eastern basin.

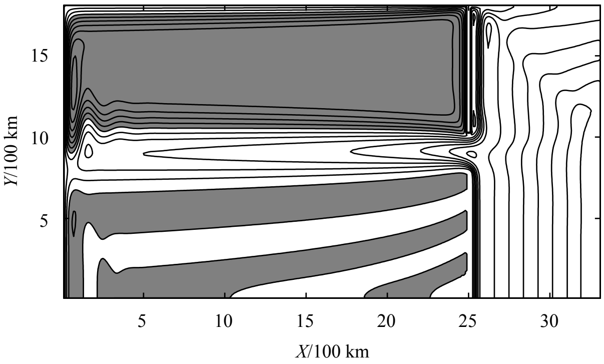

Fig. 9. The streamfunction of a leaking WBC penetrating into the western basin through the meridional gap, a throughflow exiting out of the zonal openning gap in the southwestern corner of the western basin, and the transport of the throughflow being 1/2 of which of the WBC in the eastern basin.

The existence of the throughflow is found to have no significant impact on the hysteresis loop of the WBC in the gap when the transport of the throughflow is less than or equal to 1/3 of the transport of the WBC. Figure 10 shows the hysteresis curves of the WBC in the vicinity of the gap influenced by the throughflow of different transport. The transport of the throughflow is 9/10 (blue), 4/5 (red), 1/2 (green) and ≤1/3 (black) of the WBC, respectively. When the transport of the throughflow is larger than 1/2 of the WBC, the critical points of the WBC state transitions have obviously been shifted significantly by the leaking transport of the WBC through in the western basin. The larger the throughflow transport is, the larger the change is. For instance, The Hopf bifurcation from penetrating state to eddy shedding state of the WBC without the leaking throughflow happens at the *Re*-increase course when *Re*=27, which has been shifted into *Re*=24 when the throughflow of the transport is 1/2 of the WBC, and *Re*=23 when the transport of the throughflow is 4/5 of the WBC, also *Re*=22 when the ratio of the transport of the throughflow to the WBC is 9/10. The other Hopf bifurcation from leaping state into eddy shedding state of the WBC without leaking throughflow happens at the Re-decrease course when *Re*=37.5, which has shifted into *Re*=35 when the throughflow of the transport is 1/2 of the WBC, and *Re*=34 when the transport of the throughflow is 4/5 of the WBC, also *Re*=33 when the ratio of the transport of the throughflow to the WBC is 9/10.

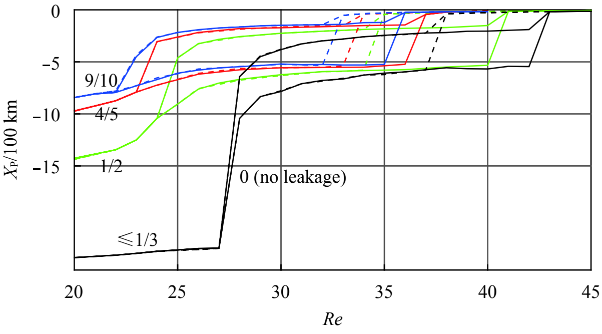

Fig. 10. The hysteresis map of the leaking WBCs intrusion into the western basin in the meridional gap. The ratio of the transport of the throughflow to the WBC is 9/10 (blue), 4/5 (red), 1/2 (green), ≤1/3 (black) respectively. The black curves are also the hysteresis of the steady WBC as comparison, which is the same as Fig. 2.

4 Discussion and conclusions

The evolution of the WBC path flowing by a meridional gap is subject to hysteresis process depending on the *Re* number of the WBC. In this study, a 1.5-layer quasi-geostrophic reduced gravity model is used to study the hysteresis of a periodic WBC or a WBC with leaking transport through the gap.

There are two main effects of the periodic and leaking WBC forcing, one is changing the critical *Re* when the WBC regime shifts, and the other is reducing the farthest westward intrusion distance of the WBC in the gap. When the period of the WBC variations is 15-year, much longer than the Rossby wave propagation time scales in the vicinity of the gap which is equal to 34.7 d, the path of the periodic WBC follows the hysteresis loop of a steady WBC. The critical *Re* numbers of the regime transitions of the hysteresis are nearly unchanged by the periodic forcing. In comparison, the Hopf bifurcation of the WBC path between steady penetrating and eddy shedding states have been altered by the periodic forcing. The change of the Hopf bifurcations in the *Re*-increase and *Re*-decrease loop produces a new domain of hysteresis, which is non-existence in the steady WBC experiments. When the period of the WBC variations decreases shorter to 3-year, the critical *Re* numbers of the WBC regime transitions also change significantly, with the domain of the hysteresis larger than that of the 15-year period forcing. When the period of the WBC changing decreases shorter to 1-year, the domain of hysteresis turns even larger as a result of the critical *Re* from leaping state to penetrating state turns even smaller, and the WBC cannot intrusion westward so deeply as the longer period situation.

When the periods of the WBC variations are 120, 90 and 60 d, which are comparable with those of the Rossby wave propagation time scales 34.7 d, the WBC path in the vicinity of the gap becomes periodic with no hysteresis, so it is significantly different with the evolution of the steady WBC. The westward intrusion extent of the WBC oscillates high frequency in a small range, occasionally reach a large value, and this may be more consistent with the real ocean than the hysteresis process. The intrusion of the WBC into the western basin generally gets smaller as the period decreases. When the WBC changing in an extremely small period such as 10 d, the evolution of WBC path in the gap would be in a doubled period. Numerical experiments have also shown that the existence of a more than half leakage of the WBC transport through the gap into the western basin has changed the hysteresis loop of the WBC path. The smaller the throughflow transport is, the smaller the change is.

These studies represent the investigation of the nonlinear

WBC path in the vicinity of a meridional gap forced by the periodic or leaking WBC. The numerical results are important because they provide a basis for understanding the impact on the evolution of the WBC in the gap by the periodic and leaking conditions. The comparison of the numerical experiment results with the altimeter sea level in the vicinity of the Luzon Strait and further studies on the dynamics of the forced evolution are undergoing and will help to under the behavior of the WBCs near gappy western boundaries and the evolution of Kuroshio in the Luzon Strait.

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