Enhanced Poleward Propagation of Barotropic Rossby Waves by the Free-Surface Divergent Effect

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Abstract

The meridional propagation of Rossby waves links different latitudes. Traditional wave propagation theory is mostly discussed in the non-divergent atmosphere. This work emphasizes the influence of the divergent effect on wave propagation by analyzing wave solutions to the linearized shallow-water quasi-geostrophic potential vorticity equation on the zonal mean flow. Changes in the basic-state quantities and wave solutions generated from consideration of the divergent effect are highlighted. Compared with the non-divergent situation, more waves are allowed to exist and propagate to much higher latitudes in the divergent case. The turning latitudes are generally moved northward when the divergent effect is included. This main conclusion is robust in the idealized super-rotational flow and 300 hPa climatological flows in winter and summer. The divergent effect also tends to slow the speed of wave propagation and favor waves reaching remoter longitudes. These findings implicate Rossby wave propagation with divergent effect may contribute more to the long-distance teleconnection than that in non-divergent case.

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1. Introduction

Rossby wave propagation is a critical dynamic process in the variability of global weather and climate (Teng et al. 2013; Screen and Simmonds 2014; Wolf et al. 2018). For example, the poleward-propagating barotropic Rossby waves triggered by tropical convection (Lee 2012; Lee et al. 2011; Yoo et al. 2012; Tseng et al. 2019; Yuan et al. 2018; Meehl et al. 2018) may have contributed to the recent rapid warming of the Arctic, leading to extreme weather events in mid-latitudes (Screen and Simmonds 2013; Cohen et al. 2014; Overland et al. 2015; Coumou et al. 2018). The typical great circle path of two-dimensional barotropic Rossby waves on a sphere (Longuet-Higgins 1964, 1965; Hoskins and Karoly 1981) is acknowledged to be an effective mechanism for teleconnections between tropical and extratropical regions (Trenberth et al. 1998; Stan et al. 2017). Rossby waves excited in the tropics propagate poleward to their turning latitude and then turn back toward the equator. The turning latitude, as the northerly limit of these waves at which they could penetrate, may determine the meridional range of the teleconnection.

The framework of Rossby wave propagation theory was established in early studies (Rossby 1939, 1945; Haurwitz 1940; Yeh 1949) and has been developed by extending the theory to two- (Longuet-Higgins 1964, 1965; Hoskins and Karoly 1981) and three-dimensional (Karoly and Hoskins 1982) waves and by considering the complex, non-uniform background flow (Hoskins and Ambrizzi 1993; Li and Nathan 1997; Li and Li 2012; Shaman et al. 2012; Li et al. 2015, 2018; Zhao et al. 2015). The barotropic non-divergent vorticity equation has been widely used as a simplified model. The properties of Rossby wave propagation in a

divergent atmosphere have not been fully discussed, although they have been explored in a number of studies (Rossby 1939, 1945; Yeh 1949; Bjerknes 1937; Bjerknes and Holmboe 1944; Cai and Huang 2013). Tropical responses to equatorial forcing is made up of barotropic and baroclinic modes (Matsuno 1966). Baroclinic modes are mostly confined in the tropics, while barotropic modes can propagate out of the tropics and arrive at extratropics. The influence of divergence on the propagation of these modes has been pointed out to be necessary (Lim and Chang 1983; Lau and Lim 1984). However, previous studies considered an uniform flow (Lim and Chang 1983) or an idealized super-rotation flow (Lau and Lim 1984). Hoskins and Karoly (1981) gave the wavenumber formula to the free-surface barotropic model and shortly discussed wave propagation with 10 km and 400 m equivalent depth for an external, barotropic mode and the first internal mode respectively. However, the effect of divergence on wave propagation in the climatological flow was not highlighted in their work and has not yet been studied in detail.

Motivated by this question, Section 2 reviews the wave theory with divergence modified from Lau and Lim (1984) and compares it with the non-divergent solutions. Section 3 reports the changes in the basic state quantities, wave number, group velocity and wave ray trajectories by calculating multiple zonal mean flows, including the idealized super-rotational flow and the June–July–August (JJA) and December–January–February (DJF) climatological flows. Conclusions are presented in Section 4.

2. Wave theory with divergence under the zonal mean flow

The shallow water quasi-geostrophic potential vorticity (SWQGPV) equation on a sphere is used as the fundamental model

$$\left(\frac{\partial}{\partial t} + \frac{u}{a \cos \varphi} \frac{\partial}{\partial \lambda} + \frac{v}{a} \frac{\partial}{\partial \varphi} \right) q = 0. \quad (1)$$

where $q = \zeta - \lambda_0^2 \psi$ is the SWQGPV, $\zeta = f + \nabla^2 \psi$ is the absolute vorticity (ASV), $\lambda_0^2 = f^2/gH$, f is the Coriolis parameter, g is the acceleration due to gravity, H is the constant depth of the fluid and $\nabla^2 = \frac{1}{a^2 \cos^2 \varphi} \left(\frac{\partial^2}{\partial \lambda^2} + \cos \varphi \frac{\partial}{\partial \varphi} \cos \varphi \frac{\partial}{\partial \varphi} \right)$. This model represents a particular mode of a baroclinic atmosphere with H fixed as a specific equivalent depth (Lau and Lim 1984). The second term of the SWQGPV represents the divergent effect from the ageostrophic flows due to the free-surface elevation. Vallis (2006) introduced the derivation of this equation on the f -plane. Schubert et al. (2009) and Blazenko (2009) showed its spherical form which can be traced back to Kuo (1956) and Charney and Stern (1962).

Following previous studies (Hoskins and Karoly 1981; Lau and Lim 1984), Eq. (1) is linearized under the zonal mean flow ($\bar{u} = \bar{u}(\varphi)$, $\bar{v} = 0$) and then projected onto the local (x, y) coordinate by Mercator projection $x = a\lambda$, $y = a \ln[(1 + \sin \varphi)/\cos \varphi]$. The equation for the perturbation streamfunction ψ' can be derived as

$$\left(\frac{\partial}{\partial t} + \bar{u}_M \frac{\partial}{\partial x} \right) (\nabla_M^2 \psi' - G \psi') + \frac{\partial \bar{q}}{\partial y} \frac{\partial \psi'}{\partial x} = 0, \quad (2)$$

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where

$$\left. \begin{aligned} \frac{\partial}{\partial x} &= \frac{\partial}{a \partial \lambda} \\ \frac{\partial}{\partial \varphi} &= \frac{\cos \varphi}{a} \frac{\partial}{\partial y} \end{aligned} \right\}, \quad (3)$$

$$\bar{u}_M = \frac{\bar{u}}{\cos \varphi}, \quad (4)$$

$$G = \lambda_0^2 \cos^2 \varphi, \quad (5)$$

$$\nabla_M^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} = \cos^2 \varphi \nabla^2, \quad (6)$$

$$\bar{q} = f + \nabla^2 \bar{\psi} - \lambda_0^2 \bar{\psi}, \quad (7)$$

$$\frac{\partial \bar{q}}{\partial y} = \beta_M - \frac{\partial}{\partial y} (\lambda_0^2 \bar{\psi}), \quad (8)$$

$$\beta_M = \frac{\partial \bar{\zeta}}{\partial y} = \frac{2\Omega \cos^2 \varphi}{a} - \frac{\partial}{\partial y} \left(\frac{1}{\cos^2 \varphi} \frac{\partial \bar{u}_M \cos^2 \varphi}{\partial y} \right). \quad (9)$$

Compared to Lau and Lim (1984), Eq.(2) is almost the same as their Eq.(1), but for the quantity $\bar{q}$, here as the meridional gradient of the background SWQGPV (BPV) instead of their quantity β (the same definition as β_M in Eq.(9)) in form of the meridional gradient of the ASV. The last term in Eq.(8), denoting the free-surface effect on the basic-state vorticity gradient, was neglected in Lau and Lim (1984). Here, H is set to be 1500 m corresponding to the gravity wave velocity ($\sqrt{gH}$) 120 m s⁻¹ and associated with the deep internal mode (Lim and Chang 1983). In this way, $\lambda_0^2 \sim \frac{10^{-8} \text{ s}^{-1}}{10^4 \text{ m s}^{-1}} \sim 10^{-12} \text{ m}^{-1}$. The climatological streamfunction at upper troposphere decreases with the latitude and is on a magnitude of $10^8 \text{ m}^2 \text{ s}^{-1}$ (see https://software.ecmwf.int/static/ERA-40_Atlas/docs/section_D/parameter_savpa200hpa.html). Thus, $\frac{\partial}{\partial y} (\lambda_0^2 \bar{\psi})$ is on the order of $10^{-10} \text{ m}^{-1} \text{ s}^{-1}$ dominating $\bar{q}_y$ since β_M is one or two orders less. Therefore, including this term is critical and further generate essential difference in wave properties.

The following set of equations shows the dispersion relation, total wavenumber, phase velocity and group velocity as

$$\omega = \bar{u}_M k - \frac{\bar{q}_y k}{k^2 + l^2 + G}, \quad (10)$$

$$K^2 = k^2 + l^2 = \frac{\bar{q}_y}{\bar{u}_M - c} - G, \quad (11)$$

$$c = \frac{\omega}{k} = \bar{u}_M - \frac{\bar{q}_y}{k^2 + l^2 + G}, \quad (12)$$

$$c_{gx} = \frac{\partial \omega}{\partial k} = \bar{u}_M - \frac{(l^2 - k^2 + G) \bar{q}_y}{(k^2 + l^2 + G)^2} = c + \frac{2k^2 \bar{q}_y}{(k^2 + l^2 + G)^2}, \quad (13)$$

$$c_{gy} = \frac{\partial \omega}{\partial l} = \frac{2kl \bar{q}_y}{(k^2 + l^2 + G)^2}. \quad (14)$$

This equation set has the same form as the equations in Hoskins and Karoly (1981) when the non-divergent assumption is considered and G ignored. This means that the non-divergent solution is a special form of the divergent solution. From Eqs.(8) and (11), we can derive

$$l_{div}^2 = \frac{\bar{q}_y}{\bar{u}_M - c} - G - k^2 = l_{ndiv}^2 + Residual, \quad (15)$$

$$l_{ndiv}^2 = \frac{\beta_M}{\bar{u}_M - c} - k^2, \quad (16)$$

$$Residual = -\frac{1}{\bar{u}_M - c} \frac{d\lambda_0^2 \bar{\psi}}{dy} - G. \quad (17)$$

l_{div} and l_{ndiv} are the refractive indices in the divergent and non-divergent theory respectively. Residual term in Eq.(15) arises from the divergent effect and denotes the difference between the divergent and non-divergent cases. If it is positive, the meridional range for the wave propagation is enlarged by the divergent effect relative to the non-divergent case, otherwise, it is confined.

Equation (8) in Lau and Lim (1984) suggests the meridional range for wave propagation is confined by the divergent effect. Differently in this study, the meridional range tends to be enlarged because the residual term in Eq.(15) tends to be positive with the first term on the order of $10^{-12} \sim 10^{-11} \text{ m}^{-2}$ and the second term G about 10^{-13} m^{-2} , for stationary waves ($c = 0$). To be noted, the first term in Eq.(17) denotes the free-surface effect on the basic state, while the second term denotes the effect on the perturbation. The above analysis suggests that the mean-state divergence effect tends to contribute to the meridional propagation rather than confine it as the perturbation divergence effect. The propagation area for stationary waves tends to become wider with the divergent effect than in the non-divergent situation—that is, more waves propagate away from the source with the divergent effect.

According to the WKB approximated solution (Hoskins and Karoly 1981), the wave amplitude along its path is proportional to $l^{-1/2}$. And there are two special latitudes for meridional propagation. One is the critical latitude with $\bar{u} = 0$. The total wavenumber becomes very large near the critical latitude, which indicates that the wave scale becomes small and its amplitude decreases. Equation (11) shows that the critical latitude ($\bar{u} = 0$) is the same in both the divergent and non-divergent cases. The other special latitude is the turning latitude, where the direction of wave propagation is reflected to the opposite direction. It can be identified as the latitude with $l = 0$. According to Eqs.(15), (16) and (17), the turning latitude has

$$k^2 = \frac{\beta_M}{\bar{u}_M} \quad (18)$$

in the non-divergent case and

$$k^2 = \frac{\beta_M}{\bar{u}_M} + Residual \quad (19)$$

in the divergent case. Because the residual item tends to be positive as above discussed, waves at the turning latitude tend to have a larger value of k in the divergent case than in the non-divergent case. Since the background flow is only latitude-dependent, k keeps unchanged with wave propagation (Hoskins and Karoly 1981). It indicates the divergent case allows shorter waves excited at lower latitudes to reach the turning latitude than the non-divergent case.

Wave disperses along the longitude and latitude at group velocity following

$$\left. \frac{dY}{dt} \right|_{c_g} = c_{gy} \quad \text{and} \quad \left. \frac{dX}{dt} \right|_{c_g} = c_{gx}. \quad (20)$$

Connecting the locations (X, Y) at time t gets the trajectory for wave energy dispersion, named wave ray. Using the derived group velocity Eqs. (13) and (14), the ray slope for stationary waves can be identified as

$$\left. \frac{dY}{dX} \right|_{c_g} = \frac{c_{gy}}{c_{gx}} = \frac{l}{k}. \quad (21)$$

It means that the stationary wave energy locally disperses along the direction of the wave vector (k, l). Using Eqs.(15), (16), and (17), the ray slope in divergent case can be written in the form of

Fig. 1. Basic states and total wavenumber as a function of latitude in the DJF flow. The left-hand panel shows the zonal mean zonal wind (black curve) and the total wavenumber in the non-divergent (blue, unit: $1/a$, a is the earth radius) and divergent (red, unit: $1/a$) cases. The middle panel shows the ASV (blue, unit: 10^{-5} s^{-1}) and the BPV (red, unit: 10^{-5} s^{-1}). The right-hand panel shows the meridional gradient of the ASV (blue, unit: $10^{-11} \text{ m}^{-1} \text{ s}^{-1}$) and BPV (red, unit: $10^{-11} \text{ m}^{-1} \text{ s}^{-1}$).

$$\frac{dY}{dX}\bigg|_{c_g} = \pm \sqrt{\frac{l_{ndiv}^2}{k^2} + \frac{Residual}{k^2}}. \quad (22)$$

Due to the positive residual item, Eq.(22) means that the stationary wave rays in the divergent case tend to have steeper slopes than those in the non-divergent case for a given zonal wavenumber.

These theoretical analysis suggests different wave properties in the non-divergent and divergent cases. Taking stationary waves as example, more detail of these differences will be shown by calculating the wave parameters given the basic states. Wave rays are obtained by integrating Eq.(22) using the fourth-order Runge-Kutta method with the initial location and zonal wavenumber fixed. The integration time used was 60 days at an interval of 720 s and the zonal wavenumber was set to 1–6. The meridional wavenumber along the ray was solved from Eqs.(15) and (16) for divergent and nondivergent cases respectively.

3. Results

3.1 basic states and wavenumber

This section considers the super-rotational flow and the DJF and JJA climatological zonal mean flow at 300 hPa from the NCEP/NCAR Reanalysis 1 dataset during 1980–2017 as basic flows. The super-rotational flow is set to be $\bar{u}_M = a\Omega/30.875$, the same as that used in Hoskins and Karoly (1981). For the DJF and JJA mean flows, the zonal mean is applied onto the smoothed spatial fields with the spectral triangular truncation at wavenumber 10 (Li et al. 2019). The level 300 hPa is chosen since it has been deemed as the “equivalent barotropic” level in previous studies (e.g. Hoskins and Karoly 1981; Hoskins and Ambrizzi 1993; Li et al. 2015). As an example, Fig. 1 shows the DJF basic state and total wavenumber as functions of latitude. The BPV has a larger magnitude and stronger meridional gradient than the ASV in the extratropics. Therefore, the total wavenumber in the divergent case (red curve in the left-hand panel) is larger than that in the non-divergent case (blue curve in the left-hand panel). The average total wavenumber over latitudes 30°N – 70°N is 5.7 in the non-divergent case and 7.8 in the divergent case. Correspondingly, the average wavelength changes from 7000 km in the non-divergent case to 5000 km in the divergent case. Another remarkable feature in the wavenumber distribution is that there is no wave at latitudes 65°S – 80°S in the non-divergent case. This is a result of the negative meridional gradient of the ASV at these latitudes; by contrast, the BPV gradient is positive. The divergent case therefore allows the occurrence of a wave at this belt.

Figure 2 shows the meridional wavenumber and group velocity as functions of latitude and zonal wavenumber for the DJF

Fig. 2. Positive meridional wavenumber (upper panels, unit: $1/a$) and group velocity (lower panels, unit: m s^{-1}) as functions of latitudes (y-axis) and zonal wavenumber (x-axis) for DJF flow. The shaded areas indicate that stationary Rossby waves could propagate meridionally in non-divergent (left-hand panel) and divergent (right-hand panel) cases. The stippling in the left-hand panel shows the range of propagation in the divergent case.

flow. The shading shows that stationary waves could exist and propagate meridionally in both the non-divergent (left-hand panel) and divergent (right-hand panel) cases. The stippling in the left-hand panel helps to compare the propagation range in the two cases. It shows a wider coverage in terms of latitude and zonal wavenumber in the divergent case than in the non-divergent case. In detail, waves with zonal wavenumbers 4–7 are not generated at latitudes north of 35°N in the non-divergent case, although they can appear in the divergent case. There is no wave at 60°S – 80°S in the non-divergent case, whereas there are waves with zonal wavenumbers up to 7 in the divergent case. For the same zonal wavenumber, the magnitude of the meridional wavenumber is clearly larger in the divergent case than in the non-divergent case at the same latitude. This means that the divergent effect tends to decrease the size of the wave. The magnitude of the meridional group velocity is smaller in the divergent case relative to the non-divergent case, which implies that the divergent effect tends to slow the meridional propagation. The average meridional group velocities over the latitudes 30°N – 70°N for zonal wavenumbers 1, 3 and 5 decrease from 12, 27 and 29 m s^{-1} in the non-divergent case to 6, 17 and 23 m s^{-1} in the divergent case.

Table 1 lists the turning latitudes for stationary waves with zonal wavenumbers 1–6 under super-rotational flow and DJF and JJA flow in the non-divergent and divergent cases, respectively. Almost all the turning latitudes for different flows and different zonal wavenumbers move farther north in the divergent case than in the non-divergent case. The shift of the turning latitude between the two cases is the largest for zonal wavenumber 3–5 (2) waves in DJF (JJA). The DJF flow has the largest magnitude of this shift. This suggests that the meridional propagation of stationary Rossby waves is sensitive to the divergent effect in DJF.

3.2 Wave rays

Figure 3 shows the wave rays for zonal wavenumbers 1–6 under super-rotational, JJA and DJF flows. Only the poleward solutions are discussed. The waves generally move toward the

Table 1. Turning latitudes for stationary waves with zonal wavenumbers 1–6 under different background flows for the non-divergent/divergent cases. The numbers in parenthesis are the differences between the two cases (units: °N).

k	Super-rotational flow	DJF	JJA
1	82.5/85 (2.5)	77.5/82.5 (5)	87.5/87.5 (0)
2	75/80 (5)	72.5/77.5 (5)	64.5/77.5 (13)
3	67.5/75 (7.5)	47.5/75 (27.5)	60/72.5 (12.5)
4	57.5/70 (12.5)	42.5/70 (27.5)	55/64.5 (9.5)
5	50/65 (15)	35/62.5 (27.5)	47.5/57.5 (10)
6	40/60 (20)	25/35 (10)	40/47.5 (7.5)

Fig. 3. Wave rays for stationary waves in non-divergent (curves with dots) and divergent cases (curves with crosses) under multiple basic flows. The colors red, orange, yellow, green, blue and purple indicate the zonal wavenumber 1–6 respectively. The markers (dots and crosses) are plotted at 2-day interval. The upper panel is for super rotational flow, middle for JJA flow, and bottom for DJF flow. The start point is (0°, 25°N).

east and north to the turning latitudes from the starting point (0°, 25°N) and are then reflected to equatorward until they are trapped at the critical latitude. This preferred great circle-like trajectory is displayed in both the divergent and non-divergent cases, but there are remarkable differences in the details of the trajectories for the same initial waves between the two cases in all the three flows, including the turning latitude, propagation speed and arriving longitude. Most wave rays in the divergent case arrive at much higher latitudes than those in non-divergent case, regardless of the flow or season. In DJF, the rays for zonal wavenumber 3–5 waves are reflected towards the equator south of 50°N in the non-divergent case, but are able to pass through 60°N in the divergent case. The zonal wavenumber 5 wave propagates remotely in longitude in the divergent case, reaching 280°E after about 10 days (Fig. 4). While in the non-divergent case, this wave can just reach 90°E after 4 days.

Under super-rotational flow, the rays move exactly along a great circle in the non-divergent case, but are modulated by the di-

Fig. 4. Evolution of ray latitudes and longitudes with the integration days for DJF flow. Solid lines indicate the divergent case, and dashed lines indicate the non-divergent case. The colors red, orange, yellow, green, blue and purple indicate zonal wavenumbers 1–6, respectively.

vergent effect into circuits that are no longer closed. The rays for zonal wavenumbers 3–6 arrive at 60°S when they move around the globe (back to longitude 0°). The zonal wavenumber 1 wave terminates at 65°N in the divergent case, whereas it reaches 20°S in non-divergent case after a 60-day integration. As a rough estimation, the meridional group velocity for the zonal wavenumber 1 wave in divergent case is 1.4° per day slower than that in the non-divergent case.

Unlike the situation in super-rotational flow, wave rays are trapped in the northern hemisphere under the JJA and DJF climatological flows as a result of tropical easterly winds. The trap line (the zero zonal mean wind latitude) in DJF (JJA) lies at about 5°N (20°N). Figure 4 shows the time evolution of the latitude and longitude along the wave rays in DJF. All the waves shown approach the trap line after reflection at the corresponding turning latitudes. They need about 50, 25, 10–20 and 5 days to reach here in the divergent case for zonal wavenumbers 1, 2, 3–5 and 6, respectively. This time is much shorter in the non-divergent case—almost half that in the divergent case. This longer time for waves to move from their starting point to the trap line in the divergent case implies that the divergent effect may favor a long-lasting lead-lag teleconnection between low and high latitudes.

4. Conclusion and discussion

I have presented a theoretical analysis of the effect of divergence on Rossby wave propagation based on the WKB solutions to the SWQGPV equation with the fluid depth H determined as 1500 m. This determination corresponds to the so-called “tropical deep internal mode” in Lim and Chang (1983) which is featured with barotropic structures at extratropical region. Changes from the basic state ASV to the BPV and changes in the wave solutions as a result of taking into account the divergent effect are emphasized. Both the theoretical analysis and wave parameter calculations in the super-rotational, DJF and JJA flows suggest that the divergent effect can enhance the poleward propagation of the tropical deep internal mode. This effect is more significant for zonal wavenumber 3–5 waves in DJF. The benefits of Rossby wave propagation from the divergent effect include (1) more latitudes allow the existence and propagation of stationary waves due to the wide range of the positive basic state BPV used as a substitute for the ASV; (2) more shorter waves can occur and arrive at higher turning latitudes; and (3) most waves reach more distant longitudes and propagate for a longer time. These benefits indicate that deep tropical internal modes in the atmosphere may generate a more remote and longer lead-lag teleconnection between the tropics and higher latitudes. They may transport more energy to the Arctic. Previous studies have revealed the contribution from the barotropic Rossby wave propagation to the tropical-polar teleconnection. However, traditional wave theory neglects the influences of divergent effect and may lead to bias in wave propagation trajectories. This work is helpful to improve the theoretical

understandings on barotropic Rossby wave propagation and then provide reference for observational analysis and modeling assessment on the related quasi-barotropic teleconnection patterns. To be noted, QGPV model (Kuo 1956; Charney and Stern 1962) has an advantage to examine three-dimensional wave properties, which is worthy to be checked in the future.

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