Equatorial Windows and Barriers for Stationary Rossby Wave Propagation

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(Manuscript received 24 October 2018, in final form 27 May 2019)

ABSTRACT

Rossby waves can cross the equator and connect the Northern Hemisphere (NH) and Southern Hemisphere (SH), or be blocked in the vicinity of the equator. This work explores the windows and barriers for the cross-equatorial waves (CEWs) by the wave ray ensemble method. The eastern Pacific and Atlantic regions are identified as common windows in both boreal winter and summer, while the Africa–Indian Ocean section exists as a window only in boreal summer. The western–central Pacific is found to be a barrier section. These results are consistent with correlation analysis of reanalysis data. Moreover, the dependence on the wavenumber of CEWs is investigated, revealing that they are restricted to long waves with zonal wavenumbers less than 6 and that their wavenumber vectors exhibit a northwest–southeast (southwest–northeast) tilt when they cross the equator from the NH to SH (from the SH to NH). This long-wave dominance of CEWs results from the spectral-selective filtering mechanism, which suggests that long waves have narrower equatorial barriers than short waves. Finally, the main wave duct associated with each window is obtained by the global passing CEW density distribution. The results indicate that the main CEW ducts roughly follow a great circle–like pathway, except for the Africa–Indian Ocean window in boreal summer, which may be modulated by the cross-equatorial monsoonal flow.

1. Introduction

The atmospheric circulations in the Northern Hemisphere (NH) and Southern Hemisphere (SH) are closely coupled with anomalies in one hemisphere generating weather and climate responses in the other. For example,

the heating anomalies linked to the Asian summer monsoon can induce subtropical responses in the SH (Lin 2009; Lee et al. 2013; Liu and Wang 2013). Ratnam et al. (2015) found that cross-equatorial waves (CEWs) play an important role in maintaining the long periods of low convective activity over southern Africa. The southern annular mode in May is a potential precursor to determine the strength of the South China Sea summer monsoon via a wave train pattern from the South Pacific (Liu et al. 2018). During the boreal summer season, anomalous Indo–western Pacific convection is closely related to rainfall anomalies in western Australia and northeastern Brazil (Zhao et al. 2019).

Supplemental information related to this paper is available at the Journals Online website: <https://doi.org/10.1175/JCLI-D-18-0722.s1>.

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DOI: 10.1175/JCLI-D-18-0722.1

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FIG. 1. (a) DJFM and (b) JJAS climatological flow at 300 hPa. The red-shaded areas show the easterly region.

Such teleconnections have been attributed to barotropic stationary Rossby wave propagation, since stationary Rossby waves can implement an efficient wave energy transport from one hemisphere to the other. Cross-equatorial propagation was first discussed by Hoskins et al. (1977), and subsequently proven by studies based on wave theory analysis (Schneider and Watterson 1984; Hoskins and Ambrizzi 1993; Li and Li 2012; Y. Li et al. 2015, hereafter L15; Zhao et al. 2015), barotropic model experiments (Schneider and Watterson 1984; Watterson and Schneider 1987; Farrell and Watterson 1985; Esler et al. 2000; Wang et al. 2005; Kraucunas and Hartmann 2007), and statistical analysis with reanalysis data (Hsu and Lin 1992; Tomas and Webster 1994; L15; Zhao et al. 2015).

The vicinity of equatorial regions is a special zone where stationary Rossby waves can either be allowed to propagate from one hemisphere to the other or be blocked by reflection or absorption. By simply assuming a zonally uniform basic flow (i.e., westerly over the extratropics and easterly at the equator), the tropical easterly zone has been deemed a propagation barrier for Rossby waves (Hoskins and Karoly 1981, hereafter HK81). This is because Rossby waves cannot propagate in the zonally uniform easterly flow. The zero-zonal-wind latitude near the equator will trap waves that propagate in from westerly regions. This latitude was referred to as the “critical line” in HK81, similar to the concept of the “critical level” for vertical propagation in even earlier studies (Booker and Bretherton 1967; Lindzen and Tung 1976). However, such an easterly barrier under the simple assumption cannot explain the interhemispheric teleconnections that undoubtedly take place. In fact, the basic flow near the equator is not always easterly. For example, westerly wind zones exist in boreal winter in several tropical regions, such as the equatorial Atlantic and eastern Pacific in the upper troposphere (see Fig. 1), through which Rossby waves can propagate from one hemisphere to the other (Webster and Holton 1982; Hsu and Lin 1992; Hoskins and Ambrizzi 1993). This theory of an equatorial

“westerly window” is generally consistent with barotropic model simulations (Webster and Holton 1982) and analyses of observations (Hsu and Lin 1992; Tomas and Webster 1994). However, the westerly window theory cannot account for the teleconnections across the tropical easterly areas that have been widely reported by previous studies (Nitta 1987; He 1990; Krishnamurti et al. 1997; Lin 2009; Lee et al. 2013; Liu and Wang 2013; Stan et al. 2017; Zhao et al. 2019). In this case, strong cross-equatorial flows play an important role since they can steer the Rossby waves propagating from one hemisphere to the other (Li and Li 2012; L15). As a result, these sections with strong cross-equatorial flows, such as the Africa–Indian Ocean region in boreal summer, are deemed another kind of window for CEWs, referred to as cross-equatorial-flow windows.

Nonetheless, our understanding of the dynamics of CEW is still far from sufficient. For example, the locations and widths of the various windows have yet to be specified. Do they change with seasons? How can we characterize the overall properties of CEWs? Is there a physical consistency between the westerly windows and cross-equatorial-flow windows? To answer these questions, we extend the traditional wave ray tracing method to the wave ray ensemble (WRE) method to obtain the overall characteristics of CEWs and their associated windows and barriers. The locations, seasonality, directionality, and dependence on wavelengths of the windows and barriers are investigated by the WRE method. A uniform mechanism is introduced for the abovementioned two types of windows for CEWs.

This study is organized as follows. Section 2 introduces the data, the diagnosis method for wave trains, fundamental wave ray theory, and the WRE method. Section 3 shows some CEW patterns observed from the reanalysis data using lead-lag correlations. The main results from the WRE are presented in section 4 and compared with the results in section 3. Specifically, the equatorial distributions of windows and barriers are identified. A spectral-selective filtering mechanism is

put forward to explain how the equatorial CEW windows and barriers depend on the wave parameters. Also, the main window-associated ducts of CEWs on the global scale are shown. Section 5 draws the conclusions and offers some further discussion.

2. Data and methods

a. Data, wave trains diagnosis method, and the basic flow for wave rays

The NCEP–NCAR Reanalysis 1 daily dataset from 1 January 1980 to 31 December 2017 (Kalnay et al. 1996) is used in this study, including the zonal and meridional velocities, from which the streamfunction field is then derived using the NCAR Command Language (NCL; <https://www.ncl.ucar.edu/>). The dataset is on a global 144×73 grid with a $2.5^\circ \times 2.5^\circ$ spatial resolution and 17 levels in the vertical direction (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 hPa) (provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, from their website at <https://www.esrl.noaa.gov/psd/>).

The one-point lead–lag correlations in the eddy streamfunction field at 300 hPa are used to diagnose the CEW trains, following Hsu and Lin (1992). Pre-processes applied to the streamfunction before the lead–lag correlation analysis include 1) removing the annual cycle from the daily time series by subtracting the long-term mean; 2) removing the zonal mean to obtain the eddy streamfunction fields; 3) filtering the low-frequency variations by using a 25–90-day Lanczos bandpass filter; and 4) extracting the time series for the months of December–March (DJFM; boreal winter) and June–September (JJAS; boreal summer), separately. Then, the lead–lag correlation analysis is performed. The significance of the correlation coefficients is tested by the two-tailed Student's t test using the effective number of degrees of freedom N_e , which is defined by the modified Chelton method (Pyper and Peterman 1998; Xie et al. 2014; Sun et al. 2015; Wang et al. 2018) as follows:

$$N_e \approx \left[\frac{1}{N} + \frac{2}{N} \sum_{j=1}^{N/5} \frac{N-j}{N} \rho_{XX}(j) \rho_{YY}(j) \right]^{-1}, \quad (1)$$

where N is the original sample size, and $\rho_{XX}(j)$ and $\rho_{YY}(j)$ are the autocorrelations of the two time series X and Y with the time lag j . These processes are also applied to the barotropic streamfunction, which is derived from the vertical integration of the zonal and meridional velocity at 12 levels:

$$u_{\text{baro}} = \frac{\int_{p_s}^{p_0} u \, dp}{\int_{p_s}^{p_0} dp}$$

and

$$v_{\text{baro}} = \frac{\int_{p_s}^{p_0} v \, dp}{\int_{p_s}^{p_0} dp}, \quad (2)$$

where p_s and p_0 are the pressure at the surface and 100 hPa, respectively.

Additionally, the 300-hPa monthly climatological winds are derived from the daily dataset, and then smoothed with the spectral triangular truncation at wavenumber 10 to remove the small-scale disturbances. The smoothed fields are employed as the background flow in the wave ray calculation. We also calculated rays in the section-averaged (60° along the latitude) zonal and meridional velocities, as used in Scaife et al. (2017), as another method to define the zonal asymmetric background flow. The results are shown in the online supplemental material and will be discussed later.

b. Wave ray theory

The wave ray tracing method, which is deduced from wave kinematics theory, has been widely used to detect the trajectory of Rossby wave propagation. Using it under superrotational basic flow (a type of idealized zonal mean flow), HK81 proved that wave rays on the sphere display as great circles. Under the zonal mean flow in boreal winter, the wave rays also display great circle-like paths, which matches well with some meridional teleconnection patterns, such as the Pacific–North America pattern (Trenberth et al. 1998; Scaife et al. 2017). Furthermore, under horizontally nonuniform basic flow, wave rays have also been used to estimate the equatorial westerly window (Branstator 1983; Lu and Zhu 1994) and the cross-equatorial-flow window (L15), as well as to explain many interhemispheric connection phenomena (Lee et al. 2013; L15; Zhao et al. 2015; Sakaguchi et al. 2016; Liu et al. 2018; Zhao et al. 2019). It should be noted that the wave ray equations vary with the background flow. Here, we introduce those based on the horizontally nonuniform basic flow as the basis of this study.

The barotropic vorticity equation on a sphere is linearized on the horizontally nonuniform basic-state streamfunction $\bar{\psi}(\lambda, \varphi)$ and simplified by the Mercator projection. Then, the perturbation streamfunction $\psi' = \psi - \bar{\psi}(\lambda, \varphi)$ satisfies the equation

$$\cos^2 \varphi \left(\frac{\partial}{\partial t} + \bar{u}_M \frac{\partial}{\partial x} + \bar{v}_M \frac{\partial}{\partial y} \right) \frac{\nabla_M^2 \psi'}{\cos^2 \varphi} + \bar{q}_y \psi'_x - \bar{q}_x \psi'_y = 0, \quad (3)$$

where t is time; $x = a\lambda$ and $y = a \ln[(1 + \sin \varphi)/\cos \varphi]$ to keep the spherical effect of Earth; λ and φ are longitude and latitude, respectively; $\nabla_M^2 = \partial^2/\partial^2 x + \partial^2/\partial^2 y$ is the Lagrangian operator; $(\bar{u}_M, \bar{v}_M) = (\bar{u}, \bar{v})/\cos \varphi$ is the background flow; $\bar{q} = \nabla_M^2 \bar{\psi}/\cos^2 \varphi + f$ is the background absolute vorticity; and $\bar{q}_x$ and $\bar{q}_y$ are, respectively, the zonal and meridional gradients of $\bar{q}$. Using the WKB method and the zeroth-order approximation to Eq. (3) as in previous studies (Karoly 1983; Li and Nathan 1997; Li and Li 2012; L15; Zhao et al. 2015), the dispersion relation that describes the relationship between the Rossby wave frequency and wavenumber is

$$\omega = \bar{u}_M k + \bar{v}_M l + \frac{\bar{q}_x l - \bar{q}_y k}{k^2 + l^2}, \quad (4)$$

where ω is the wave frequency, and k and l are the zonal and meridional wavenumbers, respectively. Let $\gamma = l/k$ represent the inclined structure of the wave vector, $c = \omega/k$ represent the phase velocity, and $K = \sqrt{k^2 + l^2}$ represent the total wavenumber; then Eq. (4) can be changed into a cubic equation about γ :

$$\bar{u}_M \gamma^3 + (\bar{v}_M - c) \gamma^2 + \left(\bar{v}_M + \frac{\bar{q}_x}{k^2} \right) \gamma + \left(\bar{v}_M - c - \frac{\bar{q}_y}{k^2} \right) = 0. \quad (5)$$

Given the initial k and stationary Rossby waves ($c = 0$), the initial meridional wavenumber l can be derived from Eq. (5). Since Eq. (5) is a cubic equation, it should have three solutions in the complex space, which represent three wave solutions. Here, only the real solutions are employed to focus on the propagation. More detail on this theory was presented in L15.

The ray path is a trajectory locally tangent to the group velocity vector (Lighthill 1978, p. 318). Hence, we can detect the pathways of the wave energy dispersion by calculating the ray trajectories. The zonal and meridional components of group velocity take the following forms:

$$\frac{d_g x}{dt} = \frac{\partial \omega}{\partial k} = u_g = \bar{u}_M + \frac{(k^2 - l^2) \bar{q}_y - 2kl \bar{q}_x}{K^4}, \quad (6)$$

$$\frac{d_g y}{dt} = \frac{\partial \omega}{\partial l} = v_g = \bar{v}_M + \frac{(k^2 - l^2) \bar{q}_x + 2kl \bar{q}_y}{K^4}, \quad (7)$$

where $d_g/dt = \partial/\partial t + \bar{u}_g \partial/\partial x + \bar{v}_g \partial/\partial y$ denotes the Lagrangian variation moving at the group velocity; and x and y here are the longitude and latitude of rays at time t .

In addition, due to the longitudinal and latitudinal variation of the background flow, both l and k change along the ray paths. Their evolution is determined by kinematic wave theory (Whitham 1960) as follows:

$$\frac{d_g k}{dt} = -\frac{\partial \omega}{\partial x} = -k \frac{\partial \bar{u}_M}{\partial x} - l \frac{\partial \bar{v}_M}{\partial x} - \frac{1}{K^2} \left(l \frac{\partial \bar{q}_x}{\partial x} - k \frac{\partial \bar{q}_y}{\partial x} \right), \quad (8)$$

$$\frac{d_g l}{dt} = -\frac{\partial \omega}{\partial y} = -k \frac{\partial \bar{u}_M}{\partial y} - l \frac{\partial \bar{v}_M}{\partial y} - \frac{1}{K^2} \left(l \frac{\partial \bar{q}_x}{\partial y} - k \frac{\partial \bar{q}_y}{\partial y} \right), \quad (9)$$

Equations (6)–(9) are termed as the wave ray tracing equation set. Therefore, once the background variables, initial position (latitude and longitude), and initial zonal wavenumber are given, the initial meridional wavenumber can be solved from Eq. (5), and then the integration of the wave ray tracing equation set will obtain the corresponding ray trajectory. The integration is terminated when the total wavenumbers become larger than 40 (corresponding to a wavelength less than 1000 km), which denotes that a large-scale Rossby wave evolves into a small-scale perturbation, termed as a wave trap.

c. WREs

It should be noted that the wave ray trajectories are sensitive to the starting location and the initial zonal and meridional wavenumbers. Such sensitivity to starting location was partly shown in L15 by plotting rays at the latitudes of 5°–30°N and 30°–5°S. However, the sensitivity to the initial wavenumbers and rays from the middle–high latitudes to the other hemisphere was not included. To detect the overall CEW characteristics, we explore statistically large samples of wave rays with different initial values. Here, we calculate the rays starting from an extended global range (85°S–85°N, 180°–175°E) with 5° intervals in both the latitudinal and longitudinal directions, and exclude the grids at the equator. For the initial zonal wavenumber k , we consider the range from 1 to 12 to make sure that the initial waves have large scales. For the initial meridional wavenumber, all real initial solutions of l are included. With the above-mentioned setting of the initial conditions, we obtain a large size of rays (up to 88 128 members) corresponding to one specific basic state. By diagnosing this large sample, it is possible to obtain the principal dynamical characteristics of Rossby wave propagation. Therefore, we refer to this method as WRE analysis. The method uses large-sample experiments and statistical analysis, which can be treated as an analog of the Monte Carlo method used for Rossby wave propagation under complex basic flow.

CEWs are measured by rays that initiate in one hemisphere and then arrive in the other beyond 10° of latitude off the equator. Since one ray may cross the equator multiple times (indicating reflection of the wave between the two hemispheres), only the first time crossing the equator is considered. In this way, we can obtain the total numbers of CEWs and the numbers of CEWs from the NH to SH (CEW_{N2S}) and from the SH to NH (CEW_{S2N}), respectively (correspondingly labeled as N_{CEW} , N_{N2S} , and N_{S2N}), as well as the distributional characteristics of wave parameters for CEWs. In addition, based on these statistical analyses, the equatorial windows or barriers can be identified as the sections with high or low N_{CEW} . This study uses the mean, +1 standard deviation (SD), and -1 SD of zonal and 12-month N_{CEW} series to quantify the equatorial windows, strong windows, and barrier sections respectively (see section 4). Thus, the windows and barriers in different seasons have common criteria of definition.

3. Lead-lag correlation results

Several window areas have been presented in the literature reviewed in the introduction. Here, we begin by reproducing the CEW trains crossing these windows and then compare their main features with the WRE results in the next section. In DJFM, the so-called westerly window is found over the equatorial eastern Pacific and the Atlantic (Hsu and Lin 1992; Hoskins and Ambrizzi 1993). We set the base points at 32.5°N , 130°W and 42.5°N , 175°W to perform the lead-lag correlation between their streamfunction time series and the global field. The results are shown in Fig. 2. The notation “lag($-n$)” indicates that the time series at the base point lags the global fields by n days, while “lag(n)” indicates that the time series at the base point leads the global fields by n days. The CEW trains (indicated as thick black curves) can be observed through the eastern Pacific and Atlantic regions.

For the eastern Pacific window (left column in Fig. 2), there is a strong positive center over the Chukchi Sea and a negative center in the south of the Bering Sea upstream of the base point at lag(-10). At lag(-7), the positive center has been established over the base point, and one negative and one positive center appear meridionally across the equator. This wave train penetrates into the South Pacific, South America, and South Atlantic on lag(-3). This is then maintained until lag(3) before weakening with the signals disappearing over the North Pacific at lag(7). Besides, there is another wave train associated with this base point. It moves southeast to Central America and terminates at the equator. Its termination at the equator may be related to the eastward and northward background flow over northern South America (see Fig. 1a). According to

wave theory, this background flow is not conducive to an NH-to-SH directional propagation of Rossby waves. For the base point 42.5°N , 175°W (right column in Fig. 2), significant positive correlation appears with negative and positive centers across southern North America and Central America at lag(-7). This wave train is observed as stemming from the robust signals over the Eurasian continent [by comparing lag(-10) and lag(-7)]. It remains amplified, extends into the North Atlantic, and further combines with the centers over tropical Atlantic on lag(-3). This hemispheric wave train finally arrives to the east of the Antarctic Peninsula. The signal at high SH latitudes becomes stronger after lag(0) and the signals over the Eurasian continent disappear at the same time. These results imply that the signals are transmitted from the NH to the SH through the eastern Pacific and Atlantic windows in DJFM. The above CEW trains are also obvious in the vertically integrated field, with similar propagation behaviors, which suggests that these wave trains are dominated by barotropic modes (see Fig. S1 in the online supplemental material). Therefore, we further plot the wave rays starting in the vicinity of the base points. Generally, the ray trajectories match the CEW train centers (see top panel in Fig. S4).

Moreover, the CEW trains are also observed when the base points are set in the SH. Taking the base points 25°S , 155°W and 20°S , 30°W as examples (Fig. 3), it seems that the former of the two is closely related to both tropical Pacific signals and a wavelike pattern spreading at SH middle latitudes at lag(-10). Later, the positive center of this SH wavelike pattern to the east of New Zealand moves equatorward to the base point and its downstream negative center becomes weakened at lag(-7), before then vanishing at lag(-3). However, the correlations at the NH are becoming strengthened and a wave train pattern emerges over North America and the Atlantic from lag(-3) and lasts for the following lags. The left panel in Fig. S2 shows this wave train pattern more clearly and more robust. The wave rays also display the pathway from the basepoint northeastward to North America and the Atlantic (see Fig. S4). Therefore, the black curve indicating this CEW train is mainly identified according to the results from Fig. S2 and wave rays. As for the base point 20°S , 30°W , the associated CEW train seems to be established with positive and negative centers distributed at intervals from the South Pacific to West Africa at lag(-7). The positive center in the South Pacific becomes weaker and then vanishes after lag(0), while the negative center over West Africa extends eastward to South Asia. The column field shows this wave train and its evolution to be similar at 300 hPa, but the signals over Africa–South Asia become weak at lag(7). In addition, other CEW trains associated with this base point can be observed. For example, the appearance of signals

FIG. 2. Lead-lag correlation coefficients between the 300-hPa eddy streamfunction at the base points and the global field in DJFM during 1980–2017, for the base points (left) 32.5°N, 130°W and (right) 42.5°N, 175°W. Contours are shown for values equal to -0.4 , -0.3 , -0.25 , -0.2 , -0.15 , -0.1 , 0.1 , 0.15 , 0.2 , 0.4 , 0.6 , and 0.8 . Stippling indicates that the correlation is significant at the 95% confidence level using a two-tailed Student's t test. Thick black curves indicate the CEW trains.

FIG. 3. As in Fig. 2, but for the base points 25°S, 155°W and 20°S, 30°W.

over the western Pacific may be related to the wave train over the Pacific, which can be seen by comparing Figs. 3d and 3b. Also, the column field suggests a wavelike pattern from the North Pacific across America and the South Atlantic to the western Antarctic, which can be seen from lag(−3) to lag(7) (Fig. S2). This north-to-south wave train may have an offsetting effect on the south-to-north wave train to West Africa and South Asia.

The above results suggest that the eastern Pacific and Atlantic windows in DJFM are two-directional waveguides for the CEWs. Corresponding to the cross-equatorial-flow windows shown in L15 in JJAS, Fig. 4 presents the lead-lag correlation maps for the base points 20°N, 10°E; 30°N, 140°W; and 40°N, 75°W. For the base point 20°N, 10°E, the correlation coefficients over the tropics display a quadrupole pattern straddling the equator, with one pair of centers over the Atlantic–Africa region and the other one over the western-central Pacific at lag(−10). This quadrupole extends eastward later, and the negative center at south of the equator is amplified over the Indian Ocean at lag(0). Meanwhile, a positive center appears at the SH middle latitudes and the negative center over the Antarctic continent extends eastward. These signals form a CEW train through the Africa–Indian Ocean section, which seems more robust at lag(3) and persists until lag(7). The barotropic component also clearly shows a similar CEW train over the Africa–Indian Ocean section [see the left panel of Fig. S3]. Also, the wave rays suggest barotropic Rossby wave propagation is an important mechanism for the development of this CEW train (see Fig. S5). Since the tropical quadrupole structure is a typical response to tropical heating (Jin and Hoskins 1995), the CEW pattern at 300 hPa is a baroclinic–barotropic coupled mode. By comparing Fig. 3 with Fig. S2, the indication is that the barotropic CEW mode could modulate the direct equatorial symmetric baroclinic responses into an asymmetric structure. Therefore, it is necessary to understand the barotropic CEW mode and its contribution to the total atmospheric responses to the tropical heating in the future.

For the base point 30°N, 140°W, the predominant signal in the tropics is also a quadrupole pattern straddling the equator, with one pair of centers over the Pacific and the other over the Atlantic–Africa at lag(−10), but the NH signals are much stronger than the SH ones. The Pacific centers extend to the eastern Pacific at lag(−7), and then the positive center north of the equator is split by a negative center (clearer in the barotropic mode shown in the middle panel of Fig. S3), and the negative center south of the equator is notably strengthened at lag(−3). At the following lag times, a weak positive center appears at SH middle latitudes and

the negative center over the Antarctic moves toward the Antarctic Peninsula, while the signals upstream of the base point gradually disappear. Combined with the wave ray trajectories, it is possible to identify this CEW train as starting in the North Pacific and traveling to the South Pacific and Antarctic via the eastern Pacific (see Fig. S5). Accompanying its development, another CEW train can be observed over the Atlantic, especially in the barotropic component (see the middle panel of Fig. S3).

The lead-lag correlation for the base point 40°N, 75°W shows the evolution of a CEW train from the eastern North America to the tropical Atlantic, south of the equator. It manifests as a split branch from a zonal wave train spanning North America and the Atlantic. This CEW train cannot reach higher latitudes in the SH, but the wave rays show a trajectory from the base point to SH high latitudes (see Fig. S5). This mismatch may be attributable to the fact that the wave ray shown is for a simple wave solution, while the correlation pattern from the reanalysis is composed of multiple wave packages. Multiple wave packages may offset each other. For example, the CEW train associated with the base point 20°S, 60°W (see Fig. S7) appears to be out of phase with the one associated with the base point 40°N, 75°W in the tropics. This out-of-phase overlap may be responsible for the termination of the NH-oriented CEW train at the SH low latitudes. However, this hypothesis needs to be further verified in the future.

Generally, the CEW trains discussed here indicate that the signals can propagate from the NH to SH in JJAS through the Indian Ocean, eastern Pacific, and Atlantic sections. However, we need to keep in mind that these correlation patterns result from multiple mechanisms besides the wave propagation, such as the baroclinic response to tropical forcing (Jin and Hoskins 1995) or the barotropic instability (Simmons et al. 1983). Furthermore, we can see that different wave trains may interfere with each other. The meridional wave trains may be coupled with the zonal wave trains. All these possibilities make it hard to completely understand the real atmosphere in terms of one mechanism. Nevertheless, the consistency between the wave ray results and both the upper-level and column field observations encourages us to further explore the overall characterization of the equatorial windows based on the WRE method.

4. WRE results

a. Equatorial windows and barriers for CEWs

Figure 5 shows the longitudinal distribution of the annual mean CEW numbers including N_{CEW} , N_{N2S} , and

FIG. 4. As in Fig. 2, but for the base points 20°N, 10°E; 30°N, 140°W; and 40°N, 75°W in JJAS.

FIG. 5. Distribution of the annual mean CEW numbers (black: N_{CEW} ; red: N_{N2S} ; blue: N_{S2N}) by longitude. The long-dashed line denotes the zonal and 12-month mean of N_{CEW} (~ 50 wave rays), and the short-dashed lines denote $+1$ and -1 SD of the zonal and 12-month N_{CEW} series (~ 74 and ~ 24 wave rays, respectively). The purple, yellow, and dark yellow shading denote the equatorial barrier (section with the $N_{CEW} \leq -1$ SD), window (section with the annual mean $N_{CEW} \geq \text{mean of } N_{CEW}$), and strong window (section with the $N_{CEW} \geq +1$ SD) for CEW, respectively.

N_{S2N} , derived from the number of rays calculated on the monthly climatological flows. The results show that the Western Hemisphere has much higher CEW numbers than the Eastern Hemisphere. The section from 160° to 10°W is identified as a weak but wide window, embedded with a strong window in the eastern equatorial Pacific (140° – 120°W). The equatorial eastern Pacific is suggested as a two-way window, which allows Rossby waves to propagate from the NH to SH and vice versa (high numbers for both N_{N2S} and N_{S2N}). There is a weak peak of N_{CEW} in the equatorial Africa–Indian Ocean (30° – 80°E) but not to be identified as a window because N_{CEW} is less than the zonal mean N_{CEW} . The barrier area is located in the section from the Maritime Continent to the equatorial western Pacific (120° – 165°E) with the lowest CEW numbers for all three measures (N_{CEW} , N_{N2S} , and N_{S2N}).

Because the basic flow is season dependent, the occurrence of CEWs is expected to possess seasonality too. Figure 6 shows the annual evolution of the equatorial total N_{CEW} , N_{N2S} , and N_{S2N} . Although these CEW numbers are composed of only about 5% of the ensemble size, previous studies based on observations have suggested that they play an important role in linking regional anomalies to the remote forcing in the opposite hemisphere (e.g., Higgins and Schubert 1996; Ratnam et al. 2015; Liu et al. 2018; Zhao et al. 2019). The CEW numbers possess seasonal variations. The value of N_{N2S} is high during June–October and low in boreal winter months, while the value of N_{S2N} is high in boreal winter and low in boreal summer. As a result, the total N_{CEW} has a strong temporal peak in October and two weak peaks in February and June, respectively. The large difference between N_{N2S} and N_{S2N} in JJAS (the former being about twice as large as the latter) suggests

FIG. 6. Annual variations of the equatorial total of the N_{CEW} (black), N_{N2S} (red), and N_{S2N} (blue).

that the Rossby waves are more likely to propagate from the NH to SH in boreal summer, while the minor difference between them in DJFM suggests that the Rossby waves may propagate across the equator in both directions equally in boreal winter. These results for DJFM and JJAS agree with the discussions in Webster and Holton (1982) and in L15 respectively. The large difference between N_{N2S} and N_{S2N} in JJAS can be attributed to the strong tropical northerly basic flow at upper levels in JJAS that is (is not) conducive to the NH-to-SH (SH-to-NH) propagation of Rossby waves.

To further investigate CEW propagation differences in boreal winter and summer, we present the zonal distributions of the seasonally averaged N_{CEW} , N_{N2S} , and N_{S2N} in DJFM and JJAS (Fig. 7). In DJFM, the Western Hemisphere is a high N_{CEW} section that can be identified as having two separated strong windows including the eastern Pacific (105° – 160°W) and Atlantic (40° – 55°W). One difference between these two windows is that the eastern Pacific window has almost balanced N_{N2S} and N_{S2N} , while the Atlantic window has higher N_{S2N} than N_{N2S} . This implies that the Atlantic window favors SH-to-NH propagation. Different from the Western Hemisphere, the Eastern Hemisphere is a section with lower N_{CEW} , and the section 100° – 170°E is identified as a barrier for CEWs because the N_{CEW} is more than one standard deviation lower than the zonal mean value.

In JJAS, there are three windows located in the Africa–Indian Ocean (15° – 65°E), the eastern Pacific (135° – 60°W), and Atlantic (60° – 5°W) regions, respectively (Fig. 7b). Compared with DJFM, the latter two windows in the

FIG. 7. As in Fig. 5, but for the (a) DJFM and (b) JJAS mean. The dashed lines are as in Fig. 5.

Western Hemisphere have lower numbers and narrower window coverage, but the difference between N_{N2S} and N_{S2N} seems to be larger in JJAS than in DJFM. The N_{N2S} is higher than N_{S2N} at any longitude. Particularly, the Africa–Indian Ocean window works much better for the NH-to-SH direction than for the opposite direction. Therefore, this window can be viewed as a CEW_{N2S} -dominant window. The Africa–Indian Ocean window measured by N_{CEW} is consistent with the cross-equatorial-flow window mentioned in L15. Furthermore, the Asian–Australian summer monsoon region (65° – 125° E) is also a CEW_{N2S} -dominant window because N_{N2S} is larger than N_{S2N} , even though it is not identifiable as a window according to the N_{CEW} values. The barrier section in JJAS is located in the western–central Pacific (130° E– 155° W), with a slight eastward shift compared to the position in DJFM.

b. Longwave dominance of cross-equatorial propagation

Figure 8 shows the probability distribution function (PDF) of zonal wavenumber k , meridional wavenumber l , and the wave inclination parameter ($\gamma = l/k$) at the cross-equatorial points for the CEW_{N2S} and CEW_{S2N} in DJFM and JJAS. The magnitude and sign of the wavenumber (k and l) denote the wave scale and its phase propagation direction, respectively. The results show that CEWs are principally concentrated in the local longwave band, with a specific inclined wave-vector structure when they cross the equator. The magnitudes of k and l of CEWs are concentrated within the range of 0–6 (over 80% of N_{CEW}) and the most probable value is about 2–3 regardless of the season and direction; k is almost always positive and l tends toward being negative (positive) for NH-to-SH (SH-to-NH) waves. As a result, the $\gamma = l/k$ tends toward being negative (positive) for NH-to-SH (SH-to-NH) waves. This indicates that NH-to-SH (SH-to-NH) waves exhibit wavenumber vectors pointing to southeast (northeast) and have constant phase lines with the northeast–southwest (northwest–southeast) tilt. The results conform to the theoretical

analysis under horizontal uniform basic flow presented in L15 [see their Eqs. (24) and (25)]. The PDF peak of γ appears at a magnitude of 1–2 and is negative (positive) for CEW_{N2S} (CEW_{S2N}). The probabilities of other γ magnitudes are much lower than the peak value. Therefore, the wavenumber vectors of CEW_{N2S} and CEW_{S2N} tend to point southeast and northeast respectively with a most probable inclination angle of 45° – 63° away from the latitude. This result is also consistent with previous theoretical analysis [Eq. (23) in L15].

To further explore the dependence of CEWs on the wavenumber, Fig. 9 shows the seasonal mean N_{CEW} per unit wavenumber for three different wave bands: ultralong waves ($0 < k \leq 3$), long waves ($3 < k \leq 6$), and short waves ($6 < k \leq 40$). Similar to Fig. 7, the windows, such as the eastern Pacific, have the highest N_{CEW} , but the barrier sections have the lowest N_{CEW} for all the three wave bands in both seasons. However, it can be seen that the ultralong and long waves have higher N_{CEW} , but the short waves have much lower N_{CEW} , which means that CEWs are mainly dominated by the ultralong and long wave bands, and short waves are rarely able to cross the equator. By comparing with the windows and barriers measured by the total N_{CEW} (shading in Fig. 9), it can be seen that the Rossby waves with longer wavelength have wider (narrower) longitudinal windows (barriers) to cross the equator. For example, the equatorial section from Africa to the Indian Ocean (about 0° – 90° E) in DJFM can be seen as a window for ultralong CEWs, but fewer long waves and no short waves can cross through it. Although the eastern Pacific and Atlantic windows in DJFM are open for all the three wave bands, much lower N_{CEW} for short waves is found relative to the other two wave bands. In JJAS, this difference among the three wave bands is more noticeable. For example, N_{CEW} displays a maximum at the longitudes of 90° – 120° E (Asian–Australian summer monsoon region) for the ultralong waves, but relatively low values for the long waves and zero for the short waves. All of the three identified windows are dominated by ultralong and long waves, with few short waves.

FIG. 8. The probability distribution function (PDF; %) of zonal wavenumber k , meridional wavenumber l , and the wave inclination structure parameter $\gamma = l/k$ at the cross-equatorial points in (a)–(c) DJFM and (d)–(f) JJAS. The red and blue curves represent the NH-to-SH and SH-to-NH directions, respectively.

These differences among the different wave bands suggest that CEWs are dependent on the wave spectrum besides the basic state.

c. Spectral-selective filtering mechanism for different zonal wavenumbers

Since the basic state varies slowly with the latitude (Hoskins and Ambrizzi 1993), the zonal wavenumbers vary along the wave rays according to Eq. (8). Hence, N_{CEW} in different wave bands depends on the initial wavenumber to a large extent. Figure 10 shows the number of nontrapped wave rays (not terminated) after a short-term integration (8 h) for the initial zonal wavenumbers 1–12. The results show that the shorter waves are more likely to be trapped at the beginning. About 24%–30%, 10%–23%, and 5%–9% of waves can keep on propagating after 8 h both in DJFM and in JJAS for initial zonal 1–3, 4–6, and 7–12 waves, respectively. It could be a reason for the concentration of

CEWs on the longer waves (Fig. 8). In addition, regardless of whether in DJFM or JJAS, more waves are locally trapped in the SH than in the NH for most wavenumbers.

When a Rossby wave propagates away from the initial position, the meridional group velocity will gradually change due to the nonuniform basic flow during the propagation. Theoretically, when a wave can approach the equator, it may also be reflected meridionally at the position where the meridional group velocity decreases to zero due to the joint effects of local background flow ($\bar{v}_M$, $\bar{q}_x$, and $\bar{q}_y$) and local wave parameters (k , l , K) [see Eq. (7) with $d_g Y/dt = 0$]. If such reflection happens before a wave moves across the equator, the wave cannot be a CEW. Hence, the zero isoline of the meridional group velocity can be a line of reflection for the CEW. Therefore, we calculate the global distribution of the meridional group velocities [v_g or $d_g Y/dt$ by Eq. (7)] by setting the wave inclination parameter γ as -1 (1) for

FIG. 9. The (a) DJFM and (b) JJAS seasonal mean N_{CEW} per unit wavenumber (N_{CEW} divided by length of each wave band) for zonal ultralong waves (red; $0 < k \leq 3$), long waves (orange; $3 < k \leq 6$), and short waves (green; $6 < k \leq 40$). The purple, yellow, and dark yellow shading are as in Fig. 7.

the NH-to-SH (SH-to-NH) directional waves, which is the most probable value shown in Fig. 8. We use such a parameter to isolate the sensitivity of the equatorial filtering effect to k . In other words, we want to investigate whether the equator could filter out more short waves than long waves when they have the same favorable tilt structure. The zero isolines of the meridional group velocity (reflecting lines) for the zonal wavenumbers 1–12 in DJFM and JJAS are derived and shown in Fig. 11. We also checked the results with γ as 2 (–2) and the wavenumber being greater than 12. The results

show that the main features for γ as 2 (–2) are principally similar to those with $\gamma = 1$ (–1). Also, the distribution of the zero isoline for larger wavenumbers is very similar to that for wavenumber 12 (see Figs. S8 and S9).

Figure 11 shows that there are always zero isolines of the meridional group velocity around the equator, which tends to reflect the wave propagation across the equator. Furthermore, the blocking belts vary with the wavenumbers, which acts as a spectral-selective filtering mechanism for the CEW. The lines of reflection for the higher zonal wavenumbers tend to cover more longitudes

FIG. 10. Quantities of the wave rays that continue propagating after 8-h integration of the wave ray equation for different initial zonal wavenumbers.

FIG. 11. The zero meridional group velocity isoline ($v_g = 0$) located between the latitudes of 35°S and 35°N , corresponding to the zonal wavenumbers $k = 1, 4, 7$, and 12 in (a), (c) DJFM and (b), (d) JJAS for the cases of (a), (b) SH-to-NH and (c), (d) NH-to-SH propagation directions. The parameter γ is fixed at 1 for the SH-to-NH direction and -1 for the NH-to-SH direction, which are treated as the optimal values shown in Fig. 8.

than the lower zonal wavenumbers. In other words, the long waves have narrower blocking sections than the short waves, which agrees with the dominance of long waves discussed in section 4b. Specifically, in DJFM, the CEW_{N2S} and CEW_{S2N} are generally blocked in the Eastern Hemisphere. The equatorial central-eastern Pacific and Atlantic are unblocking sections for all wavenumbers, which contributes to the formation of the strong cross-equatorial windows over these regions. The equatorial western Pacific is the section where all zonal 1–12 waves are reflected away from the equator, and thus the cross-equatorial barrier is formed there. The locations of the blocking and unblocking sections in DJFM agree very well with the cross-equatorial barriers and windows identified from Fig. 7. In addition, the blocking area for wavenumber 12 in the South America for CEW_{S2N} has much smaller spatial extent than the one for CEW_{N2S} . Even the waves with wavenumber 7 will be reflected in this section for CEW_{N2S} . This characteristic will induce more N_{S2N} than N_{N2S} , as shown in Fig. 7.

In JJAS, the most significant feature is that the lines of reflection for $k = 12$ and 7 are almost global in their coverage, except for the split over the eastern Pacific for

$\gamma = -1$. This means that waves with lengths shorter than 6000 km are mostly blocked before they cross the equator, but may cross the equatorial eastern Pacific from the NH to SH. As for the Atlantic and Africa–Indian Ocean windows, zonal wavenumber-4 waves and longer waves are able to cross the equator. The western-middle equatorial Pacific is a strong blocking section for both the NH-to-SH and SH-to-NH propagation of most waves. Compared to the position in DJFM, it shifts eastward slightly, agreeing well with the barriers for CEWs identified from the Fig. 7. In addition, the dominance of CEW_{N2S} over the Asian–Australian summer monsoon region (Fig. 7) is due to a wider equatorial unblocking section for the long and ultralong waves. For example, the western boundary of the line of reflection for CEW_{N2S} (wavenumber 4) is 30° eastward relative to that for CEW_{S2N} .

d. Main global CEW ducts

To present a comprehensive picture of the CEW propagation, we next put forward the global passing CEW density distribution in an attempt to obtain the main ducts associated with each identified window. For a

FIG. 12. The passing CEW density distribution corresponding to the (a)–(c) eastern Pacific (170°–70°W) and (d)–(f) western Atlantic (70°–5°W) windows in DJFM for the distribution of the (left) total, (center) NH-to-SH, and (right) SH-to-NH ducts. The definition of passing CEW density is seen in the text. The blue curves for the NH-to-SH (SH-to-NH) ducts are the great circles that interact with the east and west boundary longitudes of each window at the equator with the angle of -45° (45°). The great circle curves are plotted between the latitudes of 45°S and 45°N .

specified window, the passing CEW density distribution at every grid is defined as a ratio in the form of

$$P_{ij}|_{\text{window}} = \frac{N_{ij}}{N_{\text{window}}}, \quad (10)$$

where N_{ij} is the number of rays passing both the grid and the longitudinal section of the window, and N_{window} is the total number of rays passing through this window. In this way, the passing CEW density distribution can provide us with general information on the ray trajectories associated with the window.

Figures 12 and 13 show the global passing CEW density distributions corresponding to the different windows in DJFM and JJAS respectively. In DJFM, two windows are identified (Fig. 7a): the eastern Pacific (170°–70°W) and the Atlantic Ocean (70°–5°W). For the eastern Pacific window in DJFM, the central density distribution has a significant eastward and poleward extension in both hemispheres (Fig. 12a). When we look at it for the two different directions, we can see that the main route of the CEW_{N2S} duct may be from the North Pacific and the western part of the North America to Drake Passage across the equatorial window (Fig. 12b) and the CEW_{S2N} duct may travel along a route from the

south to Australia, through the Pacific and Americas, to the northern Eurasian continent (Fig. 12c). For the Atlantic window, the density distribution seems to be more concentrated in specific regions than that associated with the Pacific window (Fig. 12d), as the Atlantic window is narrower than the eastern Pacific window (Figs. 7a and 11). The CEW_{N2S} duct is likely to move along the route from the North Pacific, via central North America and the Atlantic, to the southern Indian Ocean (Fig. 12e). The route of the CEW_{S2N} duct is possibly from the South Pacific, crossing South America and the South Atlantic, to northern Africa and South Asia (Fig. 12f). The abovementioned CEW_{N2S} ducts resemble the eastern equatorial Pacific and North America and Atlantic waveguides summarized in Fig. 14 in Hsu and Lin (1992), but the CEW_{S2N} ducts have rarely been mentioned in the literature. Additionally, the two directional ducts for each window can be observed in the correlation maps in section 3 with positive and negative centers along the corresponding routes (indicated by the thick black curves).

In JJAS, three windows—the Africa–Indian Ocean (15°–65°E), the eastern Pacific (135°–60°W), and the Atlantic Ocean (60°–5°W) windows—are identified (Fig. 7b). For the Pacific window, the density distribution

FIG. 13. As in Fig. 12, but for JJAS and the (a)–(c) Africa–Indian Ocean (15°–65°E), (d)–(f) eastern Pacific (135°–60°W), and (g)–(i) Atlantic (60°–5°W) windows.

has large values over the window and the SH middle latitudes (Fig. 13d) and is mainly contributed by NH-to-SH directional propagation (Fig. 13e). The contribution from the SH-to-NH directional propagation is relatively weaker. This asymmetry in the two directions also exists for the Atlantic window, and this is one of the main differences between the situations in DJFM and JJAS, the other being the occurrence of the African window in JJAS. Compared with the Pacific and Atlantic windows, the density distribution of the African window is mostly near the window longitudes (Fig. 13a). The contribution from the NH-to-SH directional propagation is far stronger than that from the SH-to-NH propagation (Figs. 13b,c), with the main ducts being from northern Africa and South Asia to the southern Indian Ocean and West Australia. This duct is related to the CEW train reported by Zhao et al. (2019), which transmits anomalies over the north Indian Ocean to the West Australia and induces anomalous rainfall there. Besides,

the discussed CEW trains in the reanalysis data shown in Fig. 4 and Fig. S7 are basically located in the range of correspondent wave ducts.

Generally, the main NH-to-SH ducts exhibit a northwest-to-southeast direction, and the main SH-to-NH ducts display a southwest-to-northeast direction. In tropical and subtropical areas, they seem to roughly follow the great circle-like ducts indicated as the blue curves in Figs. 12 and 13. However, the duct associated with the Africa window in JJAS does not match the great circle curves well. It may be more influenced by the strong cross-equatorial monsoonal flow, as discussed in L15. It should be noted that the meaning of great circle-like ducts here denotes the most probable routes of large wave ensembles, different from the meaning of single great circle routes in HK81. In the extratropical area, the propagation ducts tend to be more zonal owing to the waveguide effect of the westerly jet (Hsu and Lin 1992; Hoskins and Ambrizzi 1993; Souders et al. 2014; X. Li et al. 2015).

5. Conclusions

Previous studies have pointed out the importance of CEWs in global teleconnections. To identify the equatorial windows and barriers for CEWs, we develop the WRE method based on the wave ray tracing method under horizontally nonuniform basic flow. Relative to the wave ray tracing method, the WRE method can quantify the propagation properties of Rossby waves based on the statistics of a large ensemble of rays. Hence, we can obtain much more detail on CEWs than in previous studies. Using the WRE, this study presents the location, seasonality, and directionality of the CEW windows and barriers. The windows can be categorized into “westerly windows” and “cross-equatorial-flow windows” based on the background flow according to previous studies. We propose the spectral-selective filtering mechanism as a uniform dynamical mechanism for the two types of windows. Here, the spectral-selective filtering mechanism acts as a mutual selection between the background flow and the CEWs.

The eastern Pacific and Atlantic sections are revealed as common windows in both DJFM and JJAS, while the Africa–Indian Ocean section appears as a window in JJAS. The western–central Pacific section is found as a barrier in both seasons by blocking most of the waves. These findings from the WRE results are supported by lead–lag correlation analyses, which present clear wave trains through the window sections and few signals near the barrier sections (see Fig. S6). In addition, the windows of boreal winter have basically equal CEW numbers for the two directions, while the boreal summer windows are dominated by NH-to-SH CEWs. The directionality in boreal summer is consistent with the clearer wavelike correlations in the SH for NH base points (Fig. 4), while there are fewer correlations in the NH for SH base points (Fig. S7).

Furthermore, this work presents the wavenumber dependence of each window and barrier for CEWs, which has rarely been investigated in previous studies. CEWs are generally dominated by long waves with zonal wavenumbers less than 6, and tend to exhibit a northwest–southeast (southwest–northeast)-tilting wave vector when coming from the NH (SH) to the SH (NH). The most probable inclination angles are about 45° – 63° away from the latitude, regardless of the season and direction. Analyses on the zero isoline of the meridional group velocity indicate that shorter waves have wider equatorial barriers than longer waves. Therefore, it is more difficult for short waves to propagate to the opposite hemisphere. The strongest blocking section for Rossby waves is located over the western and central Pacific Ocean. The dependence of CEWs on the wave

FIG. 14. Schematic diagram for the main CEW ducts in (a) DJFM and (b) JJAS. The blue (red) arrows denote the NH-to-SH (SH-to-NH) propagation ducts shown in Figs. 12 and 13. The thick arrows indicate high N_{CEW} and thin arrows indicate low N_{CEW} . The equatorial windows and barriers are indicated by a transparent yellow belt around the equator. Darker yellow denotes stronger barrier sections, while transparency denotes windows.

scale is defined as the spectral-selective filtering mechanism near the equator. Essentially, it indicates that the westerly window and cross-equatorial-flow window have consistency.

This study also determines globally the main ducts associated with each identified window. Figure 14 shows this schematically for DJFM and JJAS. The NH-to-SH and SH-to-NH ducts tend to tilt in the northwest–southeast and southwest–northeast directions, respectively, as per the great circle–like ducts in the tropics, but become more zonal in their routes when approaching to the extratropical westerly zone. This implies that the interhemispheric Rossby waves act as an energy transfer mechanism between the NH and SH extratropical atmosphere. For example, the waves from the North Pacific in DJFM can cross the equatorial eastern Pacific and Atlantic to the westerly zone in the SH; the waves from the SH westerly zone can enter the NH westerly zone. These results provide novel insights into the underlying mechanisms for interhemispheric and tropical–extratropical teleconnections, and are helpful in our quest to understand the predictability of regional climate variability induced by the remote forcing in the opposite hemisphere.

However, there are several aspects in this work that should be noted. First is the background flow. Using different smoothing methods to generate the background flow may slightly change the WRE results shown here. Indeed, we tested the results under the flow smoothed by the section-averaged method used in Scaife et al. (2017). The windows and barriers were basically consistent, but with some changes in their strength and position (see Figs. S10–S12). The second aspect is the sensitivity of the WRE results to the height level. Since the wave ray calculation is closely dependent on the background flow, the WRE results would change significantly if they are examined at 500 hPa or other lower levels. The 850-hPa ray trajectories shown in L15 are generally opposite in the direction to those at the upper level due to the vertical overturning cell. Here, the WRE method is applied at 300 hPa, which has been used as an equivalent barotropic level in many related studies (e.g., HK81; Branstator 1983; Hoskins and Ambrizzi 1993; L15). Furthermore, verification of WRE results discussed in this work needs to be further explored. We investigated the correlation analysis on the 25–90-day-bandpass streamfunction to support the WRE results. Actually, we also checked the 90-day low-pass field and found more robust correlations between the two hemispheres, like the teleconnectivity analysis on the seasonal mean field shown in L15 and Zhao et al. (2015). However, the evolutions were hard to detect in this lower-frequency band, so the bandpass filter results are shown in this presentation. Last, we admit that the CEW trains in the correlation analysis usually become weak after they enter the opposite hemisphere, especially relative to the signals in the same hemisphere. However, we still cannot ignore their potential importance in the global teleconnection considering the findings in section 3. The CEW trains may modulate the direct tropical responses to the forcing, may interfere or join in the other wave trains, and may be amplified at the higher latitudes as predicted in HK81 theory. Therefore, more theoretical and diagnostic works on these aspects are encouraged.

Acknowledgments. J. Feng conceived the study and performed the analysis in section 4; Y. Li performed the other analysis; J. Feng and Y. Li wrote the drafts. The wave ray tracing codes were provided by Y. Li, J. Li, and S. Zhao. All of the authors contributed to improve the quality of this paper and are grateful for the insightful comments from the reviewers. The National Natural Science Foundation of China (Grants 41575060, 41705135, and 41790474) and the SOA International Cooperation Program on Global Change and Air–Sea Interactions

(GASI-IPOVAL-03) jointly supported this study. Portions of this study were supported by the Regional and Global Model Analysis (RGMA) component of the Earth and Environmental System Modeling Program of the U.S. Department of Energy's Office of Biological & Environmental Research (BER) via National Science Foundation IA 1844590.

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