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Evolution of Boreal-Summer Quasi-Stationary Rossby Waves on Daily Time Scales

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Abstract

Boreal-summer circulation exhibits prominent Rossby wave structures over the Northern Hemisphere midlatitudes. These waves can form recurrent circumglobal structures, organize summer circulation, and contribute to persistent and concurrent extreme weather. However, they are commonly identified in seasonal-mean or low-frequency fields, and their characteristics on daily time scales remain less clearly understood. In this study, we examine the characteristics of quasi-stationary Rossby waves (QSRWs) on daily time scales. We first identify dominant stationary Rossby wave patterns from seasonal-mean upper-tropospheric

meridional wind, then project daily-mean meridional wind anomalies onto these seasonally defined patterns to measure their day-to-day expression. The leading two patterns are dominated by zonal wavenumbers 6 and 5, respectively. Peak-centered composites show that both patterns remain coherent for about 1 week, with their anomaly centers near the same longitudes throughout the event period. Similar quasi-stationary behavior and persistence are evident in representative individual events. Although the longitudinal positions of the individual centers change little, the phase lines rotate systematically during the event. They are tilted from northwest to southeast before the peak, become nearly meridional around the peak, and tilt from northeast to southwest afterward. This rotation is associated with the poleward increase in phase speed, with the northern portion of each wave center moving relatively eastward and the southern portion moving relatively westward. These results show that the stationary patterns evident in seasonal-mean circulation recur in daily circulation as QSRW events with a distinct daily-to-subseasonal life cycle.

Keywords: Rossby Waves, Stationary Waves, Subseasonal Variability, Atmospheric Circulation

Introduction

Boreal-summer circulation exhibits prominent Rossby wave structures over the Northern Hemisphere midlatitudes. These waves are often identified in seasonal-mean or low-frequency fields as slowly varying planetary-scale patterns. Among them, zonal wavenumbers 5 to 8 (hereafter wave-5 to wave-8) have received particular attention because they can form recurrent circumglobal structures and contribute to the organization of summer circulation^{1,2}. When amplified and persistent, these large-scale structures can organize circulation anomalies over widely separated regions and provide favorable conditions for concurrent extreme weather. Understanding how these quasi-stationary structures are expressed and evolve on daily to subseasonal time scales is therefore important for linking planetary-scale circulation variability to persistent regional weather.

Previous studies have interpreted boreal-summer Rossby waves mainly from a quasi-stationary perspective. In this framework, high-amplitude planetary waves are regarded as slowly varying or phase-locked circulation anomalies. Quasi-resonant amplification has been suggested as a mechanism that can amplify slow-moving Rossby waves under favorable

waveguide conditions^{3,4}. Other studies have emphasized the recurrent structure and preferred phase positions of wave-5 and wave-7 patterns in summer circulation^{5,1}. Stationary Rossby waves have also been identified in monthly subseasonal variability⁶, while high-amplitude and phase-preferred waves have been examined using weekly mean or low-pass-filtered circulation fields^{7,8}. Subseasonal wave-5 variability has also been linked to the development of summer heat waves⁹, while idealized-model experiments have shown that topographic forcing can promote phase locking and reduce the zonal phase speed of amplified wave-5 and wave-6 events that persist for approximately one week¹⁰. These studies have established that specific zonal wave structures are robust features of boreal-summer circulation across a range of time scales.

However, a stationary Rossby wave pattern diagnosed from seasonal-mean fields does not necessarily imply that the same structure appears as a fixed pattern on individual days. Daily circulation contains both slowly varying components and transient Rossby wave activity. A seasonal-mean wave pattern may therefore reflect the recurrent projection of daily variability onto a preferred spatial structure. More generally, atmospheric persistence may arise either from the continuous maintenance of a coherent circulation anomaly or from repeated occurrences of shorter-lived disturbances with similar spatial configurations¹¹.

A complementary line of research has emphasized Rossby wave packets and recurrent wave activity. From this perspective, persistent large-scale circulation anomalies can arise from repeated amplification of transient Rossby wave packets in similar longitude sectors^{12,13}. This view highlights the evolution and recurrence of transient disturbances, whereas the stationary-wave perspective emphasizes the persistent spatial structure seen in seasonal-mean or low-frequency fields. This distinction has received renewed attention in analyses of the recurrent hemispheric wave-7 pattern during summer 2018. Riboldi and Russo¹⁴ argued that temporal filtering can cause transient Rossby waves to appear as a quasi-stationary circumglobal pattern, whereas Kornhuber et al.¹⁵ maintained that a persistent low-frequency wave-7 structure remains detectable and dynamically relevant despite superimposed transient wave activity. These studies highlight the need to examine how seasonally preferred stationary-wave patterns are realized in unfiltered daily circulation, while distinguishing persistence in their longitudinal phase from changes in their two-dimensional spatial structure.

In this study, we examine the characteristics of quasi-stationary Rossby waves (QSRWs) as they appear on daily time scales. The dominant stationary Rossby wave patterns are first defined from seasonal-mean upper-tropospheric meridional wind anomalies. Daily mean

meridional wind anomalies without temporal filtering are then projected onto these seasonally defined patterns to measure their day-to-day expression. Continuous QSRW events are detected from the resulting daily indices. This projection-based framework allows us to evaluate how stationary Rossby wave structures, which are prominent in seasonal-mean circulation, are represented in daily mean fields.

Using this approach, we characterize the form and behavior of QSRWs on daily to subseasonal time scales. We specifically examine whether seasonally defined stationary-wave patterns remain quasi-stationary in longitude when expressed in unfiltered daily circulation, and how their meridional structure evolves through individual event life cycles. This daily-scale perspective complements previous analyses based on seasonal means and temporally filtered circulation fields. We show that the dominant wave-6 and wave-5 patterns recur as coherent QSRW events lasting about one week. While their anomaly centers remain near preferred longitudes, their phase lines rotate systematically from northwest–southeast to nearly meridional and then northeast–southwest. This evolution is dynamically consistent with the meridional variation in Rossby-wave phase speed. These results reveal a repeatable daily-to-subseasonal evolution in which zonal quasi-stationarity coexists with systematic meridional structural change.

Results

Figure 1 shows the leading two EOF modes of boreal-summer stationary wave variability. EOF1 is dominated by wave-6, whereas EOF2 is dominated by wave-5. In contrast, EOF3 contains substantial contributions from both wave-5 and wave-7 (Supplementary Figure S2). We therefore focus on EOF1 and EOF2. These results indicate that wave-6 and wave-5 represent the two largest modes of seasonal stationary-wave variability in the present EOF analysis, with extrema located in specific longitude sectors.

The daily projection indices have e-folding decorrelation times of approximately 3–4 days (Supplementary Figure S3a). Using a five-day threshold criterion that exceeds this decorrelation timescale, the detected QSRW events have mean durations of about one week (Supplementary Figure S3b). Figure 2 shows the peak-centered temporal evolution of these events. For both modes, the wave-6 and wave-5 structures remain coherent for approximately one week, with the major anomaly centers remaining near their preferred longitudes around the event peak. Similar behavior is evident in the strongest individual event for each mode

(Supplementary Figure S4), indicating that the quasi-stationary structure is not solely a feature of the composite mean. Thus, the seasonally dominant stationary-wave patterns are repeatedly expressed as coherent QSRW events in unfiltered daily circulation.

Figure 3 shows the spatial evolution of the QSRW events around their peak. Both modes exhibit circumglobal geopotential height anomalies with alternating ridges and troughs across the Northern Hemisphere. The patterns are particularly pronounced over North America for EOF1 and over Eurasia for EOF2. This regional contrast may partly reflect the influence of the zonally asymmetric summertime mean flow, which can shape the spatial scales and geographical distribution of waveguide teleconnections¹⁶. Although the major anomaly centers remain at nearly fixed longitudes, the phase lines rotate systematically during the event life cycle. They are oriented from northwest to southeast before the peak, become nearly meridional around day 0, and rotate toward a northeast-southwest orientation afterward. Thus, the QSRWs remain quasi-stationary in longitude while undergoing a substantial evolution in their meridional structure.

The phase-line rotation can be expressed in terms of the meridional wavenumber l . For a plane wave with phase $\theta = kx + ly$, the slope of a constant-phase line is

$$\frac{dy}{dx} = -\frac{k}{l} \quad (2)$$

For a fixed positive zonal wavenumber k , the observed rotation therefore corresponds to a systematic change in l , passing through values near zero when the phase lines become nearly meridional. The accompanying amplitude change is also geometrically consistent with the barotropic vorticity relation,

$$\zeta' = -(k^2 + l^2)\psi' \quad (3)$$

For a given vorticity amplitude and fixed k , the streamfunction amplitude scales as $(k^2 + l^2)^{-1}$ and is therefore largest as $|l|$ approaches zero. The increase in wave amplitude toward the event peak and its subsequent decrease are thus consistent with the observed evolution of the phase-line orientation.

Figure 4 provides a spectral measure of this structural evolution. For both QSRW modes, the dominant meridional wavenumber decreases systematically through the event peak, approaching $l \approx 0$ around day 0 before changing sign afterward. The normalized meridional

spectral amplitude exceeds 0.4 for approximately 1 week, corresponding to the period when the QSRW structure is most coherent. The positive-to-negative transition of l is therefore robust during the active period and provides spectral support for the phase-line rotation shown in Figure 3.

Figure 5 provides a dynamical interpretation of this systematic rotation. Figure 5a shows the zonal-mean zonal wind, Rossby-wave phase speed, and the corresponding meridional frequency gradient. Under the barotropic Rossby wave dispersion relation,

$$\omega = k\bar{U} - \frac{k\beta_e}{k^2 + l^2}, \quad (4)$$

$$c_x = \frac{\omega}{k} = \bar{U} - \frac{\beta_e}{k^2 + l^2} \quad (5)$$

where $\bar{U}$ is the zonal-mean zonal wind and $\beta_e = \beta - \partial^2 \bar{U} / \partial y^2$ is the effective meridional gradient of absolute vorticity. The phase speed and its meridional gradient were evaluated at $l = 0$. Near the event peak, where $l \approx 0$, the diagnosed phase speed generally increases poleward across the active midlatitudes, becoming less westward or more eastward at higher latitudes (Figure 5a).

Figure 5b schematically illustrates how this meridional variation in phase speed can produce the observed phase-line rotation. Because the northern portion of the wave center has a larger zonal phase speed than the southern portion, it becomes progressively displaced eastward relative to the southern portion, rotating the phase lines from a northwest–southeast orientation through a nearly meridional orientation to a northeast–southwest orientation.

The phase-line rotation can also be expressed using the local wave phase $\theta(x, y, t)$, for which the meridional wavenumber and frequency are defined as

$$l = \frac{\partial \theta}{\partial y}, \quad \omega = -\frac{\partial \theta}{\partial t} \quad (6)$$

Taking the time derivative of l gives

$$\frac{\partial l}{\partial t} = \frac{\partial}{\partial y} \left(\frac{\partial \theta}{\partial t} \right) = -\frac{\partial \omega}{\partial y} \quad (7)$$

The meridional frequency gradient $\partial\omega/\partial y$ tends to be predominantly positive across the midlatitude waveguide (Figure 5a), indicating a systematic decrease in l with time. This is dynamically consistent with the phase-line rotation illustrated in Figure 5b.

In summary, the seasonally dominant wave-6 and wave-5 patterns are repeatedly expressed in daily circulation as QSRW events lasting approximately one week. Their zonal phase remains nearly fixed, while their meridional structure evolves systematically through the event life cycle. The phase lines rotate from a northwest–southeast orientation before the peak to a nearly meridional orientation near the peak and then to a northeast–southwest orientation afterward, with the wave amplitude reaching its maximum near the transition. These results connect the stationary patterns evident in seasonal-mean circulation to a repeatable daily-to-subseasonal life cycle.

Discussion

The results show that the dominant stationary Rossby wave patterns evident in boreal-summer seasonal-mean circulation have a coherent expression on daily time scales. The leading wave-6 and wave-5 patterns recur as QSRW events that persist for approximately one week in unfiltered daily circulation, and their circumglobal structures are evident in both the peak-centered composites and individual events. Unlike analyses based on monthly, weekly, or low-pass-filtered fields, the present approach identifies the continuous day-to-day expression and peak-centered evolution of seasonally defined stationary waves. More importantly, the QSRWs are not spatially stationary throughout their lifetime. Their zonal phase remains nearly fixed while their meridional structure evolves systematically through development, peak amplitude, and decay. This distinction provides a more complete view of what quasi-stationarity represents on daily to subseasonal time scales.

Interpreting these events requires distinguishing between quasi-stationarity and recurrence. Atmospheric persistence can result from the continuous maintenance of a circulation state or from repeated occurrences of similar states¹¹. In particular, recurrent Rossby wave patterns consist of successive transient wave packets that amplify in similar longitude sectors and repeatedly produce ridges and troughs over the same regions¹³. Temporally averaged circulation may therefore appear stationary even when the underlying wave packets propagate. This diagnostic issue was highlighted in the discussion of the early-summer 2018 wave-7 pattern. Kornhuber et al.⁵ identified a recurrent hemispheric wave-7 structure, whereas Riboldi

and Russo¹⁴ emphasized that temporal filtering can obscure the transient and incomplete character of the underlying wave packets. A subsequent reply argued that the recurrent low-frequency wave-7 structure remains relevant to the organization of the large-scale circulation¹⁵. The present analysis does not explicitly diagnose wave-packet envelopes or group propagation and therefore cannot quantify the contribution of recurrent transient wave packets to individual QSRW events. Nevertheless, the wave-6 and wave-5 anomaly centers persist at nearly the same longitudes on consecutive unfiltered daily mean maps, indicating that their quasi-stationary appearance cannot be attributed solely to multi-day temporal filtering. These results support the existence of coherent QSRW structures in daily circulation while allowing transient wave activity to contribute to their amplification. In this sense, the stationary-wave and wave-packet perspectives may represent distinct but potentially complementary aspects of boreal-summer Rossby wave behavior.

A distinct feature of the QSRW life cycle is the systematic rotation of the phase lines while their longitudinal positions remain nearly fixed. The phase lines rotate from a northwest–southeast orientation before the event peak to a northeast–southwest orientation afterward. Consistently, the dominant meridional wavenumber changes from positive to negative values, with the wave amplitude reaching its maximum as the meridional wavenumber approaches zero. This evolution is consistent with the poleward increase in zonal phase speed. The northern portion of each wave becomes progressively displaced eastward relative to the southern portion, producing the observed phase-line rotation. Thus, quasi-stationarity primarily refers to the zonal phase position of the waves and does not imply an invariant spatial structure. Instead, the evolving meridional structure reflects a consistent sequence of development, peak amplitude, and decay over approximately one week.

The simultaneous presence of QSRW anomaly centers across widely separated longitudes provides a large-scale circulation configuration that may organize persistent and concurrent extreme weather^{1,2}. However, this study does not directly examine surface temperature and precipitation extremes, and the results therefore do not establish a causal relationship between the detected QSRWs and particular extreme events. Further analysis is required to determine how individual QSRW nodes influence regional weather and whether their week-long persistence increases the probability of concurrent extremes.

An important remaining question is what initiates and maintains individual QSRW events. Model experiments suggest that stationary forcings, land–atmosphere interactions, and atmospheric waveguide structure can influence the amplitude, persistence, and preferred

longitude of quasi-stationary waves^{10,17,18}. Interactive soil moisture has also been shown to modify the summer circulation climatology and enhance circumglobal wave amplitudes over land¹⁹. However, the roles of these processes in initiating and maintaining individual boreal-summer QSRW events remain unclear. Identifying these sources and evaluating the predictability of QSRW onset, amplitude, and decay therefore remain important directions for future research²⁰. The present daily projection framework provides a basis for addressing these questions and for further examining the connection between QSRWs and concurrent extreme weather.

Methods

Reanalysis data

This study uses ERA5 reanalysis data²¹ to examine boreal-summer Rossby waves over the Northern Hemisphere. The original ERA5 fields are provided on a 0.25° latitude-longitude grid and are regridded to a 2.5° grid.

Seasonal stationary-wave patterns are derived from JJA-mean fields during 1940–2025, whereas daily fields during May–September 1991–2025 are used to examine their expression and evolution on daily time scales. The extended daily period is used to retain the full lead-lag window for events occurring near the beginning or end of the JJA season. Daily anomalies are calculated by removing the long-term daily climatology.

Detection of quasi-stationary Rossby wave events

The stationary Rossby wave patterns are defined from JJA seasonal-mean 250 hPa meridional wind during 1940–2025. For each year, the meridional wind is averaged over 20°–60°N to obtain a zonal profile. An empirical orthogonal function (EOF) analysis is then applied to these seasonal-mean zonal profiles. The first two EOF modes are retained as the dominant stationary-wave patterns and are subsequently used to identify their expression in daily circulation.

To quantify the daily expression of these seasonally defined patterns, we project unfiltered daily-mean 250 hPa meridional wind anomalies onto the EOF patterns during May to September 1991–2025. The daily fields are averaged over 20°–60°N using the same latitude band as in the EOF analysis. For each mode, the daily index is calculated as

$$I_m(t) = \frac{1}{\lambda_m} \sum_{\lambda} v'(\theta, t) EOF_m(\lambda) \quad (1)$$

where $v'(\theta, t)$ is the daily meridional wind anomaly, $EOF_m(\theta)$ is the EOF pattern for mode m , λ_m is the corresponding eigenvalue, and θ denotes longitude. This index represents the daily amplitude of the corresponding seasonally-defined stationary wave pattern after normalization by its EOF eigenvalue. The index is then standardized by its standard deviation over May–September 1991–2025. The JJA means of the daily projection indices closely reproduce the interannual variability of the original seasonal PCs over their common period of 1991–2025, with temporal correlations of 1.00 for both modes (Supplementary Figure S1).

Here, a QSRW event is operationally defined as a period during which the absolute value of the standardized daily projection index exceeds one standard deviation for at least five consecutive days. The five-day persistence criterion is chosen to identify signals that persist beyond the approximately 4-day e-folding decorrelation time of the daily indices (Supplementary Figure S3a). Positive and negative phase QSRW events are both retained, because they represent opposite phases of the same stationary wave pattern. For each event, the day with the largest absolute projection index is defined as the event peak (day 0), and the absolute value of the index on that day is defined as the event intensity.

Composite analysis is performed relative to the peak date. Daily wind and geopotential height anomalies are composited using lead and lag days centered on day 0. Negative-phase QSRW events are sign-reversed before compositing so that the two phases are represented with a common polarity. The resulting composites are used to characterize the daily structure and evolution of QSRW events.

Diagnosis of meridional wavenumber evolution

The evolution of the meridional wave structure is diagnosed from the peak-centered QSRW composites using a two-step Fourier analysis. For each EOF mode and lag day, the composited 250-hPa geopotential height anomaly is first decomposed in longitude, and only the dominant zonal wavenumber associated with each EOF pattern is retained, with $k = 6$ for EOF1 and $k = 5$ for EOF2. The resulting complex Fourier coefficient is multiplied by a Hann taper and a square-root cosine-latitude weight before a second Fourier transform is applied in latitude over 20°–60°N. The meridional spectral power is defined as the squared amplitude of the resulting latitude Fourier spectrum.

For each lag day, the dominant meridional wavenumber l is defined as the wavenumber with the maximum meridional spectral power. The fractional contribution of each l is calculated relative to the total meridional spectral power. A normalized meridional spectral amplitude is also calculated to identify periods during which the retained zonal-wave component is sufficiently strong. The diagnosed dominant l is highlighted when the normalized amplitude exceeds 0.4. The evolution of l provides a spectral measure of the phase-line rotation seen in the horizontal QSRW structure.

Data Availability

ERA5 reanalysis data used in this study are publicly available through the Copernicus Climate Data Store (CDS).

Code availability

The analysis code used to support the findings of this study is available from the corresponding author upon reasonable request.

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Author contributions

N.C. performed the analyses and wrote the original draft. M.-I.L. supervised the study and contributed to the interpretation of the results. E.S. contributed to study coordination. F.L. also contributed to the interpretation of the results. M.-I.L., E.S., and F.L. reviewed and edited the manuscript. S.T. and S.L. contributed to discussions of the results and reviewed the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Figures

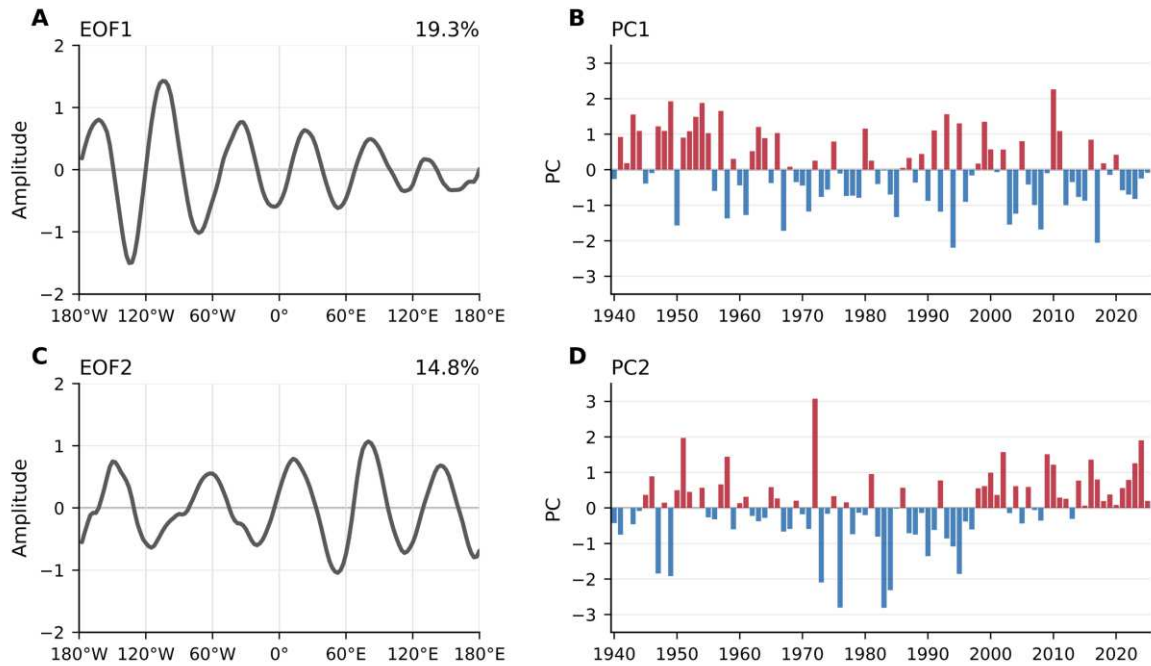


Figure 1. Leading EOF modes of boreal-summer stationary Rossby wave variability. (a, c) EOF1 and EOF2 patterns of JJA seasonal-mean 250-hPa meridional wind averaged over 20°–60°N during 1940–2025 (units: m s^{-1}). Values in the upper-right corners indicate the fractions of variance accounted for by each mode. (b, d) Corresponding normalized principal component (PC) time series.

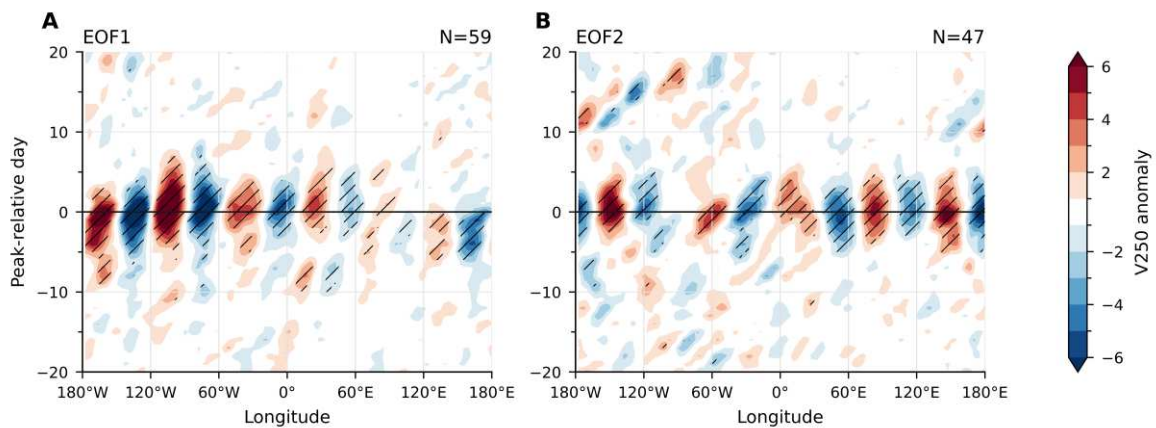


Figure 2. Peak-centered evolution of QSRW meridional wind anomalies. Hovmöller diagrams of composited 250-hPa meridional wind anomalies averaged over 20°–60°N for QSRW events associated with (a) EOF1 and (b) EOF2 (units: m s^{-1}). Negative-phase events are sign-reversed before compositing so that both phases are represented with a common polarity. Day 0 denotes the event peak, and composites are shown from day -20 to day +20. Hatching indicates anomalies significant at the 95% confidence level based on a Student's t-test.

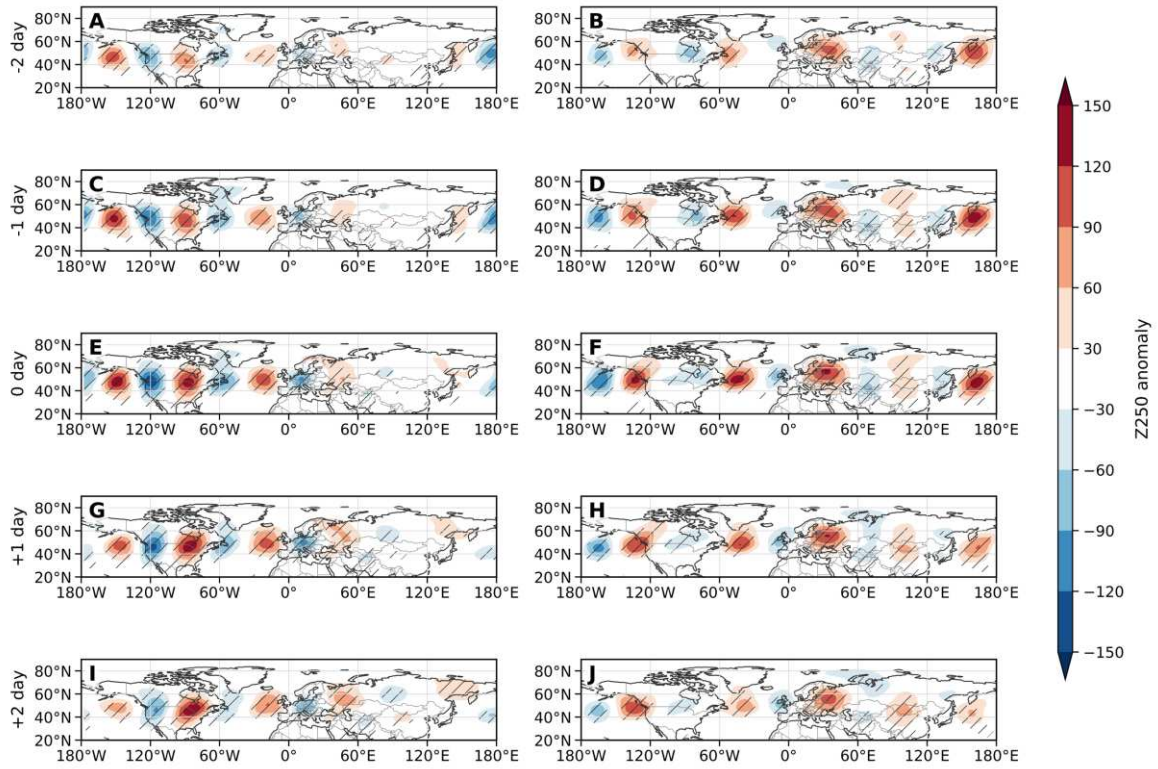


Figure 3. Spatial evolution of QSRW geopotential height anomalies. Composed 250-hPa geopotential height anomalies for QSRW events associated with EOF1 (left column) and EOF2 (right column) (units: m). Rows show days -2, -1, 0, +1, and +2 relative to the event peak. Hatching indicates anomalies significant at the 95% confidence level based on a Student's t-test.

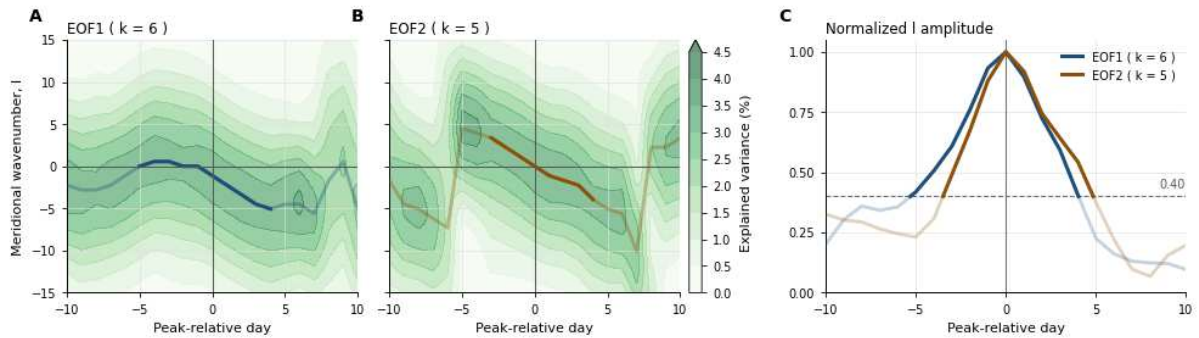


Figure 4. Evolution of the meridional wavenumber during QSRW events. (a, b) Fractional meridional spectral power as a function of meridional wavenumber l and lag day for (a) EOF1 and (b) EOF2 (units: %). Solid lines indicate the dominant l with maximum spectral power at each lag day, and thick segments indicate days when the normalized meridional spectral amplitude in (c) exceeds 0.4. (c) Normalized meridional spectral amplitude for EOF1 and EOF2.

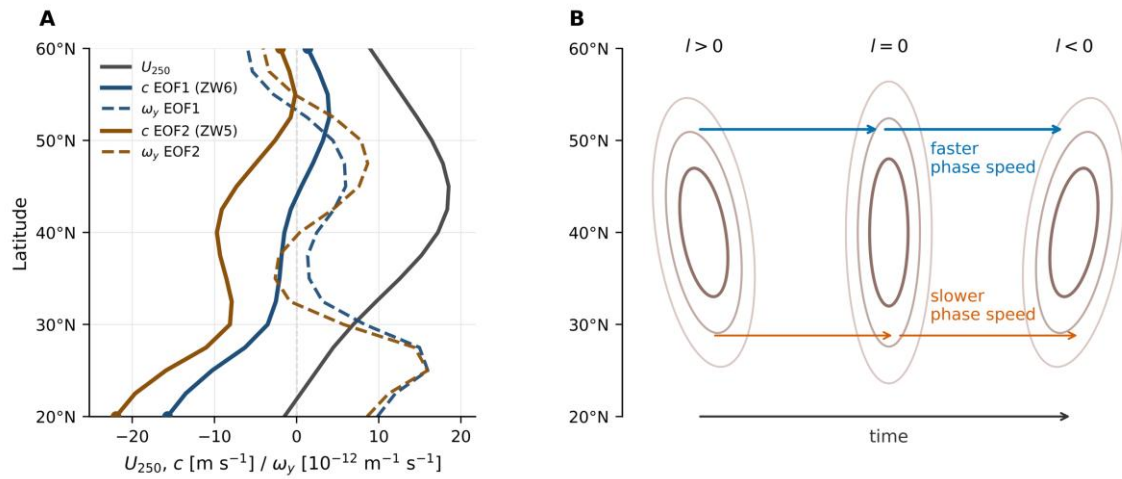


Figure 5. Background flow and schematic of QSRW phase-line rotation. (a) Zonal-mean 250-hPa zonal wind (gray), Rossby-wave zonal phase speed (solid lines), and the corresponding meridional frequency gradient (dashed lines) for EOF1 and EOF2. (b) Schematic diagram illustrating the phase-line rotation resulting from the poleward increase in zonal phase speed. The northern portion of the wave becomes progressively displaced eastward relative to the southern portion. The arrows illustrate relative zonal displacement through time rather than the absolute direction of wave propagation.

Supplementary Files

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