

Key Points:

- The Tibetan Plateau 20–30-day oscillation intensified during 1995–2005, significantly shaping regional dipole precipitation patterns
- An eastward-displaced positive SNAO facilitated downstream Rossby wave propagation along the Eurasian waveguide, driving the decadal surge
- SNAO-induced baroclinic energy conversion provides critical upper-level energy, preserving the oscillation's vertical coherence

Supporting Information:

Supporting Information may be found in the online version of this article.

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Decadal Surge in Tibetan Plateau 20–30-Day Oscillation Intensity (1995–2005) Linked to Summer NAO Structure and Baroclinic Energy Conversion

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Abstract The 20–30-day intraseasonal oscillation (ISO) over the Tibetan Plateau (TP) significantly modulates summer precipitation, accounting for over 10% of regional rainfall variability. This study identifies a decadal intensification of the summer 20–30-day ISO during 1995–2005 and examines its multidecadal covariation with the summer North Atlantic Oscillation (SNAO). The intensification coincides with a positive phase and eastward-displaced SNAO, which facilitates enhanced Rossby wave propagation toward the central and eastern TP along the Eurasian waveguide. Rather than directly forcing intraseasonal variability, the SNAO modulates the local dynamical environment and vertical motion, thereby regulating the growth of the TP ISO. Energetic diagnostics reveal that baroclinic energy conversion plays a central role in sustaining the oscillation. Crucially, the SNAO-induced forcing provides compensatory energy in the upper troposphere, preserving the vertical coherence and deep-tropospheric structure of the ISO. These findings indicate that the decadal surge arises from frequency-selective energy allocation and optimized growth conditions, highlighting the critical role of teleconnection morphology in shaping the TP hydroclimate.

Plain Language Summary The Tibetan Plateau (TP), often called the “Third Pole,” experiences rhythmic atmospheric patterns known as intraseasonal oscillations, which influence both local and downstream rainfall. While most studies have focused on the 10–20-day cycle, our research highlights a notable strengthening of the TP’s 20–30-day cycle during 1995–2005. We find that this decadal surge is closely associated with a large-scale climate pattern over the North Atlantic, known as the summer North Atlantic Oscillation (SNAO). During this period, the SNAO frequently stays in a positive phase and shifts eastward, altering atmospheric circulation across Eurasia. Rather than directly generating or transporting these oscillations, the SNAO creates a background environment that allows the 20–30-day cycle to intensify and persist. Specifically, atmospheric energy processes become more efficient at sustaining this oscillation during the surge period. These findings deepen our understanding of how distant climate patterns influence the TP and may help improve predictions of regional subseasonal climate variability.

1. Introduction

As a ubiquitous feature of the global atmosphere, intraseasonal oscillation (ISO) is a primary source of predictability on subseasonal-to-seasonal (S2S) timescales (Chen et al., 2001; Kikuchi & Wang, 2009; Xiang et al., 2024). Since its discovery, ISO research has extended to the subtropics and extratropics (Ren et al., 2022; Stan et al., 2017; Yang et al., 2024; Zhu et al., 2024). Substantial evidence suggests that ISO exerts pronounced impacts on regional climate variability, including anomalies in precipitation, atmospheric circulation, and extreme weather events (Chen et al., 2025; Xiu et al., 2025; Zhou et al., 2025).

The Tibetan Plateau (TP) is a critical region of mid-latitude ISO activity, with dominant periodicities at 10–20, 20–30, and 30–60 days (Wang & Duan, 2015; Yang et al., 2010). The 10–20-day (quasi-biweekly) oscillation is the most energetic and has been extensively studied due to its profound influence on TP precipitation and

downstream extremes (Li et al., 2018; Wang & Duan, 2015; Wang, Wang, et al., 2019; Zhang et al., 2024; Zhu et al., 2025). In contrast, the 30–60-day ISO exhibits pronounced interannual variability and is often investigated through specific case studies (Sun & Chen, 1994; Wang et al., 2009). Despite these advances, the 20–30-day oscillation remains comparatively understudied. Emerging evidence suggests that this mode is dynamically distinct from the 10–20-day oscillation, featuring different multi-scale variability and climate impacts (Zhu et al., 2025).

The variability of the TP ISO arises from complex interactions among tropical forcing, extratropical circulation, and local feedbacks. From the tropical perspective, northward-propagating convection plays an important role; for instance, the 10–20-day ISO often originates over the equatorial western Pacific and propagates northwestward toward the Bay of Bengal and northern India before influencing the southeastern TP (Wang & Duan, 2015; Yang et al., 2017). Simultaneously, extratropical dynamics play a central role in shaping the large-scale background environment for TP ISO. Variations in the subtropical westerly jet and Eurasian Rossby wave trains—often originating from the North Atlantic sector—regulate energy conversion within TP submonthly atmospheric disturbances (Fujinami & Yasunari, 2004, 2009; Hu et al., 2016; Wang et al., 2018). In addition, local diabatic heating (Q_1) anomalies and background land-atmosphere properties further modulate the ISO's amplitude and phase (Murakami, 1981; Wu et al., 2015), effectively distinguishing TP ISO from purely tropical modes.

Within this dynamical context, recent studies have increasingly emphasized the significance of ISO intensity (hereafter ISOI). The 10–20-day ISOI has been shown to exert a robust influence on hydrological extremes over the Yangtze River Basin (Tian et al., 2023; Yu et al., 2018). More recently, Zhu et al. (2025) reported a significant long-term weakening of both the 10–20-day and 20–30-day ISOI over the TP, with the 20–30-day ISOI exhibiting more pronounced multidecadal variability. Moreover, their associated precipitation patterns differ markedly: the 10–20-day ISOI is primarily linked to southern TP precipitation, whereas the 20–30-day ISOI corresponds to a meridional dipole structure across the TP. These contrasts underscore that the 20–30-day oscillation possesses distinct dynamics and modulation mechanisms, particularly on multidecadal timescales, which motivates a more focused investigation.

Accordingly, this study aims to investigate the decadal variability of the 20–30-day ISOI in the TP summer atmospheric heat source (Q_1) during 1979–2020. By identifying potential modulators across diverse climate regimes, we seek to link large-scale circulation anomalies with localized intraseasonal signals. Furthermore, we examine the associated physical pathways and energetic mechanisms (e.g., baroclinic energy conversion) governing ISOI fluctuations. These findings provide new insights into the decadal non-stationarity of the TP intra-seasonal variability and offer a theoretical basis for improving S2S predictions.

2. Data and Methods

2.1. Data

This study utilizes the CN05.1 daily precipitation data set ($0.25^\circ \times 0.25^\circ$) based on observational stations across China (Wu & Gao, 2013). Atmospheric circulation fields, including geopotential height, winds, temperature, and sea level pressure (SLP), are obtained from the JRA-55 Reanalysis (Kobayashi, 2015) at a horizontal resolution of $1.25^\circ \times 1.25^\circ$. The monthly North Atlantic Oscillation (NAO) index is obtained from the NOAA Climate Prediction Center (CPC). To account for the seasonality of the NAO, the CPC index is derived using a Rotated Principal Component Analysis (RPCA) based on monthly loading patterns (Barnston & Livezey, 1987), which allows for a distinct representation of the summer mode (SNAO). The monthly index is averaged over June–August (JJA) to represent the summer variability. To further ensure robustness, we cross-validated the CPC index with an alternative SNAO index calculated following Dunstone et al. (2023), yielding a high correlation of 0.88 for the period 1979–2020 (Figure S1 in Supporting Information S1). All key results were reproduced using the alternative index, yielding consistent conclusions, indicating that the results are not sensitive to the choice of SNAO definition. The analysis focuses on the boreal summer (JJA) during the period of 1979–2020.

2.2. Methods

The vertically integrated atmospheric apparent heat source ($\langle Q_1 \rangle$) over the troposphere (from surface to 100 hPa) is derived from JRA-55 reanalysis using the residual budget method (Yanai, 1961; Yanai et al., 1973). The reliability of JRA-55-derived $\langle Q_1 \rangle$ over the TP has been extensively validated across multiple timescales in

previous studies (Wang, Wang, et al., 2019; Wang, Guo, & Zhong, 2019; Zhu et al., 2025), showing strong alignment with station observations and satellite-based products. To extract the intraseasonal component, the climatological annual cycle is first removed from the raw daily data, followed by a 5-day running mean to suppress high-frequency noise, consistent with established procedures (Lee et al., 2013; Yang et al., 2014). The resulting anomalies are analyzed using wavelet techniques to identify dominant periodicities, and a Lanczos band-pass filter is then employed to isolate signals within specific frequency bands.

To trace the source regions and propagation pathways of Rossby wave trains, the horizontal wave activity flux (WAF) is calculated following Takaya and Nakamura (2001):

$$W = \frac{P \cos \phi}{2|U|} \left[\frac{U}{a^2 \cos^2 \phi} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \lambda^2} \right] + \frac{V}{a^2 \cos^2 \phi} \left[\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right] \right] + \frac{U}{a^2 \cos \phi} \left[\frac{\partial \psi'}{\partial \lambda} \frac{\partial \psi'}{\partial \phi} - \psi' \frac{\partial^2 \psi'}{\partial \lambda \partial \phi} \right] + \frac{V}{a^2} \left[\left(\frac{\partial \psi'}{\partial \lambda} \right)^2 - \psi' \frac{\partial^2 \psi'}{\partial \phi^2} \right] \quad (1)$$

where $|U| = (u, v)$ represents the basic-state horizontal flow, ψ' denotes the perturbation stream function, a is the Earth's radius, and P is pressure normalized by 1,000 hPa. Here, ϕ and λ indicate latitude and longitude, respectively.

To quantify the physical mechanisms governing ISOI fluctuations, we diagnose the barotropic kinetic energy conversion (CK) and baroclinic available potential energy conversion (CP) (Du & Lu, 2021; Kosaka et al., 2009; Kosaka & Nakamura, 2006):

$$CK = \frac{v'^2 - u'^2}{2} \left(\frac{\partial \bar{u}}{\partial x} - \frac{\partial \bar{v}}{\partial y} \right) - u' v' \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) \quad (2)$$

$$CP = -\frac{f}{S} \left(v' T' \frac{\partial \bar{u}}{\partial p} - u' T' \frac{\partial \bar{v}}{\partial p} \right) \quad (3)$$

$$S = \frac{R \bar{T}}{C_p P} - \frac{\partial \bar{T}}{\partial p} \quad (4)$$

where overbars and primes denote the summer mean state and the 20–30-day filtered components, respectively. Variables u , v , T and P denote zonal wind, meridional wind, temperature, and pressure, respectively; f is the Coriolis parameter, S is the static stability, C_p is the specific heat at constant pressure, and R is the gas constant of dry air. Positive values of CK (CP) indicate a transfer of kinetic (available potential) energy from the mean flow to the intraseasonal disturbances through barotropic (baroclinic) processes, whereas negative values represent energy loss. The two terms on the right-hand side of Equation 3 are referred to as CP_1 and CP_2 , representing the contributions from vertical shear of zonal and meridional winds, respectively. The CP and CK terms are calculated at each grid point and subsequently averaged over the TP region.

3. Results

3.1. Variations of TP 20–30-day Oscillation Intensity

The first leading empirical orthogonal function (EOF1) mode of the intraseasonal $\langle Q_1 \rangle$ component over the TP during summer (1979–2020) exhibits a prominent south-north dipole pattern centered over the southern TP (Figure 1a). Similar spatial structures are captured in the EOF1 modes of the band-pass-filtered 10–20-day and 20–30-day components (Figures S2a and S2b in Supporting Information S1), indicating a consistent regional projection center across different intraseasonal timescales. This visual similarity is primarily because the southern TP constitutes the most prominent climatological center for summer atmospheric heating and convective activity, onto which distinct subseasonal perturbations naturally project.

The mean power spectrum of the corresponding principal component (PC1) is presented in Figure 1b, showing a dominant peak in the 10–20-day period alongside a secondary but distinct peak in the 20–30-day band. In terms of local magnitude, the 10–20-day mode dominates the local daily variability, accounting for approximately

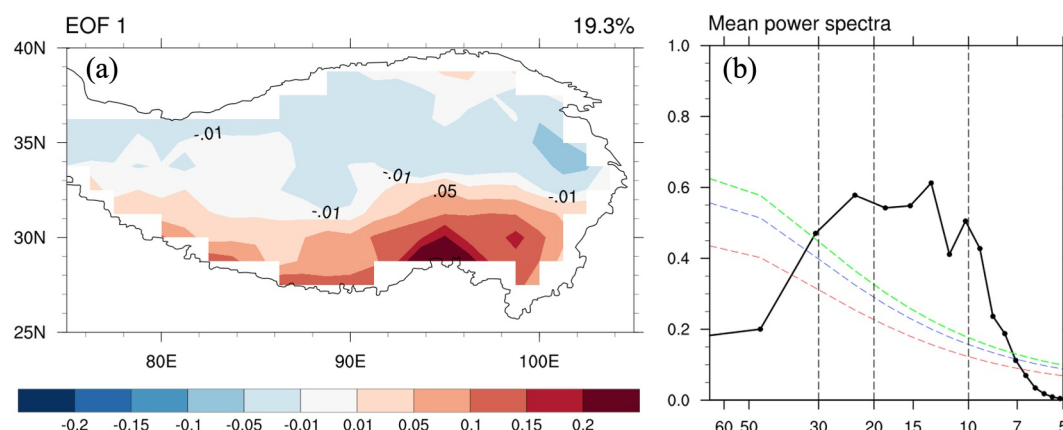


Figure 1. (a) Spatial pattern of the first leading EOF mode (EOF1) for the intraseasonal $\langle Q_1 \rangle$ component over the TP during the boreal summer for the period 1979–2020. (b) Mean power spectra of the corresponding first principal component (PC1). The red dashed line represents the Markov red noise spectrum, while the blue and green dashed lines indicate the 99% prior and posterior confidence levels, respectively.

30%–60% of the total subseasonal variance across the TP (Figure S2d in Supporting Information S1), whereas the 20–30-day component contributes a smaller portion of around 10% (Figure 2c). In terms of their leading empirical modes, the explained variance of EOF1 for the 20–30-day filtered field is 20.9%, which is highly comparable to the 18.7% explained by the 10–20-day filtered field (Figures S2a and S2b in Supporting Information S1). This comparable leading-mode performance indicates that both oscillations are systematic, large-scale coherent modes over the plateau, matching each other in structural importance despite their discrepancy in total variance.

Crucially, despite sharing overlapping static footprints over the TP, they represent fundamentally distinct dynamical regimes governed by different tropical source regions and life-cycle tracks (Figures S3 and S4 in Supporting Information S1). The 10–20-day QBWO typically originates over the tropical western North Pacific and propagates northwestward via northern India (Figure S3 in Supporting Information S1), whereas the 20–30-day ISO stems from the equatorial western Indian Ocean and propagates northward across the Arabian Sea and the Bay of Bengal (Figure S4 in Supporting Information S1). This distinct divergence in upstream pathways establishes their independent physical nature, providing a rigorous basis for isolated investigations into the unique decadal evolution of the 20–30-day mode (Figures 2a and 2b).

Figure 2a shows the wavelet analysis of the PC1 of the intraseasonal $\langle Q_1 \rangle$ component. Both the 10–20-day and 20–30-day oscillations exhibit persistent and statistically significant power throughout much of the study period, whereas the 30–60-day variability appears more intermittently, consistent with previous findings (Wang & Duan, 2015). Notably, the relative dominance of 10–20-day and 20–30-day bands varies over time: the 10–20-day activity is more robust during the late 1980s, whereas the 20–30-day band shows a marked enhancement during 1995–2005. Furthermore, a broader multidecadal shift is evident, characterized by a widespread attenuation of ISO signals across all frequency bands following 2005, with a gradual recovery emerging in the subsequent decade.

To quantitatively assess the decadal evolution of the ISO signals, ISOI is defined as the summer variance of the bandpass-filtered PC1 of the $\langle Q_1 \rangle$ over the TP. This definition is applied to both the 10–20-day and 20–30-day bands to facilitate a direct comparison of their temporal evolution. The 10–20-day ISOI (Figure S5 in Supporting Information S1) is characterized by a long-term weakening trend alongside strong interannual fluctuations, whereas the 20–30-day ISOI undergoes a more pronounced interdecadal transition (Figure 2b). Specifically, the 20–30-day mode exhibits a relatively neutral decadal phase with mixed signals prior to 1995 (Period I), followed by an anomalous decadal surge during 1995–2005 (Period II), and a subsequent prolonged quiescent phase after 2005 (Period III). This divergent behavior, especially the surge during Period II, highlights the unique role of the 20–30-day oscillation in recent decadal shifts of TP atmospheric heating.

Further, we formally verify the statistical robustness of this decadal surge during Period II, given that the 20–30-day mode accounts for only $\sim 10\%$ of the total daily variability. A two-sample t -test and an F -test were performed,

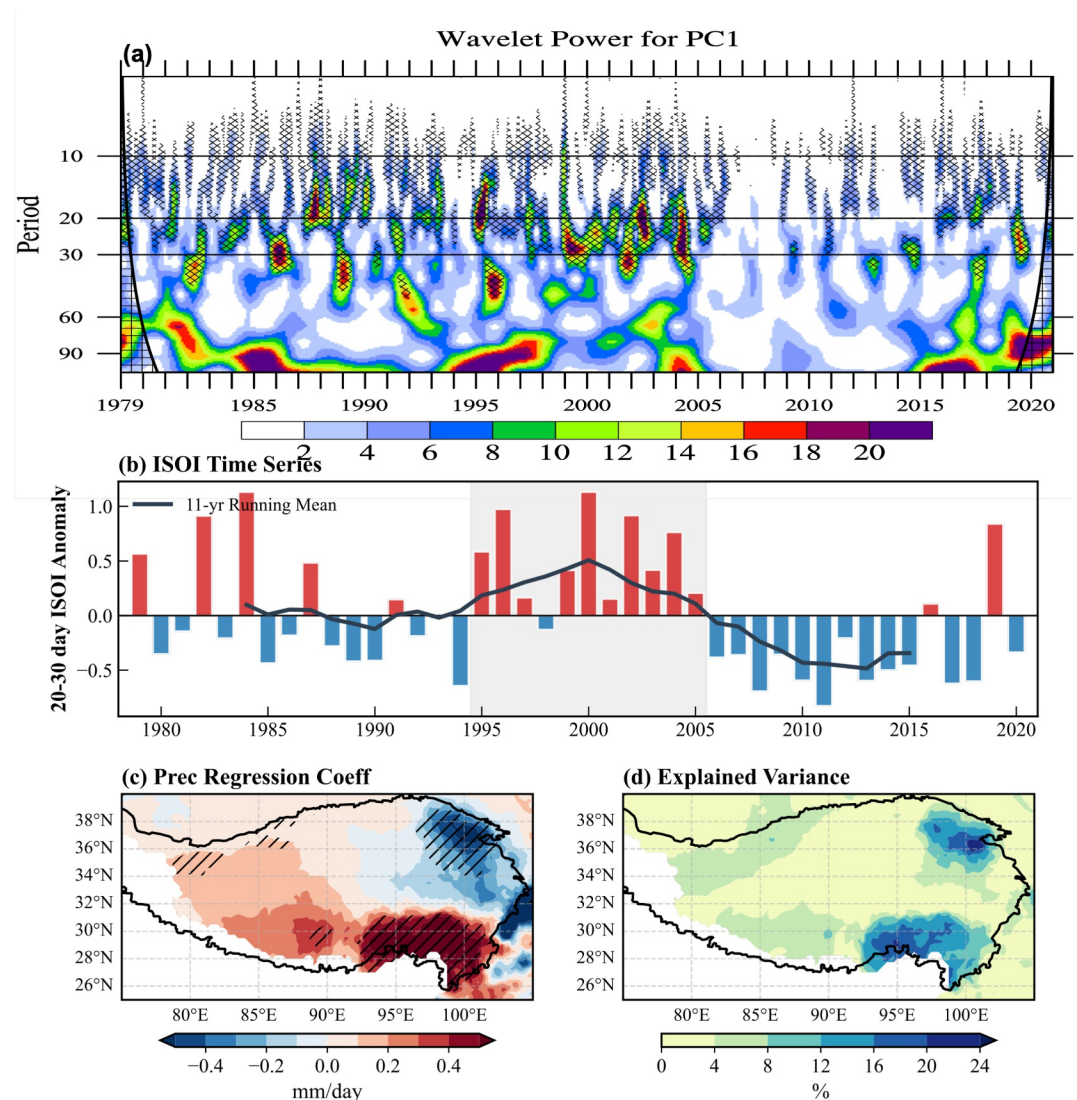


Figure 2. (a) Wavelet power spectrum of the PC1 of TP $\langle Q_1 \rangle$ during 1979–2020. Hatched areas indicate significance above the 95% confidence level. (b) Time series of 20–30-day ISOI anomalies (bars) and its 11-year running mean (black curve). (c) Spatial distribution of summer precipitation anomalies regressed onto the 20–30-day ISOI index. Hatched areas denote significance at the 90% confidence level. (d) Variance fraction of summer precipitation explained by the 20–30-day ISOI index, calculated as the ratio of the regressed precipitation variance to total summer precipitation variance.

comparing the ISOI intensity during the surge decade (1995–2005, $N_1 = 11$) against the background period (1979–1994 and 2006–2020, $N_2 = 31$). The mean intensity during 1995–2005 (1.46) is substantially higher than the background average (0.83), and the t -test confirms this decadal step-change is significant at the 99.9% confidence level ($t = 3.86$, $p = 0.0004$). Concurrently, the F -test shows no significant variance discrepancy between the two periods (variance of 0.15 vs. 0.25, $p = 0.40$). This equality of variances indicates that the 1995–2005 surge represents a sustained, stable elevated state rather than a transient anomaly skewed by isolated extreme years, confirming a robust climatological shift.

The climatic significance of the 20–30-day ISOI is further illustrated in Figure 2c, which shows the regression of summer precipitation anomalies onto the ISOI. A prominent meridional dipole pattern emerges, characterized by significant positive anomalies over the southern and western TP and negative anomalies across the northeastern region. This pattern indicates that an enhanced 20–30-day oscillation is associated with a “south-wet, north-dry” precipitation configuration. Notably, while both 10–20-day and 20–30-day modes naturally influence the southern TP due to the dominant summer monsoon water vapor transport, their configurations over the northern

TP distinctly diverge, as the 10–20-day anomalies there are fragmented and statistically non-significant. This dipole for the 20–30-day mode is dynamically supported by an ISO-related meridional circulation cell, which enhances moisture transport from the Arabian Sea to the southern TP and promotes local ascending motion, while concurrently inducing relative subsidence over the northern TP (Zhu et al., 2025). The contribution of this oscillation to regional precipitation variability is quantified in Figure 2d, where the ratio of the 20–30-day regressed precipitation variance to the total summer precipitation variance exceeds 10% over large areas of the TP, reaching over 20% in key regions. These results indicate that the 20–30-day oscillation represents a physically meaningful mode with important hydrological impacts. Accordingly, the remainder of this study focuses on unraveling the physical mechanisms underlying its pronounced intensification of the 20–30-day ISOI during Period II (1995–2005).

3.2. NAO Modulation of the 1995–2005 TP-ISOI Surge

Correlation analysis (Figure 3a) reveals a positive relationship between the TP 20–30-day ISOI and the concurrent SNAO index during Period II ($r = 0.54$, $p = 0.084$), which exhibits marginal statistical significance due to the restricted degrees of freedom. To evaluate the robustness of this coupling more rigorously without relying on asymptotic normality assumptions, we further employ a non-parametric Phase Randomization Test with 10,000 independent Monte Carlo replications. This approach constructs an empirical null distribution by randomizing the Fourier phase alignment while strictly preserving the intrinsic power spectra and autocorrelation structures of both time series (Ebisuzaki, 1997). The resulting non-parametric two-tailed p -value is 0.044 ($p < 0.05$), which successfully passes the conventional 95% confidence threshold. This independent non-parametric verification confirms that the coupled covariation between the SNAO and the TP 20–30-day ISOI during this decade is statistically meaningful and highly unlikely to be a byproduct of random noise or serial persistence.

In contrast, the correlation coefficients during Period I and III are both negative and statistically non-significant (Figure 3a). To isolate the intrinsic connection with the SNAO, partial correlation analyses were conducted by controlling for other major climate modes, including the Pacific Decadal Oscillation (PDO) and the El Niño–Southern Oscillation (ENSO). The ISOI–SNAO correlation remains remarkably stable, exhibiting slight increases to 0.57 (PDO removed) and 0.55 (ENSO removed). These statistical exclusions successfully rule out a tropical or Pacific origin for the decadal surge, underscoring the dominant and independent role of North Atlantic atmospheric forcing during Period II.

Meanwhile, the SNAO index similarly exhibits a pronounced decadal transition (Figure 3a). During 1979–2006, the SNAO remains predominantly in a positive phase, with only five years of negative anomalies, whereas 2007–2020 is characterized by a nearly continuous negative phase, interrupted by only three positive years. This phase reversal aligns remarkably well—within a margin of just one year—with the abrupt weakening of the TP 20–30-day ISOI after 2005. From a statistical perspective, the decadal surge during 1995–2005 can be partly interpreted as the cumulative effect of interannual variability. Given the significant positive correlation between the SNAO and the 20–30-day ISOI during this period, the prevalence of positive SNAO conditions leads to more frequent positive ISOI anomalies, thereby elevating the decadal-mean intensity of the oscillation.

However, the SNAO phase alone cannot fully explain the observed decadal surge of the TP 20–30-day ISOI. Although the SNAO remains predominantly in a positive phase during both Period I and II, the 20–30-day ISOI is significantly enhanced only in Period II. This disparity suggests that a positive SNAO phase is a necessary but insufficient condition for ISOI intensification. We therefore hypothesize that the downstream impact of the SNAO depends not only on its phase and amplitude but also on its spatial configuration.

To test this hypothesis, summer SLP anomalies are regressed onto the SNAO index for the three distinct periods (Figures 3b–3d). The regression patterns reveal pronounced interdecadal shifts in the spatial structure of the SNAO. During Period III, SLP anomalies exhibit a zonally elongated pattern that is displaced westward and southward. In Period I, the SNAO is characterized by fragmented centers of action split between the North Atlantic and Northern Europe—a configuration that likely limits the coherence of downstream energy propagation. In contrast, Period II exhibits a distinct structural reorganization, with a single, intensified center dominating Northern Europe. This action center is positioned further eastward and is substantially stronger than its Period I counterpart.

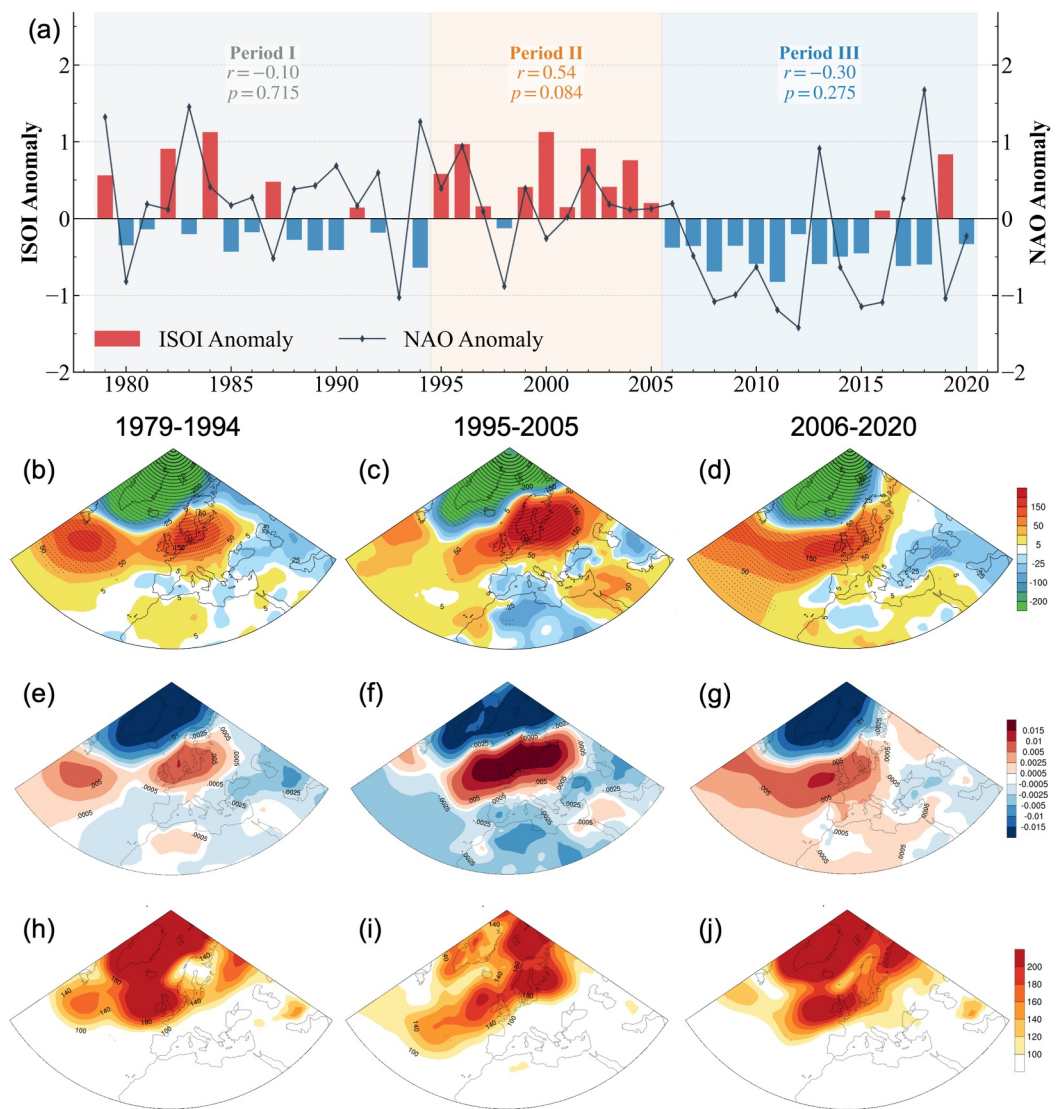


Figure 3. (a) Time series of summer 20–30 days ISOI anomalies for TP <Q1> (bars) and the SNAO index (black line) during 1979–2020. The symbol r denotes the correlation coefficient between the two series for three periods: Period I (1979–1994), Period II (1995–2005), and Period III (2006–2020). (b–d) Regressed anomalies of summer sea level pressure (SLP) onto the SNAO index, (e–g) the EOF1 of North Atlantic SLP, and (h–j) the standard deviation of summer North Atlantic SLP anomalies (hPa) for (b, e, and h) Period I, (c, f, and i) Period II and (d, g, and j) Period III. Dotted areas indicate significance exceeding the 90% confidence level.

Eastward displacement of NAO centers is a documented phenomenon in North Atlantic variability, previously identified in wintertime circulation (Hilmer & Jung, 2000; Jung et al., 2003; Lu & Greatbatch, 2002) and reproduced in climate model simulations under greenhouse gas forcing (Ulbrich & Christoph, 1999). To ensure that the identified structural changes are not artifacts of a fixed-location SNAO index, an independent EOF analysis on summer SLP anomalies was conducted (Figures 3e–3g), confirming that these structural reconfigurations are intrinsic features of atmospheric internal variability.

The physical consistency of these shifts is further demonstrated by comparing the regressed SLP centers with the total SLP standard deviation (Figures 3h–3j). In Period I, the standard deviation maximum is spatially separated from the fragmented SNAO centers, indicating weak energetic coherence. In contrast, Period II exhibits a pronounced spatial alignment between the intensified SNAO center and the standard deviation maximum over Northern Europe, suggesting that the SNAO represents the most energetic and dynamically coherent circulation mode during this decade. By Period III, both the SNAO centers and the standard deviation maximum retreat

southwestward. Together, these results reveal that the exceptional intensification of the TP 20–30-day ISOI in Period II coincides with an optimal alignment between SNAO structure and the region of maximum atmospheric variability, thereby facilitating efficient downstream energy transmission toward the TP.

3.3. Physical Mechanisms of the SNAO-Modulated TP ISO Intensification

The robust decadal correlation between the SNAO and the TP 20–30-day ISOI during Period II (Figure 3a) raises two critical questions: (a) Why does the SNAO preferentially modulate the 20–30-day over other ISO modes (e.g., the 10–20-day)? and (b) How does the SNAO-related signal propagate and amplify locally? In Section 3.3.1, we first verify the frequency-selective nature of the SNAO's influence before diagnosing the underlying wave-train dynamics and energetics.

3.3.1. Frequency-Selective Response of the TP $\langle Q_1 \rangle$

The preferential modulation of the 20–30-day oscillation is primarily rooted in the close alignment of decadal transitions between the SNAO and the 20–30-day ISOI. As shown in the time-series analysis (Figures 2b and 3a), both indices exhibited a prominent and simultaneous shift around 2005. In contrast, the 10–20-day is dominated by a long-term weakening trend and intense interannual noise, lacking a clear decadal connection with the SNAO. This synchrony suggests that the sustained positive phase and eastward shift of the SNAO action center during Period II (Figure 3c) likely provided favorable large-scale circulation conditions that facilitated the intensification of 20–30-day ISO over the TP.

To further confirm this frequency-selective modulation, we have conducted a stage-by-stage mean power spectrum analysis of the TP $\langle Q_1 \rangle$ across three distinct periods (Figures 4a–4c). This analysis serves as a “control experiment” to distinguish the intrinsic variability of the TP ISOI from the forced modulation associated with the SNAO. Clearly, the 10–20-day consistently exhibits a sharp and statistically significant peak across all three periods (Figures 4a–4c). Its energy fraction remains substantial and relatively stable (Figure 4d), suggesting it represents an intrinsic eigenfrequency of the TP $\langle Q_1 \rangle$ variability that operates largely independently of the decadal SNAO shifts. In contrast, the 20–30-day component undergoes a dramatic transformation specifically during Period II. Coinciding with the structural optimization of the SNAO, its spectral power intensity rises significantly, reaching a magnitude highly comparable to the dominant 10–20-day signal (Figure 4b).

Quantitatively, the energy fraction of 20–30-day increases from 2.96% in Period I to 10.46% in Period II (Figure 4d), before declining again to a negligible level (only 0.61%) in Period III. This frequency-specific intensification during Period II demonstrates that the SNAO acts as an efficient frequency-selective amplifier. Rather than modulating the entire subseasonal spectrum uniformly, the SNAO's downstream influence is primarily manifested as a preferential enhancement of the 20–30-day perturbations. The occurrence of this phenomenon specifically during the decadal peak of the SNAO suggests that the large-scale circulation anomalies associated with the North Atlantic teleconnection create a background environment uniquely conducive to this specific frequency band.

The decadal evolution of the energy fractions (Figure 4d) provides further quantitative evidence for a seesaw-like redistribution of spectral energy between the two primary ISO bands. From Period I to Period II, as the SNAO enters its active decadal phase, the energy fraction of the 10–20-day mode undergoes a notable decline (from ~56.5% to ~34.7%), whereas that of the 20–30-day band experiences a nearly 3.5-fold intensification (rising from 2.96% to 10.46%). This phase-locked transition suggests that the SNAO-forced background circulation effectively shifts the dominance of the TP ISO system toward lower-frequency oscillations. From Period II to Period III, following the weakening of the SNAO decadal signal after 2005, the energy hierarchy largely reverts to its intrinsic state: the 20–30-day signal dissipates (falling to 0.61%), while the 10–20-day band regains its dominance (recovering to ~45.74%).

This multidecadal alternation aligns well with the wavelet analysis in Figure 2a, confirming that the multidecadal surge of the TP ISO is not a uniform strengthening across all frequencies, but rather a frequency-selective reorganization driven by the large-scale teleconnections.

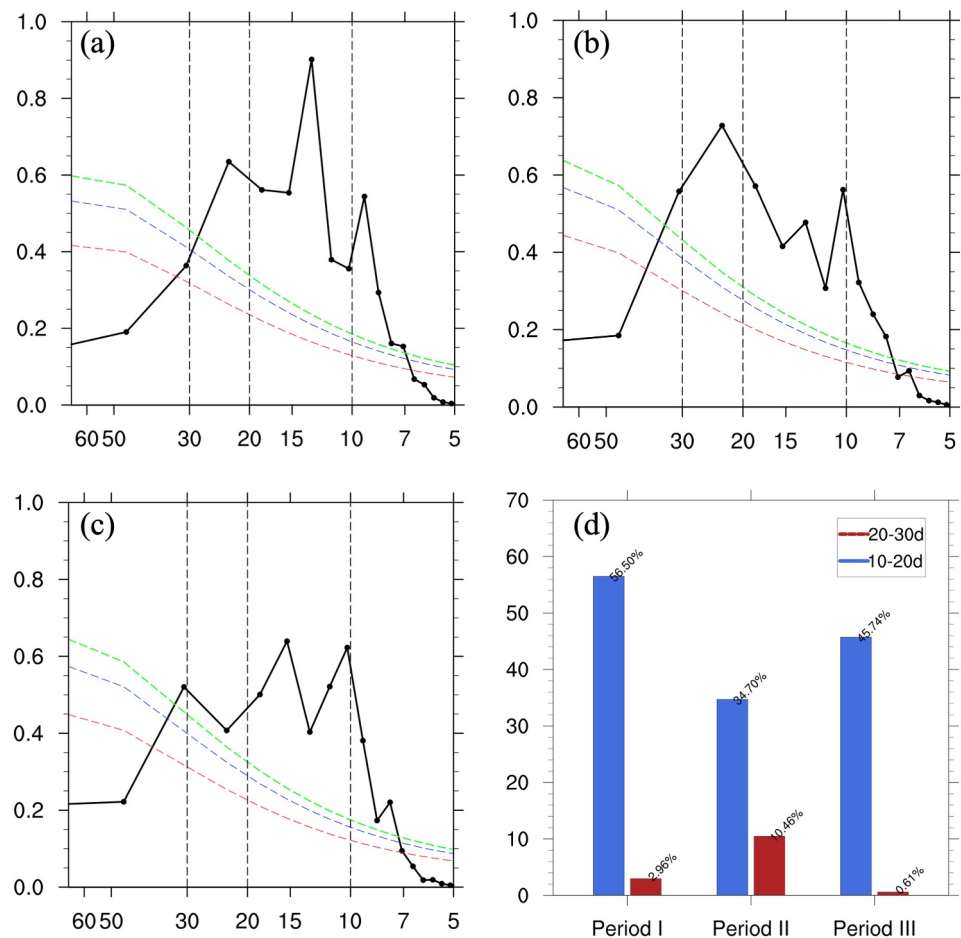


Figure 4. Decadal shifts in the spectral characteristics of the TP $\langle Q_1 \rangle$. Mean power spectra of the summer $\langle Q_1 \rangle$ during three periods: (a) Period I (1979–1994), (b) Period II (1995–2005), and (c) Period III (2006–2020). The red dashed line represents the Markov red noise spectrum, while the blue and green dashed lines indicate the 99% prior and posterior confidence levels, respectively. (d) The variance fraction (%) of the 10–20-day (blue bars) and 20–30-day (dark red bars) oscillation relative to the total intraseasonal variance across three periods.

3.3.2. SNAO-Linked Remote Wave-Train Propagation

The synchronized eastward displacement and positive phase of the SNAO during Period II are expected to strongly modulate downstream Rossby wave propagation. To elucidate the underlying physical pathways, 200-hPa geopotential height anomalies and WAF vectors are regressed onto the SNAO index (Figure 5). The results confirm that the influence of the SNAO on the TP depends jointly on its phase and spatial configuration.

Although the SNAO remains positive during both Periods I and II, their downstream influences differ markedly due to structural shifts. During Period I (Figure 5a), the fragmented centers of action fail to excite a coherent wave train, leaving the TP largely isolated from North Atlantic forcing. In contrast, the eastward-displaced configuration during Period II (Figure 5b) supports a well-organized wave-train that propagates across Eurasia and directly impinges on the central and eastern TP (27° – 38° N, 90° – 105° E), thereby providing large-scale dynamical forcing for the observed enhancement of the 20–30-day ISOI.

During Period III (Figure 5c), the negative SNAO phase, combined with a southwestward retreat of its action center, redirects the wave train toward Africa, effectively disrupting the North Atlantic-TP teleconnection. These results demonstrate that the establishment of a TP-reaching wave train is highly sensitive to the combined alignment of the SNAO's phase and spatial position: efficient downstream propagation occurs only when a positive SNAO phase coincides with an eastward-displaced center. While the SNAO-related wave activity at 500 hPa is weaker (Figure S6 in Supporting Information S1), it still exhibits a similar equivalent barotropic

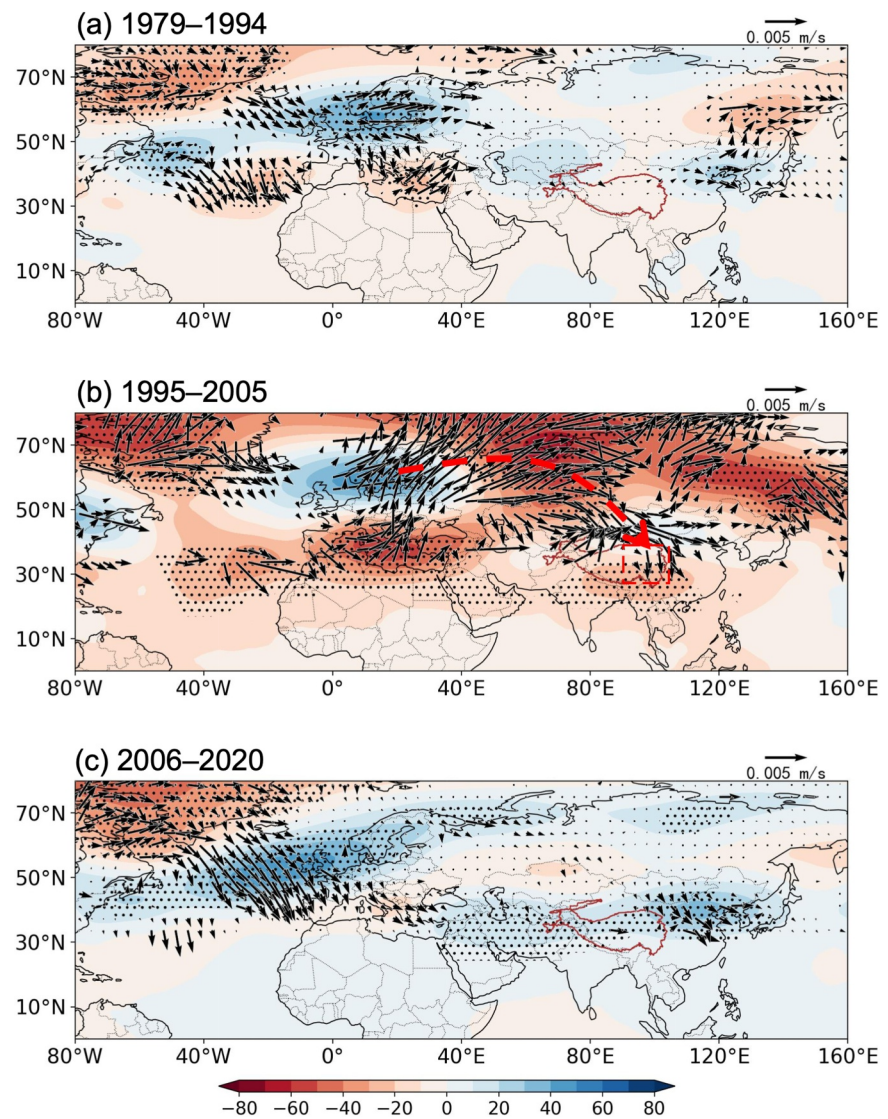


Figure 5. Regressed horizontal wave activity flux (vectors, $\text{m}^2 \text{s}^{-2}$) and geopotential height (shaded, gpm) at 200 hPa onto the SNAO index during (a) Period I, (b) Period II, and (c) Period III. Dotted areas indicate geopotential height significance above the 90% confidence level. The red rectangle in (b) denotes the central-eastern TP region (27° – 38°N , 90° – 105°E).

structure to that of the upper levels. This mid-tropospheric wave activity likely propagates along the northern periphery of the TP, suggesting that while the teleconnection is primarily concentrated in the upper troposphere, it simultaneously impacts the mid-to-lower troposphere via steering along the TP's northern boundary.

To investigate how the SNAO remote influence modulates the upper-level flow structure, we present the summer-mean 200-hPa zonal wind (U200) anomalies regressed onto the SNAO index across the three periods, overlaid with the period-specific mean background U200 jet (Figure 6). While the mean background westerly jet remains relatively stationary across all three periods, the SNAO-induced U200 response exhibits pronounced decadal variations. During Period II (Figure 6b), a prominent and geographically continuous band of positive U200 anomalies stretches southeastward from Northern Europe across Central Asia toward the regions north of the TP and East Asia. The constructive superposition of this intense westerly anomaly onto the background flow reinforces the local upper-level westerly duct, establishing a remarkably efficient high-latitude anomalous waveguide corridor. This waveguide pathway seamlessly guides the downstream propagation of the SNAO-related wave energy toward the TP sector, perfectly coinciding with the high-latitude wave activity route shown in Figure 5b.

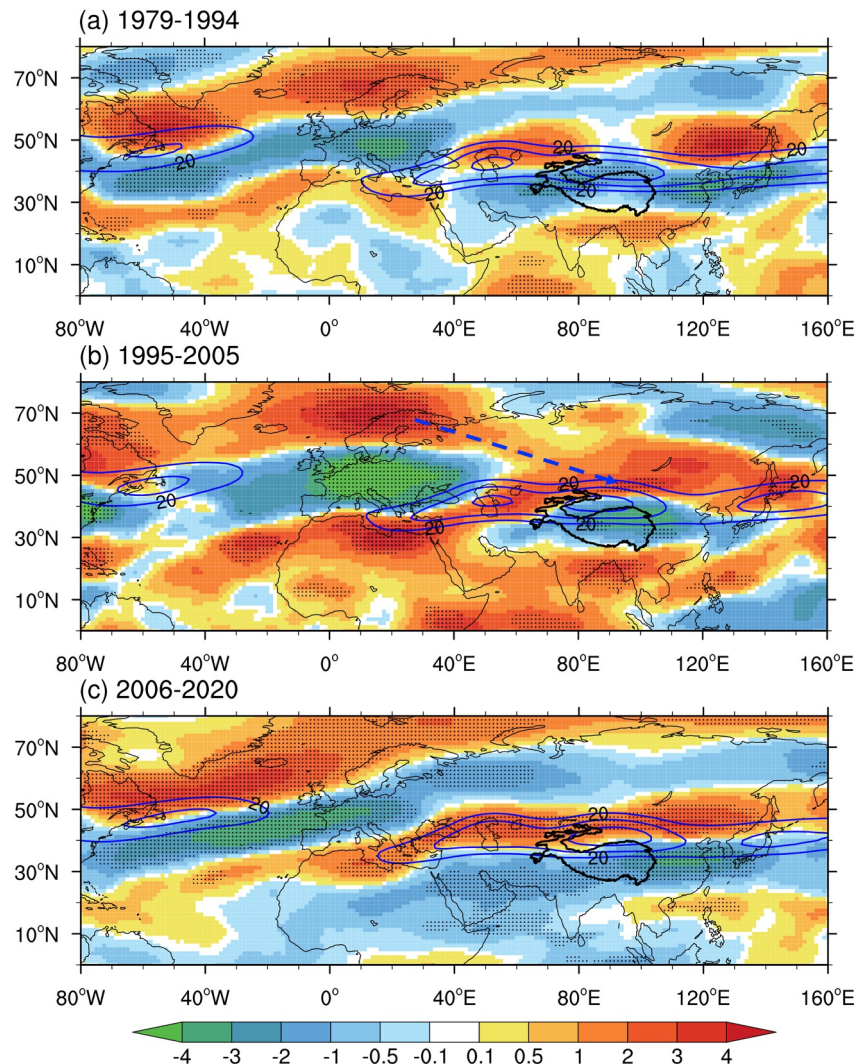


Figure 6. Regressed summer-mean zonal wind at 200 hPa (U200, shaded, m s^{-1}) onto the SNAO index during (a) Period I, (b) Period II, and (c) Period III. The solid blue contours denote the mean total U200 background field for each corresponding period (contours at 20, 25, and 30 m s^{-1}). Dotted areas indicate regressed anomalies significant above the 90% confidence level. The dashed blue arrow in (b) highlights the prominent SNAO-induced anomalous high-latitude westerly waveguide path extending from the Northern Europe toward the TP.

In sharp contrast, during the inactive periods, this high-latitude waveguide duct is disrupted or reorganized. The U200 regression exhibits a spatially fragmented anomaly pattern in Period I (Figure 6a). By Period III (Figure 6c), it is replaced by a broad redistribution of the mid-to-high latitude flow, characterized by a distinct weakening over the North Atlantic-European sector but a continuous strengthening of the westerlies stretching across central Asia into the East Asian jet region. Notably, while the localized U200 response over the TP remains consistently dominated by uniform negative anomalies across all three periods, the large-scale high-latitude waveguide channeling remote wave activity from the North Atlantic to the TP mid-to-high latitudes is uniquely organized and continuous only during Period II. This striking structural contrast in the anomalous westerly corridor provides robust validation for the decadal modulation of the North Atlantic-TP teleconnection.

3.3.3. Local Energy Conversion and In Situ Growth

While WAF traces the trajectory of energy propagation, quantifying the associated energy conversion processes is essential for understanding how these waves sustain TP ISO activity. Interactions between ISO-scale perturbations and the mean flow—via barotropic (CK) and baroclinic (CP) conversions—play a key role in ISO maintenance

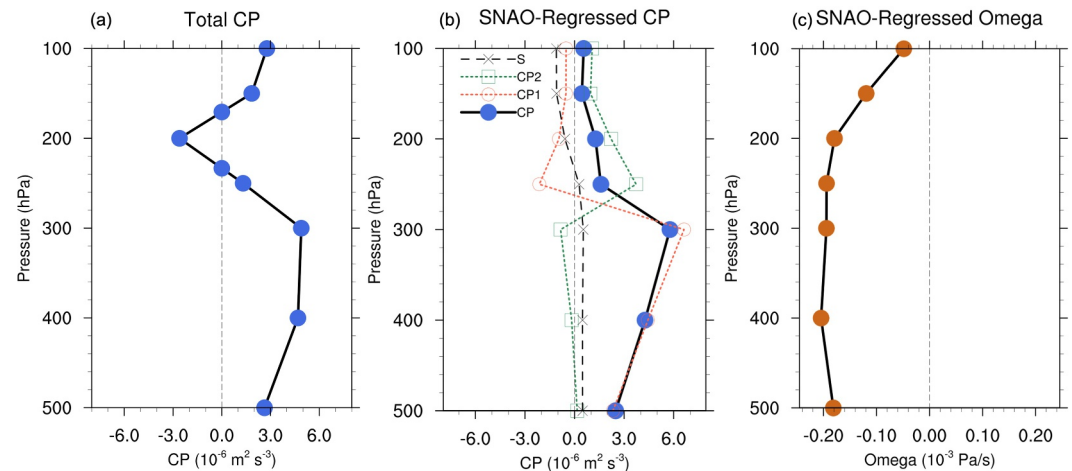


Figure 7. (a) Vertical profile of the total baroclinic energy conversion (CP; $10^{-6} \text{ m}^2 \text{ s}^{-3}$), averaged over the central-eastern TP region during Period II (1995–2005). (b) Same as (a), but for the SNAO-reconstructed fields of CP (CP_{SNAO}), its individual components (CP_1 and CP_2 ; $10^{-6} \text{ m}^2 \text{ s}^{-3}$), and the static stability parameter (S ; $10^{-6} \text{ K Pa}^{-1}$), all obtained through linear regression onto the SNAO index. (c) As in (b), but for the omega field (Pa s^{-1}).

(Guo et al., 2025; Zhu & Yang, 2021). We therefore examine the local energetic processes over the central and eastern TP to determine how the SNAO during Period II facilitates energy extraction from the mean flow to support the decadal enhancement of the 20–30-day ISOI.

Area-averaged vertical profiles of total energy conversion (CK and CP) over the central-eastern TP are shown in Figure 7 and Figure S7 in Supporting Information S1. During Period II, the 20–30-day ISOI is maintained by the combined effects of CK and CP processes. Total CK peaks in the upper troposphere near 150 hPa (Figure S7a in Supporting Information S1), whereas total CP remains positive throughout the air column—except for a negative dip at 200 hPa—and reaches a maximum near 300 hPa (Figure 7a). However, isolating the SNAO-related contribution reveals a marked contrast between these two mechanisms. Although the vertical profile of SNAO-related CK (CK_{SNAO}) resembles the total CK profile (Figure S7 in Supporting Information S1), its magnitude is nearly two orders of magnitude smaller, suggesting that the SNAO plays a limited role in modulating the TP ISO through barotropic energy conversion.

In contrast, the SNAO-reconstructed baroclinic component (CP_{SNAO}) exhibits a dominant influence. In the lower troposphere, CP_{SNAO} closely matches the total CP in both magnitude and vertical distribution, implying that the SNAO significantly enhances the primary baroclinic energy source by optimizing the low-level thermodynamic environment. More importantly, a critical role of the SNAO-induced forcing is manifested in the upper troposphere (above 250 hPa). While the total CP weakens or even turns negative aloft—suggesting a tendency for vertical decoupling—the CP_{SNAO} provides a persistent positive energy source that compensates for these upper-level energy deficits. Therefore, while low-level baroclinic conversion serves as the primary energy source for ISO growth, the SNAO-induced contribution aloft acts as a “structural stabilizer.” By offsetting upper-level sinks, it effectively anchors the disturbance across the entire troposphere, thereby preserving the vertical coherence and deep-tropospheric structure of the ISO.

The vertical structure maintenance is further elucidated by the bifurcation of CP_{SNAO} , which exhibits a clear separation between its two components, CP_1 and CP_2 , near 300 hPa. Below this level, the mid-tropospheric energy maximum is predominantly driven by CP_1 . Above 300 hPa, however, CP_2 becomes dominant and offsets the negative contribution from CP_1 . This vertical transition is closely linked to the SNAO-induced profile of static stability (S), which governs the complementary roles of CP_1 and CP_2 (Figure 7b). Through this mechanism, the SNAO-related baroclinic conversion effectively offsets upper-level energy dissipation, ensuring the synchronized intensification of the ISO across different vertical layers. This vertical integration is instrumental in the sustained vigor of the 20–30-day ISO observed throughout Period II.

To bridge the gap between upper-level wave propagation and lower-level energy conversion, we analyze the SNAO-regressed omega field (Figure 7c). The SNAO influence is initiated in the upper troposphere as a Rossby

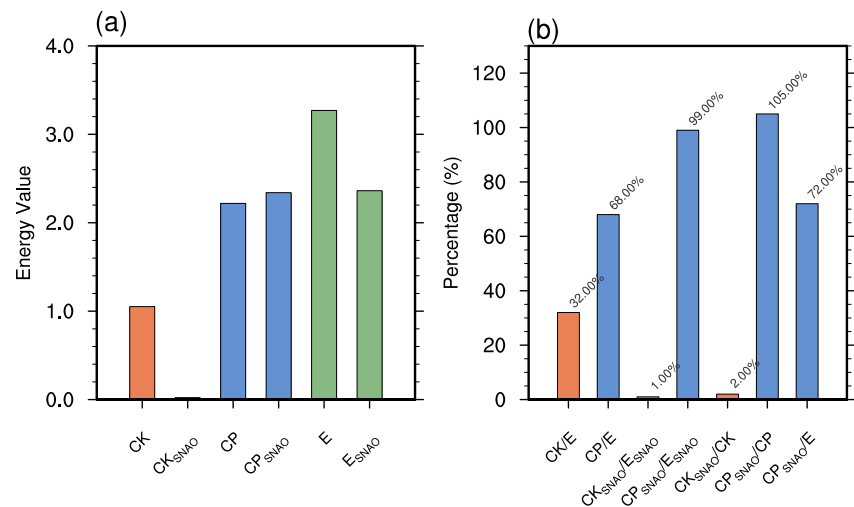


Figure 8. (a) Regional averages ($10^{-6} \text{ m}^2 \text{ s}^{-3}$) of vertically integrated energy budget (CK, CP and their sum E ; CK_{SNAO}, CP_{SNAO} and their sum E_{SNAO}) over the central and eastern TP during Period II (1995–2005). (b) Fractional contributions of each component.

wave train propagating along the Eurasian waveguide. This wave activity acts as a dynamical pathway, inducing robust vertical motion anomalies in the mid-troposphere (300–500 hPa). These anomalies interact with the strong background thermal gradients and static stability over the TP, triggering local baroclinic instability. Consequently, the energy that maintains the 20–30-day oscillation is generated locally, with the peak conversion occurring near 300 hPa where vertical motion and thermodynamic conditions are optimally aligned.

The decisive role of the SNAO is further confirmed by a spectral energy perspective based on the vertically integrated energy budget. During Period II, the vertical integrated total CP accounts for 68% of the total energy maintenance ($E = \text{CK} + \text{CP}$) associated with the 20–30-day ISOI over the central-eastern TP, whereas total CK accounts for the remaining 32% (Figure 8). Notably, CP_{SNAO} contributes 105% of the total CP, directly quantifying the crucial compensatory role of the SNAO aloft where it offsets upper-level negative CP anomalies. In sharp contrast, the CK_{SNAO} is negligible, contributing a mere 2.00% to the total CK and representing only 1.00% of the total SNAO-induced energetic maintenance (E_{SNAO}) (Figure 8b). Consequently, CP_{SNAO} overwhelmingly dominates the SNAO-linked energy pathway, accounting for 99% of E_{SNAO} and collectively making up 72% of the E during this period. This quantitative breakdown unambiguously highlights the exclusive and dominant role of baroclinic energy conversion in driving the decadal surge.

Notably, the surge of the 20–30-day oscillation is a result of frequency-selective energy allocation rather than a simple increase in total energy. Comparison between Periods II and III reveals that while total energy conversion (E) can be higher in non-surge periods, the SNAO specifically optimizes the coupling between circulation and thermodynamic structure for the 20–30-day band. During Period II, approximately 10.46% of total spectral energy is concentrated in this band, whereas in other periods, energy is redistributed toward higher frequencies (e.g., 10–20 days) (Figure 4d). This highlights that the SNAO serves as the critical dynamical modulator that ensures the net energy gain of the 20–30-day mode exceeds local dissipation.

4. Discussion

A central implication of this study is that the NAO's downstream influence depends not merely on its phase (Sung et al., 2010; Zhang et al., 2025), but critically on its spatial configuration. The contrast between Periods I and II reveals that a positive SNAO phase alone is completely inadequate to modulate downstream patterns; only when it synergizes with an eastward-displaced, structurally coherent center can it effectively couple with the Eurasian waveguide to excite a well-organized, TP-reaching Rossby wave train. Crucially, this coupled [positive phase + eastward shift] configuration operates as an optimal and highly effective driver rather than a strictly necessary condition for the TP 20–30-day intensification. As verified by historical independent years with strong TP ISOI outside Period II (such as 1979, 1982, 1984, 1987, and 2019; see Table S1 in Supporting Information S1

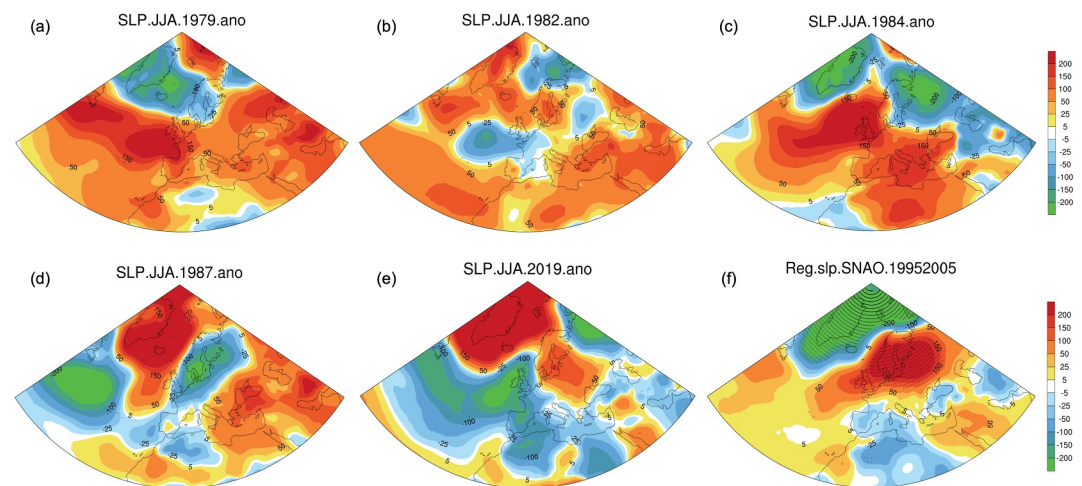


Figure 9. Anomalies of summer mean sea level pressure (SLP, hPa) over the North Atlantic and European sectors for individual strong TP 20–30-day ISOI years: (a) 1979, (b) 1982, (c) 1984, (d) 1987, (e) 2019. (f) The SLP fields regressed onto the SNAO index during the multidecadal surge period (Period II: 1995–2005).

and Figure 9), a strong subseasonal oscillation can be stochastically triggered by alternative tropical or local pathways without the presence of the dual-condition SNAO pattern. For instance, the positive SNAO anomalies in 1982 were fragmented and weak over Western Europe, while the center in 1984 was located too far westward over the North Atlantic to successfully build the Eurasian waveguide corridor. Furthermore, the SNAO in 2019 completely reversed into a strong negative phase (Figure 3a). The true necessity of the 1995–2005 decadal background lies in its ocean-atmosphere stabilization, which locked this otherwise transient, rare dual-condition configuration into a prolonged, persistent climate regime, thereby transforming isolated seasonal flukes into a systematic decadal frequency-selective surge.

Energetically, the SNAO acts as a “dynamical sustainer” for TP 20–30-day disturbances during Period II through a spatially coordinated vertical mechanism. In the lower troposphere, CP_{SNAO} mirrors the total CP in both magnitude and distribution, indicating that the SNAO-induced vertical motion efficiently extracts baroclinic energy from the TP’s thermal environment, serving as the primary driver of ISO growth. More uniquely, in the upper troposphere (above 250 hPa) where the background environment typically acts as an energy sink, the SNAO provides a persistent supplementary baroclinic energy supply (CP_{SNAO}). This top-down support compensates for local energy deficits, preserving the vertical coherence and deep tropospheric structure of the ISO. This underscores that the SNAO’s modulation is twofold: it maximizes energy extraction in the lower layers and prevents structural decay in the upper layers.

Furthermore, our results underscore a striking “scale selectivity” in TP-extratropical teleconnections. While previous studies have linked the Arctic Oscillation (AO) to the TP 10–20-day oscillation (Wang et al., 2018; Zhu et al., 2026), this study demonstrates that the 20–30-day ISO mode is obviously modulated by the SNAO through a decadal window of opportunity. This frequency-specific selective amplification is rigorously supported by our energy budget and alternative-factor exclusions. Energetically, CP_{SNAO} fully saturates the total CP maximum at the 300-hPa core layer during Period II (Figure 7), leaving no remaining dynamic headroom for alternative teleconnections to drive this surge. Statistically, removing tropical signals (ENSO and PDO) via partial correlation leaves the SNAO–ISOI coupling remarkably stable (r increases to 0.55–0.57), ruling out a tropical or Pacific origin. Crucially, a parallel stage-by-stage power spectrum analysis of the TP surface sensible heat (SH) flux reveals that the 20–30-day cycle of surface thermal forcing remains highly stable and invariant across all three periods (Figure S8a–S8c in Supporting Information S1). While the atmospheric convective heating ($<Q_1>$) 20–30-day variance fraction abruptly vanishes during Period III, dropping to a mere 0.61%, the surface SH flux consistently maintains a stable variance pool of 6.77% (Figure S8d in Supporting Information S1). This asynchronous multidecadal transition physically invalidates the localized land-atmosphere feedback hypothesis. Such scale-dependent and externally forced responses highlight that the 20–30-day mode possesses unique dynamic sensitivities, necessitating a decadal perspective to capture its transient coupling with North Atlantic forcing.

The transition to a quiescent phase after 2005 (Period III) highlights the decadal non-stationarity of this link. As climate models project potential eastward shifts in North Atlantic variability under greenhouse forcing (Ulbrich & Christoph, 1999), the SNAO's role as a modulator may become increasingly significant. Our study suggests that future changes in TP ISO activity may arise from shifts in teleconnection structure and spatial phase, even in the absence of systematic changes in their intensity.

5. Conclusions

This study investigates the decadal evolution of the 20–30-day ISOI over the TP and its linkage to the SNAO during the period 1979–2020. The primary findings are summarized as follows:

1. The TP 20–30-day ISOI exhibits a significant decadal surge during 1995–2005, which is dynamically associated with an eastward-displaced positive SNAO configuration. This structural reconfiguration effectively coupled the North Atlantic forcing with the Eurasian waveguide, facilitating a more coherent and potent downstream Rossby wave train toward the TP.
2. Energetic diagnostics indicate that SNAO-reconstructed baroclinic conversion (CP_{SNAO}) was the primary sustainer of the intensified ISO. CP_{SNAO} accounts for approximately 72% of the total regional energetic maintenance. The SNAO-related wave activity facilitates anomalous tropospheric vertical motion, which interacts with the TP's background thermal environment to modulate local baroclinic instability.
3. The SNAO influences the TP-ISO through a coordinated vertical pathway. While the lower troposphere serves as the primary zone for energy extraction, the SNAO provides essential compensatory baroclinic energy in the upper troposphere (above 250 hPa). By offsetting local energy sinks at high altitudes, this “top-down” support preserves the vertical coherence and deep-tropospheric structure of the ISO signal.
4. The SNAO–TP-ISO linkage is characterized by striking scale selectivity. During the active multidecadal period (1995–2005), the SNAO-induced forcing preferentially funneled energy into the 20–30-day band, ensuring its net energy gain exceeded dissipation. This decadal “window of opportunity” differentiates the 20–30-day mode from other intraseasonal scales, offering a new dynamical framework for understanding frequency-specific climate variability over the TP.

In summary, these results establish a robust dynamical link between extratropical teleconnection morphology and local energy cycles. The findings underscore the critical role of teleconnection structure in shaping intraseasonal variability and provide valuable insights for improving the subseasonal-to-seasonal (S2S) predictability of summer climate over the TP and its downstream regions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The JRA-55 reanalysis data used in this study were obtained from the Japan Meteorological Agency (Kobayashi, 2015), available at https://www.data.jma.go.jp/jra/html/JRA-55/index_en.html. The CN05.1 daily precipitation data set was accessed through the Nansen-Zhu International Research Centre (Wu & Gao, 2013) at <https://nzc.iap.ac.cn/list?cid=24>. The monthly NAO index was provided by the NOAA Climate Prediction Center (NOAA CPC, 2020) and is available at <https://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml>.

Acknowledgments

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