



Asymmetric meridional outward propagation of the summertime Tibetan Plateau quasi-biweekly oscillation: mechanisms and energetics

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Abstract

During boreal summer, the Tibetan Plateau (TP) exhibits prominent quasi-biweekly oscillations (QBWO) that profoundly modulate regional and downstream weather and climate. Utilizing JRA-55 reanalysis data, alongside moist static energy (*MSE*) budget and barotropic energy diagnostics, this study uncovers the contrasting mechanisms governing the systematic meridional propagation of the TP QBWO. Our results reveal a striking meridional asymmetry: while the northward branch rapidly dissipates within the TP interior (~6 days), the southward counterpart features remarkable longevity (~12 days), surmounting the Himalayas to modulate South Asian monsoon precipitation before terminating near 5°N. Diagnostics show that the short-lived northward branch is dynamically dominated, primarily fueled by upscale kinetic energy extraction from the horizontal shear of the Subtropical Westerly Jet. Conversely, the persistent southward branch is governed by a spatially coordinated thermodynamic-dynamic coupling chain. Low-level anomalous southerlies act as the primary pioneer by impinging on the steep background meridional moisture gradient on the southern TP slopes, driving strong positive horizontal *MSE* advection. This thermodynamic pre-conditioning extends into lower latitudes (15°–25°N), creating a precursory zone of moisture instability that leads the convective core by 5°–10° latitude. Concurrently, high-cloud-induced longwave radiative heating on the southern TP flank acts synergistically with low-level moisture import to reinforce and sustain this leading instability corridor, guiding the equatorward propagation along the path of least resistance. These findings offer a novel thermodynamic-dynamic coupling framework for understanding the bidirectional transmission of TP weather systems.

Keywords Tibetan Plateau · Quasi-biweekly oscillation (QBWO) · Asymmetric meridional propagation · Moist static energy (*MSE*) budget · Thermodynamic-dynamic coupling

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1 Introduction

The Tibetan Plateau (TP), widely heralded as the “Third Pole” (Yao et al. 2012) and the “Asian Water Tower” (Lu et al. 2005; Xu et al. 2008, 2014; Yao et al. 2019), exerts a profound influence on the global climate system through intricate land-ocean-atmosphere interactions (Xu et al. 2002; Yang et al. 2020; You et al. 2020; Lu et al. 2021; Huang et al. 2023). During the boreal summer, the TP acts as a massive elevated heat source. Its intense diabatic heating in the middle troposphere drives regional and hemispheric atmospheric circulations, thereby governing the East and South Asian summer monsoons and shaping weather patterns across the Northern Hemisphere (Yeh et al. 1957; Yanai et

al. 1992; Wu et al. 1997, 2012, 2015; Lu et al. 2021; Yu et al. 2021; Hu et al. 2022a, b; Luo et al. 2024).

Extensive research has identified the TP as a region of vigorous intraseasonal oscillations (ISOs), with quasi-biweekly oscillation (QBWO; 10–20-day) being the dominant mode during the active monsoon season (Wang and Duan 2015; Hu et al. 2016; Li et al. 2018a; Yuan et al. 2023; Guo et al. 2024; Zhu et al. 2025, 2026). These QBWO signals significantly modulate the active and break phases of the monsoon and drive precipitation anomalies in both local and downstream regions (Wang and Duan 2015; Li et al. 2018b; Wang et al. 2019; Hu et al. 2023). Recent studies highlight that the interannual variations in TP QBWO intensity trigger asymmetric precipitation responses across China, particularly enhancing Yangtze River rainfall while suppressing precipitation over the southern TP (Yu et al. 2018; Guo et al. 2025; Zhu et al. 2026).

Despite its importance, the full life cycle of the TP QBWO remains incompletely understood. Previous studies broadly classify its meridional propagation into TP-ward (inflow) and off-TP (outward) branches (Wang and Duan 2015; Zhu et al. 2026). While TP-ward signals imported from low or high latitudes have been extensively documented (Jiang et al. 2004; Wang et al. 2017, 2018; Yang et al. 2017; Hu et al. 2022a, b), growing evidence indicates that the TP also acts as an active wave, generating off-TP signals that propagate northward toward mid-latitudes and/or southward toward the tropics. (e.g., Sun and Chen 1994; Peng and Wu 1995; Xu and Zhu 2002). However, the distinct behaviors and governing mechanisms of these off-TP branches remain elusive. Given the stark contrast between the moisture-rich monsoon region to the south and the arid mid-latitude interior to the north, their evolutionary pathways are likely asymmetric. Identifying which branch is more persistent, and unraveling the specific internal feedback or steering mechanisms that sustain it, is crucial for improving regional subseasonal precipitation forecasts.

Addressing this requires a unified dynamic-thermodynamics diagnostic framework. Given the contrasting environmental background flanking the TP, the northward branch is expected to be closely tied to mid-latitude jet dynamics, whereas southward propagation across subtropical-tropical transitions likely hinges on thermodynamic-moisture coupling. The Moist Static Energy (*MSE*) budget serves as a robust framework to isolate key processes—such as horizontal advection and cloud-radiative feedbacks—that drive environmental moisture pre-conditioning ahead of convection (Peters and Bretherton 2006; Kuang 2011; Maloney 2009; Lin et al. 2025; He et al. 2026). Compelling observational evidence from tropical studies (Back and Bretherton 2006; Benedict and Randall 2007; Sooraj and Seo 2013; Wolding and Maloney 2015; Lin et al. 2025) underscores

the pivotal role of moisture pre-conditioning in guiding ISO propagation. Whether such thermodynamic-dynamic regulation governs off-TP QBWO propagation remains unexplored.

This study pursues two primary objectives: (1) to characterize the divergent southward and northward propagation pathways of the TP QBWO, systematically evaluating the spatial-temporal structures and the degree of asymmetry during their lifecycles, and (2) to uncover the contrasting physical mechanisms, with particular emphasis on unraveling the key thermodynamic and dynamic processes that drive and sustain the southward-propagating mode, thereby identifying the primary physical constraints that dictate the off-plateau propagation of TP QBWO.

The remainder of this paper is organized as follows. Section 2 details the datasets and *MSE* (*m*) framework. Section 3 presents the asymmetric propagation features of the TP QBWO. Section 4 delves into the underlying physical mechanisms governing this meridional propagation from the perspectives of *m* budget and energetics. Finally, Sect. 5 summarizes the key findings and discusses their broader climatic implications.

2 Data and methods

2.1 Data

This study utilizes the daily Japanese 55-year Reanalysis (JRA-55) dataset (Kobayashi et al. 2015) spanning the 42-year period from 1979 to 2020 during boreal summer. Variables extracted at multiple pressure levels with a horizontal resolution of $1.25^\circ \times 1.25^\circ$ include zonal and meridional winds (u , v), vertical velocity (ω), air temperature (T), specific humidity (q), and geopotential height (H). Column-integrated and surface variables, including surface and top-of-the-atmosphere radiative fluxes (longwave and shortwave), high cloud cover, and total surface precipitation, are also obtained from JRA-55. The use of reanalysis-derived precipitation provides critical sea-surface continuity, allowing for an uninterrupted tracking of the QBWO life cycle across the land-sea interface.

To complement the reanalysis product and rigorously evaluate its reliability against real-world measurements, the daily unified gauge-based precipitation dataset over global land areas, featuring a finer horizontal resolution of $0.5^\circ \times 0.5^\circ$, is obtained from the NOAA Climate Prediction Center (CPC) (Chen et al. 2008). This high-resolution, observation-based dataset is employed exclusively to cross-validate the land-based hydrological footprints of the QBWO, thereby confirming that the key findings of this

study are robust and free from potential reanalysis model systematic biases.

2.2 Methods

2.2.1 Intraseasonal signal extraction

To isolate the QBWO signals, the climatological annual cycle is first removed from the daily raw data to obtain anomalies. A 5-day running mean is subsequently applied to these anomalies to suppress high-frequency weather noise (Yang et al. 2010). Finally, a Lanczos band-pass filter (Duchon 1979) is implemented to extract the fluctuations within the 10–20-day frequency band. Extensive observational and theoretical studies have demonstrated that this 10–20-day window represents the dominant spectral peak of TP ISO during the summer season (e.g. Wang and Duan 2015; Hu et al. 2016; Li et al. 2018a). Applying this targeted filter effectively isolates the primary QBWO mode while avoiding contamination from higher-frequency synoptic transient noise (< 10 days) as well as lower-frequency intraseasonal signals (> 20 days).

Additionally, the vertically integrated apparent heat source ($\langle Q_1 \rangle$) from the surface to 100 hPa is estimated via the residual budget method (Yanai 1961; Yanai et al. 1973), based on JRA-55 reanalysis. The fidelity of JRA-55 in capturing $\langle Q_1 \rangle$ variability over the complex terrain of the TP has been thoroughly validated by previous studies (Wang et al. 2019; Zhu et al. 2025), showing robust alignment with independent station observations and satellite estimates.

2.2.2 Wave-mean flow interaction framework

To elucidate the distinct physical processes driving the multi-directional bifurcation of the TP QBWO, two complementary diagnostic frameworks are employed. The northward propagation of QBWO signals toward mid-to-high latitudes—where strong vertical and horizontal shears of the westerlies dominate—is investigated through the lens of wave-mean flow interactions. We quantify the kinetic and available potential energy exchanges between the summer (June–August) climatological mean flow and the 10–20-day perturbations by calculating the barotropic kinetic energy conversion (CK) and baroclinic available potential energy conversion (CP) (Kosaka and Nakamura 2006; Kosaka et al. 2009):

$$CK = \frac{v'^2 - u'^2}{2} \left(\frac{\partial \bar{u}}{\partial x} - \frac{\partial \bar{v}}{\partial y} \right) - u'v' \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right) \quad (1)$$

$$CP = -\frac{f}{S} \left(v'T' \frac{\partial \bar{u}}{\partial p} - u'T' \frac{\partial \bar{v}}{\partial p} \right) \quad (2)$$

where the static stability parameter S is defined as:

$$S = \frac{R\bar{T}}{C_p\bar{p}} - \frac{\partial \bar{T}}{\partial p} \quad (3)$$

Here, the overbars and primes represent the summer climatological mean state and the 10–20-day filtered anomalies, respectively. The constants include the Coriolis parameter (f), the specific heat at constant pressure (c_p), and the gas constant for dry air (R). Dynamically, positive values of CK (CP) signify an upscale energy transfer from the background mean flow to the intraseasonal perturbations via barotropic (baroclinic) processes, fostering the growth and maintenance of the northward branch; conversely, negative values denote a dissipation of eddy energy back into the mean flow.

2.2.3 MSE budget framework (southward propagation)

Conversely, because the southward propagation path moves toward the moisture-rich monsoonal tropics, it is primarily governed by thermodynamic processes than by pure mid-latitude wave dynamics. To examine this tropical-subtropical transition, we employ a m budget analysis. The m is defined as $m = c_p T + gz + Lq$, where $c_p T$, gz , and Lq represent the sensible heat, geopotential height (potential energy), and latent heat components, respectively. Following Maloney (2009) and Kiranmayi and Maloney (2011), the m tendency equation can be expressed as:

$$\frac{\partial \langle m \rangle}{\partial t} = -\langle \vec{V} \cdot \nabla m \rangle - \langle \omega \frac{\partial m}{\partial p} \rangle + F_{rad} + F_{sfc} \quad (4)$$

where $-\langle \vec{V} \cdot \nabla m \rangle$ and $-\langle \omega \frac{\partial m}{\partial p} \rangle$ represent the anomalous horizontal and vertical advection terms, respectively. The term F_{rad} signifies the net column-integrated radiative heating anomaly (the sum of net shortwave and longwave radiation budgets at both the surface and the top of the atmosphere), and F_{sfc} denotes the anomalous surface flux (the sum of surface latent and sensible heat fluxes). By meticulously diagnosing the contribution of each term in the m budget, we can quantitatively discern whether the systematic southward migration is sustained by internal moisture-convection feedbacks, cloud-radiative trapping, or large-scale dynamical transport.

3 Characteristics of asymmetric propagation of the TP QBWO

Figure 1 presents the latitude-time cross-sections of the 10–20-day filtered $\langle Q_1 \rangle$ anomalies averaged over the core longitude of the TP (70°–100°E). Alongside signals propagating onto the TP from lower and higher latitudes, a distinguishing feature of the summertime TP heat source is the pronounced off-plateau meridional propagation of QBWO signals.

Specifically, QBWO convective disturbances typically initiate over the southern TP (south of 30°N) and bifurcate

into two pathways: a northward branch migrating into higher latitudes, and a southward branch shifting systematically toward the tropics. While these dual pathways often occur concurrently—suggesting wave dispersion from the TP source region—isolated events are also observed, such as the robust standalone southward branch on 2 August 2010. Crucially, the two branches exhibit a striking evolutionary asymmetry. Many southward-propagating signals undergo a marked secondary intensification upon reaching the steep southern slopes of the TP and the adjacent tropical regions (e.g., 1986, 1996, and 2010). This localized enhancement implies that the southward branch extracts additional energy

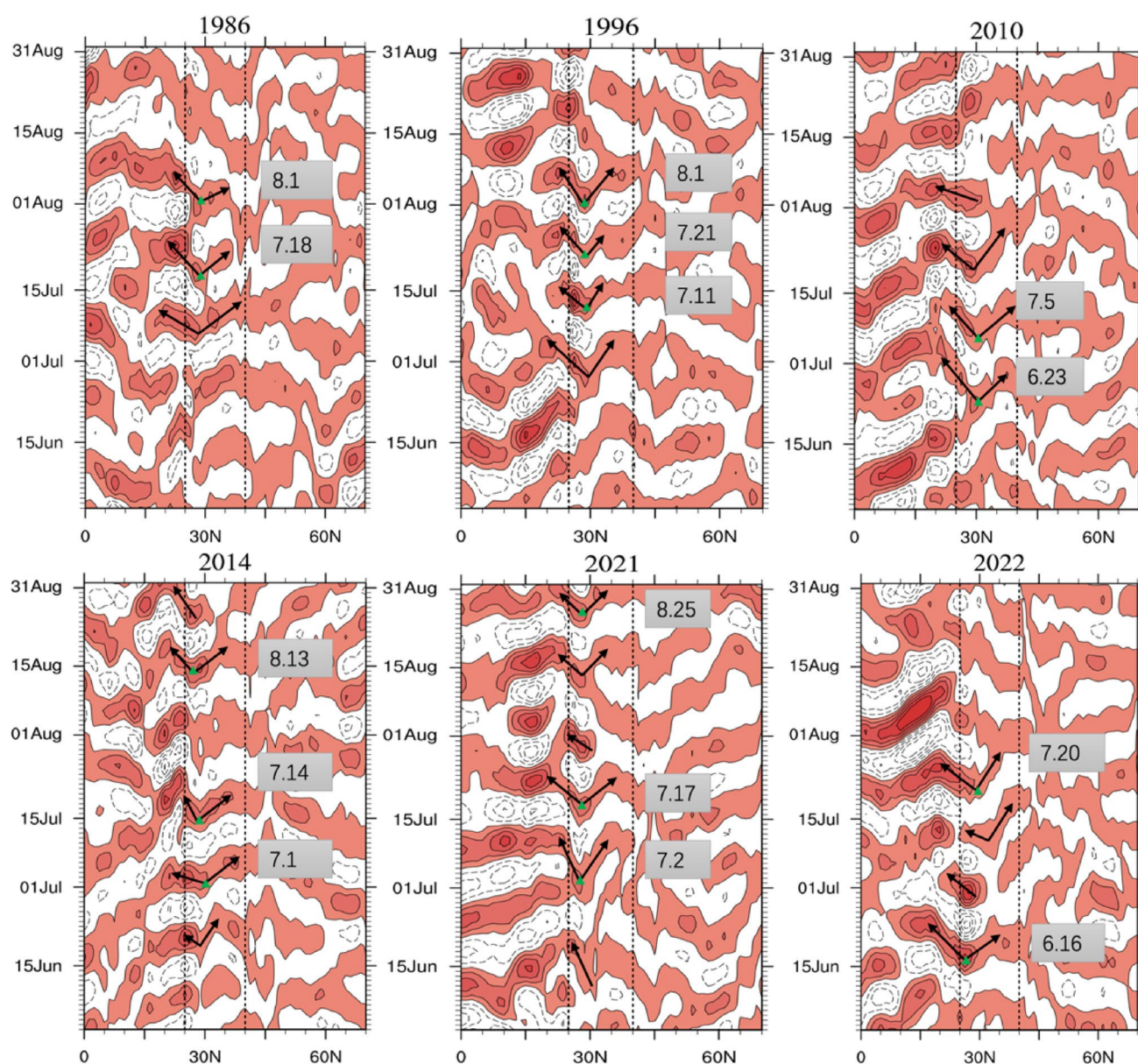


Fig. 1 Latitude-time cross-sections of the 10–20-day band-pass filtered apparent heat source $\langle Q_1 \rangle$ (W m⁻²) averaged over 70°–100°E for six selected typical years. Black arrows illustrate the off-plateau propagation of QBWO signals from the TP toward higher and/or lower lati-

tudes. Green triangles, annotated with specific dates, mark significant QBWO events whose intensities exceeded a threshold of 0.8 standard deviations. Vertical dashed lines indicate the latitudinal boundaries of the TP region (25°–40°N)

from the moisture-rich and thermodynamically unstable background state of the lower latitudes. Conversely, the northward branch gradually decays upon entering the arid mid-latitude westerlies—a thermodynamic contrast that will be thoroughly elucidated via the m budget analysis in Sect. 4. This asymmetric meridional propagation demonstrates that the TP acts as a crucial bidirectional atmospheric bridge, simultaneously modulating mid-latitude wave trains and tropical monsoon systems through coupled dynamical and thermodynamical interactions.

To further investigate the life cycle, vertical structure, and physical mechanisms of the bifurcated TP QBWO, a comprehensive composite analysis is conducted. Representative events are identified by performing an Empirical Orthogonal Function (EOF) analysis on the 10–20-day filtered $\langle Q_1 \rangle$ anomalies over the TP. The first principal component (PC1) serves as the primary selection index, as its dominant spatial mode (EOF1) features a convective center anchored over the southern TP (Zhu et al. 2026), perfectly aligning with the features in Fig. 1.

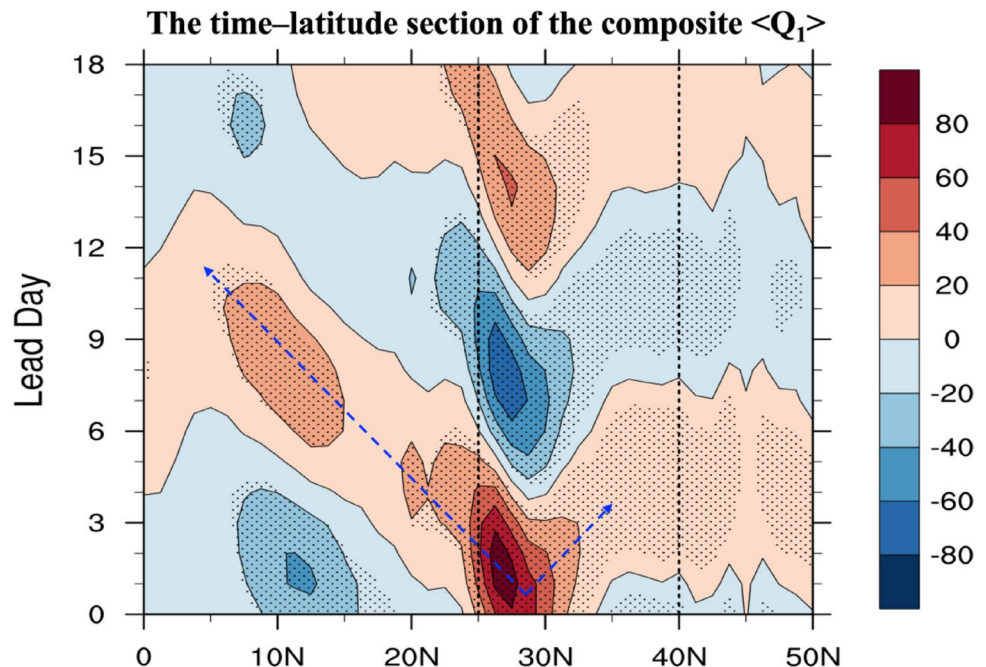
Crucially, we focus on events exhibiting concurrent bidirectional propagation. This focus allows for a simultaneous contrast of the mechanisms driving both branches within a single framework. A robust QBWO event is identified when the normalized PC1 magnitude exceeds 0.8 standard deviations (Fig. S1), with Day 0 designated as the peak convective intensity over the southern TP (annotated in Fig. 1). This EOF-based criterion objectively isolates the coherent spatiotemporal modes while filtering out random noise. To ensure the reliability, the PC1-based index was cross-validated against a 10–20-day filtered region-averaged $\langle Q_1 \rangle$ index over the southern TP ($25^\circ\text{--}32^\circ\text{N}$, $70^\circ\text{--}100^\circ\text{E}$),

yielding highly consistent results. Under these stringent criteria, 47 robust events were identified during 1979–2020 to construct the composite lifecycles.

Figure 2 illustrates the composite latitude–time cross-section of 10–20-day filtered $\langle Q_1 \rangle$ anomalies averaged over $70^\circ\text{--}100^\circ\text{E}$. The composite evolution vividly demonstrates a pronounced asymmetry between the two off-TP branches. The short-lived northward branch persists for approximately 6 days, propagating into the TP interior up to 35°N , where it converges with southward-dipping mid-latitude signals at an estimated phase speed of 2.25° latitude day^{-1} . In contrast, the southward branch exhibits remarkable longevity (~ 12 days) and spatial extension, migrating systematically equatorward past the steep southern TP slope to reach the equatorial oceans near 5°N at a slightly faster speed of 2.4° latitude day^{-1} . This substantial disparity in temporal duration, spatial footprint, and propagation speed implies that the two pathways operate under fundamentally distinct dynamical and thermodynamical environments—a feature warranting a deeper diagnostic investigation in the following sections.

The spatiotemporal evolutions of the composite 10–20-day filtered $\langle Q_1 \rangle$ and the associated moisture conditions from Day 0 to Day 18 are presented in Figs. 3 and 4. On Day 0, a robust center of positive QBWO convection coupled with strong moisture convergence is anchored over the southern TP. This localized disturbance initiates a distinct bi-directional migration by Day 2, branching simultaneously toward the higher latitudes and the monsoonal tropics. Concurrently, a pre-existing mid-latitude convective anomaly originating north of 50°N shifts southward, eventually merging with the northward-propagating branch over

Fig. 2 Composite latitude–time cross-section of the 10–20-day band-pass filtered $\langle Q_1 \rangle$ anomalies (W m^{-2}) averaged over the $70^\circ\text{--}100^\circ\text{E}$ longitudinal band for the period 1979–2020 (based on 47 robust cases). Day 0 designates the mature phase of peak convective intensity over the southern TP. The blue dashed arrows illustrate the distinct southward and northward propagating pathways, and vertical dashed lines delineate the latitudinal boundaries of the TP. Stippled areas exceed the 95% confidence level



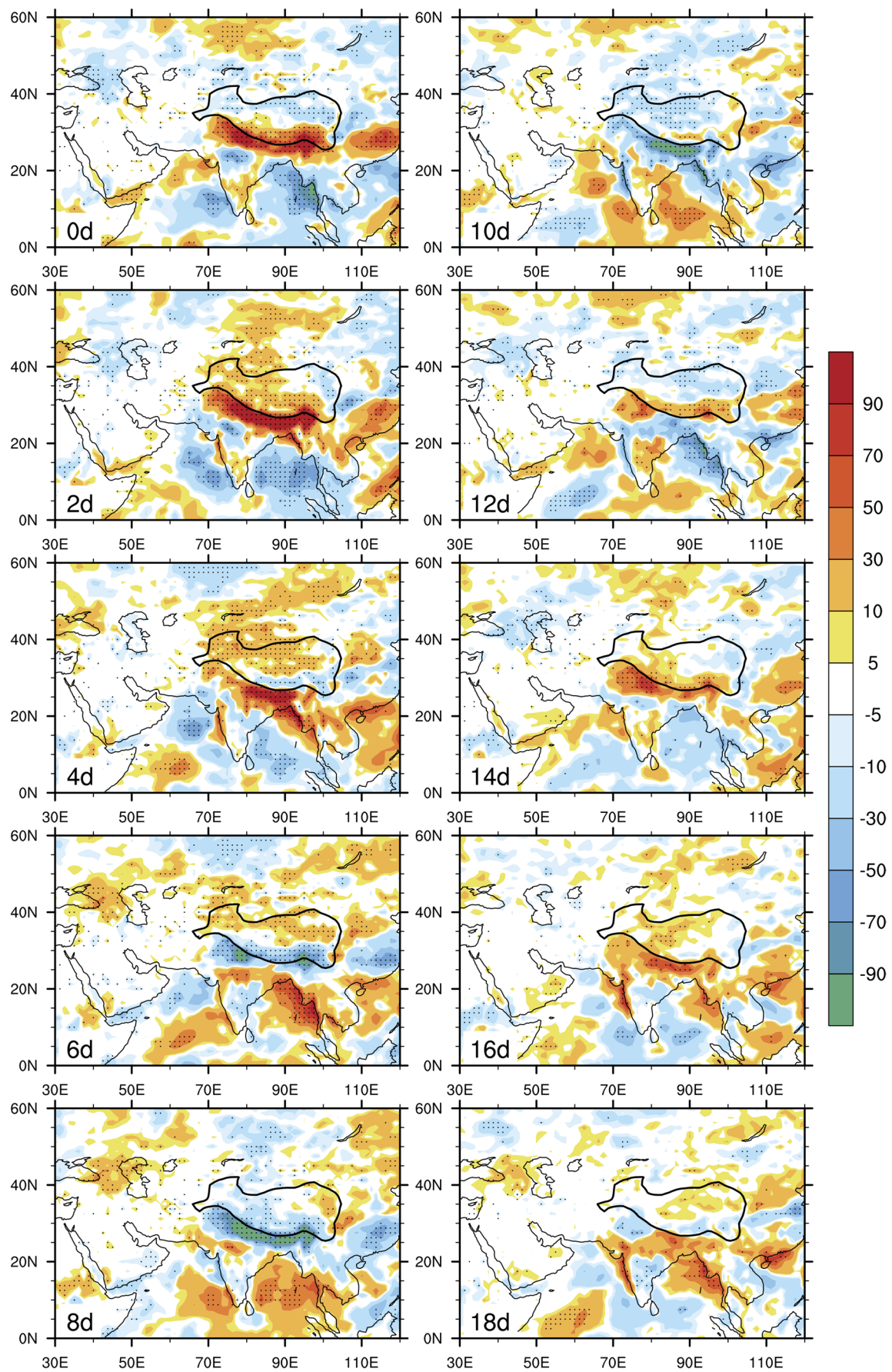


Fig. 3 Evolution of the 10–20-day filtered $\langle Q_1 \rangle$ (W m^{-2}) composite from day 0 to 18. Day 0 designates the mature phase of peak convective intensity over the southern TP. The dotted areas exceed the 95% confidence level. The black solid thick curves are drawn to indicate the TP area with height above 2000 m (the same below)

the TP interior during Days 2–4. This convergence period is characterized by prominent anomalous cyclonic moisture transport and the formation of a significant moisture convergence zone covering the central-to-northern TP. Following this interaction, the northward-propagating branch rapidly loses its thermodynamic sustenance and dissipates completely within the TP interior by Day 8.

In stark contrast, the southward branch exhibits remarkable persistence and a much larger spatial extent. The positive convective anomalies advance progressively through northern India, the Bay of Bengal (BOB), and the Indochina Peninsula by Day 6. During the early stage of this southward migration (Days 2–6), a significant anomalous anticyclonic circulation is established to the south/southwest of the main convective center (Fig. 4). Although the moisture divergence associated with this anticyclone appears to locally oppose the convective column at first glance, this spatial configuration is dynamically instrumental in steering the equatorward propagation. The anomalous northerlies on the eastern flank of the anticyclone transport dry air from higher latitudes into the rear (northern side) of the QBWO signal, facilitating its decay at the tail end. Conversely, anomalous southerlies on its western flank dramatically enhance moist advection from the tropical oceans toward the leading edge (southern side) of the disturbance. Furthermore, the divergence and associated descending motion induced by this anomalous anticyclonic circulation effectively suppress ambient convection to the south, thereby safeguarding the organized structure of the oncoming QBWO and preventing its premature dissipation.

By Day 8, the QBWO convective center fully occupies the core region of the BOB. During its subsequent mature-to-decaying phase (Days 8–12), as the signal continues its equatorward trek, the convective center and its southern periphery become embedded within a pronounced anomalous cyclonic circulation. This late-stage cyclonic configuration substantially intensifies the moisture convergence, providing robust thermodynamic replenishment that sustains the QBWO signal over the open tropical oceans. Although the convection eventually diminishes upon entering environments of lower background instability, this tight moisture-circulation coupling maintains the structural integrity of the disturbance until it systematically vanishes near 5°N by Day 14, completing its southward life cycle.

To verify that the diagnosed QBWO signals manifest as physically significant weather modulations rather than statistical artifacts of band-pass filtering, we examine the

evolution of the total, unfiltered daily precipitation anomalies during the composite cycle (Fig. 5). Utilizing the global JRA-55 precipitation dataset—which covers both land and ocean surfaces—allow us to capture the complete land-to-sea lifecycle of the QBWO, seamlessly bridging atmospheric thermodynamic diagnostics with real-world hydrological variations. To ensure the observational fidelity, a parallel composite analysis was performed using the CPC global land precipitation dataset. The resulting land-based anomalies (Fig. S2) exhibit strong spatial and phase alignment with JRA-55, confirming that the diagnosed hydroclimate responses are robust and independent of reanalysis model biases.

As shown in Fig. 5, the evolution of raw precipitation anomalies displays high spatial consistency and phase coherence with the filtered convective centers. At Day 0, a robust, zonally elongated positive precipitation center (exceeding 4 mm day^{-1}) is anchored along the southern slopes of the TP, marking the peak phase of local monsoonal convection over the rugged terrain. Following Day 0, the unfiltered precipitation clearly illustrates the bifurcated propagation of the QBWO. While a minor, short-lived rainfall signal drifts northward into the arid interior of the central TP, the primary rainband initiates a systematic, organized equatorward migration.

As this southward branch clears the topographic barrier of the TP, the rainband undergoes a pronounced secondary intensification over northern India, the northern BOB, and the Indochina Peninsula. Notably, by Day 8, the enhanced precipitation core fully occupies the warm waters of the central BOB. This continuous land-to-sea transition aligns with the late-stage anomalous cyclonic moisture convergence (Fig. 4), providing robust observational evidence that the TP-originated QBWO acts as a critical pacemaker modulating the broader South Asian summer monsoon. The southward branch exhibits remarkable persistence as it tracks equatorward across the Indian Ocean, maintaining a coherent wave-like structure before gradually decaying near 5°N around Days 12–14 as the background thermodynamic instability diminishes.

4 Physical mechanisms underlying the bi-directional propagation

4.1 Vertical structural characteristics and preliminary dynamical configurations

While horizontal diagnostics (Figs. 3 and 4) capture the propagation pathways, the underlying mechanisms are better elucidated from a meridional-vertical perspective. To isolate the essential features during initiation and bifurcation,

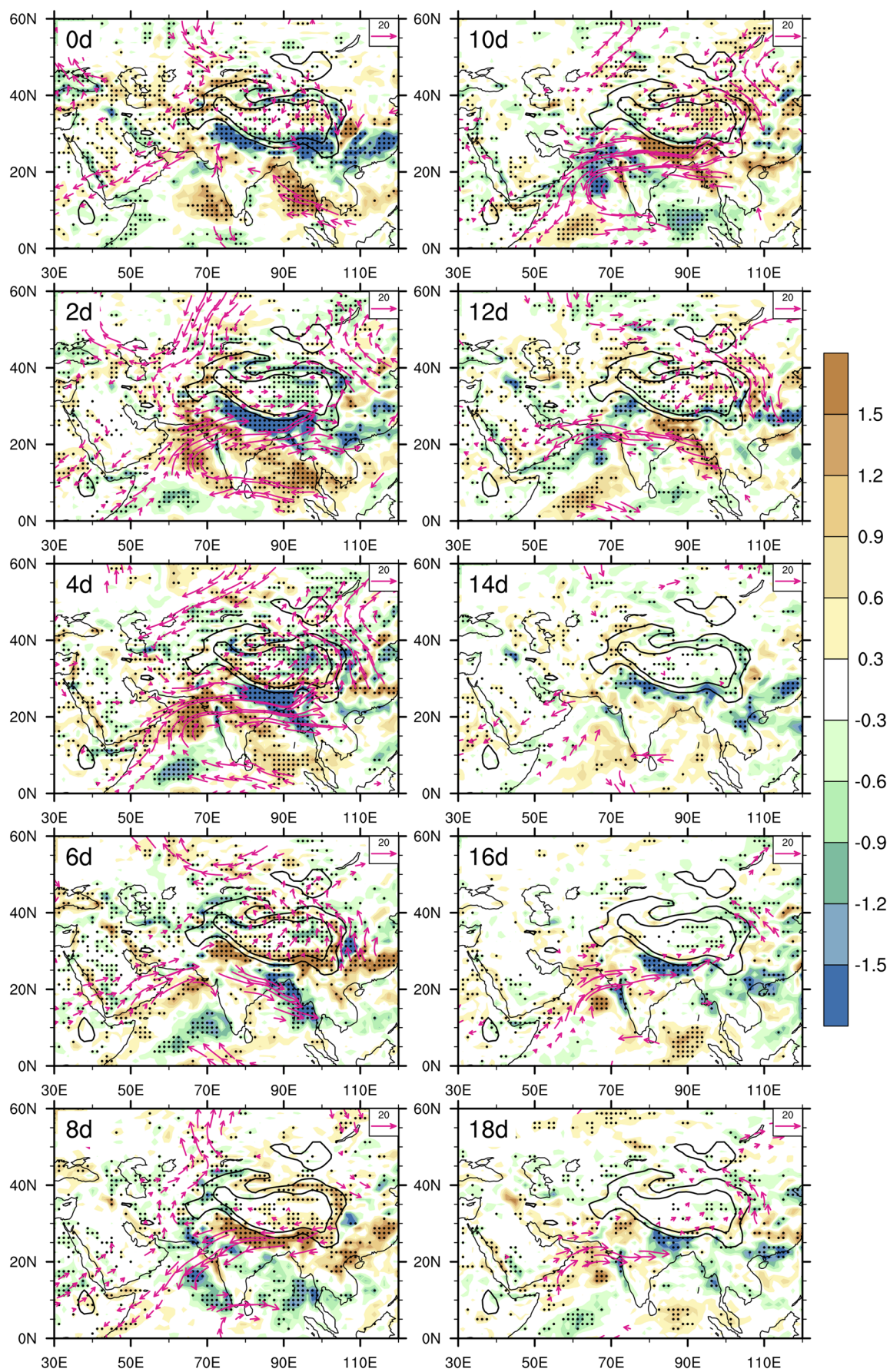


Fig. 4 As in Fig. 3, but for the 10–20-day filtered vertically integrated water vapor flux (vectors; $\text{kg m}^{-1} \text{s}^{-1}$) and moisture flux divergence ($10^{-5} \text{ kg m}^{-2} \text{s}^{-1}$). The dotted areas and vectors exceed the 95% confidence level

we examine meridional–vertical cross-sections of key atmospheric variables at Day 0 (peak intensity phase over the TP) and Day 2 (onset of spatial splitting; Fig. 6).

On Day 0 (Figs. 6a–d), the primary convective center is anchored near 28°N , marked by deep anomalous ascent extending to 100 hPa (Fig. 6a), tightly coupled with low-level convergence and upper-level divergence (Fig. 6b). Notably, a prominent low-level moisture tongue (~ 700 hPa) extends the southern flank of the convection (Fig. 6c), serving as a thermodynamic precursor for equatorward propagation. Conversely, low-level convergence is asymmetric, being visibly stronger on the northern flank (Fig. 6b). This asymmetry induces a localized cyclonic vorticity anomaly in the lower-to-middle troposphere to the north (Fig. 6d), promoting planetary boundary layer moisture convergence and driving a northward shift of convective heating, consistent with the mechanism proposed by Jiang et al. (2004).

In stark contrast, a deep, near-barotropic anticyclonic vorticity anomaly occupies the entire troposphere south of the convective center on Day 0 (Fig. 6d). Dynamically, this feature exerts a damping effect on the southward migration via associated subsidence and suppressed convergence. This sharp contrast underscores a fundamental mechanistic divergence between the two propagation branches: while the northward migration is driven by constructive, ahead-of-convection dynamical feedback, southward propagation must overcome severe dynamical resistance. Consequently, southward expansion is predominantly governed by thermodynamic priming within the lower-tropospheric moisture tongue (Fig. 6c), which overrides the unfavorable initial vorticity field.

By Day 2 (Figs. 6e–h), the structural divergence between the two branches becomes more pronounced. While the main convective center shifts to 27°N , a secondary ascending motion emerges over the central TP near 32°N . The southward branch exhibit a noticeable southward-tilted vertical structure and enhanced moisture loading aloft (Figs. 6e, g). As convection reaches the steep southern slope of the TP, low-level convergence and upper-level divergence intensify markedly (Fig. 6f), reorganizing and reinforcing the convective system as it transitions toward the tropical oceans. Conversely, the northward branch is driven by a deep, barotropic cyclonic vorticity anomaly on its northern flank (Fig. 6h), fueling a rapid initial surge of the QBWO signal into the TP interior. However, this branch is vertically constrained and lacks sustained moisture support (Figs. 6e, g). Deprived of moisture replenishment to offset intense

dynamical consumption, the northward branch rapidly dissipates within the TP interior, explaining its brief lifecycle (Fig. 3).

In summary, initial asymmetric propagation stems from contrasting physical coupling: a thermodynamically guided southward path that overcomes initial dynamical resistance, versus a dynamically driven but moisture-limited northward burst.

4.2 Northward propagation: role of the subtropical westerly jet and barotropic energy conversions (CK)

The meridional-vertical structural diagnostics in Sect. 4.1 establish that the northward-propagating QBWO branch is spearheaded by a deep, near-barotropic cyclonic vorticity column. The robust intensification of this upper-level vorticity tower as it advances into higher latitudes implies a vigorous dynamical coupling between the intraseasonal perturbation and the summer climatological background flow. Given its trajectory, the Subtropical Westerly Jet (SWJ)—characterized by intense potential vorticity gradients and pronounced horizontal wind shear—emerges as the primary energetic conduit driving this northward surge.

While vertical shear ($\partial \bar{u} / \partial z$) of the SWJ could theoretically generate anomalous vorticity via tilting of horizontal vortex tubes by convective updrafts, the vertically aligned, barotropic structure points toward a more fundamental mechanism: energy extraction from background

horizontal shear ($\partial \bar{u} / \partial y$). To quantitatively evaluate this wave-mean flow interaction, we perform a formal barotropic kinetic energy conversion (CK) diagnostic budget.

The mean dynamical environment and energy transfer distributions are illustrated in Fig. 7. The summer mean zonal wind ($\bar{u}$; Fig. 7a) features a powerful subtropical jet core centered near 40°N in the upper troposphere (200 hPa). Notably, the latitudinal band between 28°N and 35°N —where the northward branch undergoes rapid acceleration and structural expansion—coincides with the sharp southern flank of the SWJ, a region of strong meridional shear

($\partial \bar{u} / \partial y > 0$).

Total CK displays a statistically significant positive center in the upper troposphere (250–100 hPa), precisely co-located with the northward-propagating cyclonic vorticity tower (Figs. 6d, h). This spatial alignment provides unambiguous evidence that QBWO perturbations actively extract kinetic energy from the mean flow via an upscale energy transfer. Decomposing the CK budget reveals that this conversion is

overwhelmingly dominated by the meridional shear term

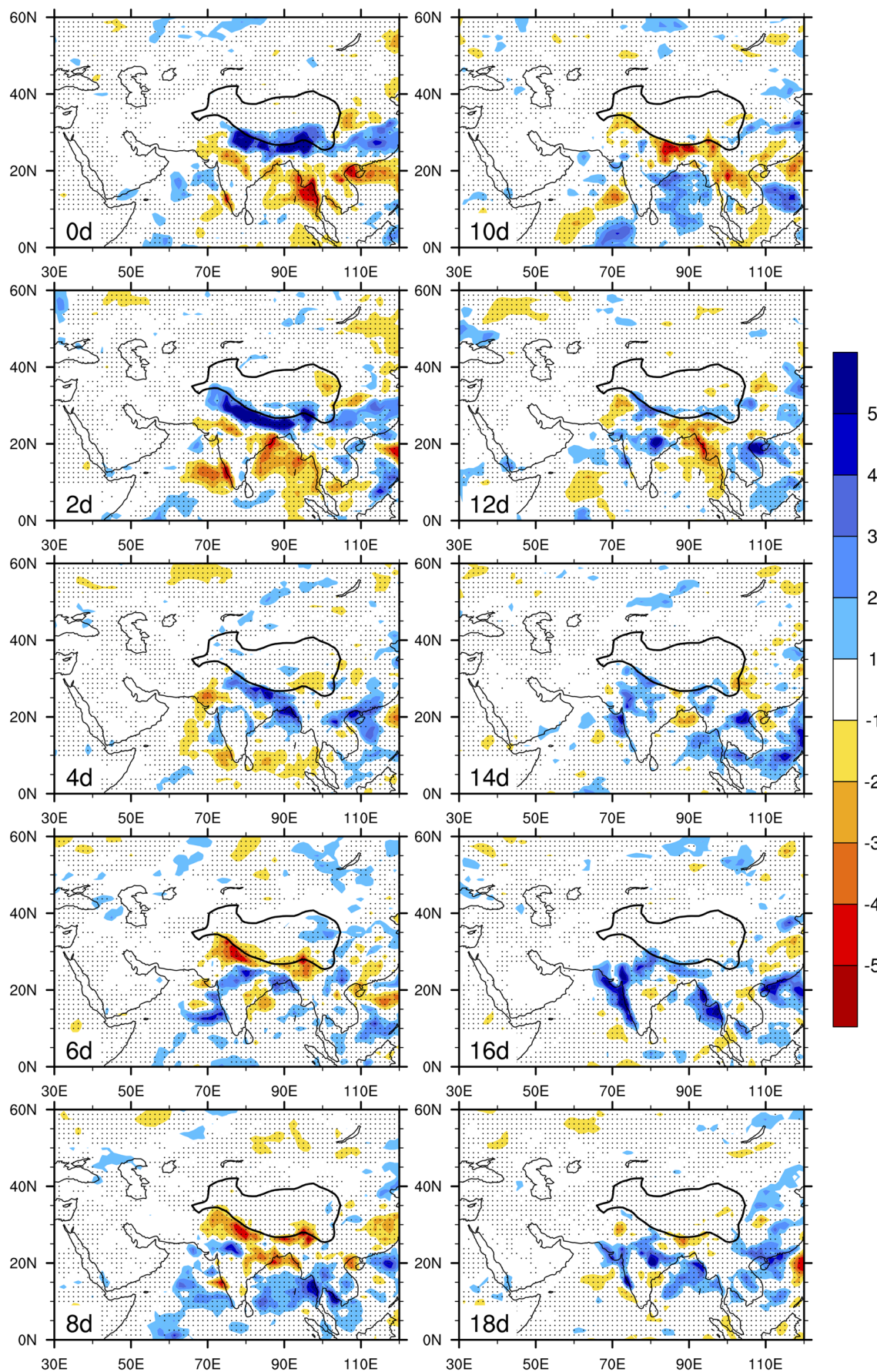


Fig. 5 As in Fig. 3, but for the raw precipitation (mm day^{-1}) from JRA-55 dataset. The dotted areas and vectors exceed the 95% confidence level

($CK3 = -u'v' \partial \bar{u} / \partial y$), as evidenced by the virtually identical spatial configuration and magnitude between total CK and $CK3$ (Fig. 7c). This confirms that anomalous eddy momentum transport ($u'v'$) interacts constructively with the jet's horizontal shear to fuel northward propagation.

Concurrently, baroclinic conversion (CP) from background available potential energy to eddy kinetic energy was examined (Fig. 7d). However, CP is markedly weaker than CK and is localized much further north (beyond 35°N). This spatial mismatch indicates that while baroclinic conversion operates near the jet axis, it plays a negligible role in the initial surge and mid-stage maintenance of the QBWO northward branch over the central TP.

Consequently, the northward propagation is identified as a primarily barotropic process fundamentally fueled by the horizontal shear of the SWJ. The heavy reliance of this branch on localized dynamical shear forcing, combined with the lack of low-level moisture-convection feedback within the TP interior, explains its rapid collapse and dissipation away from the jet's southern flank. This dynamically dominated mechanism stands in stark contrast to the thermodynamically primed, moisture-coupled pathway governing the persistent southward branch, further underscoring the fundamental asymmetry of the bifurcated TP QBWO system.

4.3 Southward propagation: MSE budget analysis and moisture advection decomposition

In contrast to the dynamically driven northward branch, the southward propagation of the TP QBWO is primarily governed by thermodynamic processes, and a localized m budget analysis is conducted (Fig. 8). Furthermore, to pinpoint the precise drivers of this thermodynamic pre-conditioning, horizontal moisture advection is decomposed into contributions from the background mean state and perturbation fields.

4.3.1 MSE budget and environmental pre-conditioning

The meridional-vertical configuration of the total m budget during the active southward migration is illustrated in Fig. 8. In Fig. 8a, a statistically significant positive m anomaly is observed in the lower-to-middle troposphere (850–600 hPa) on the southern flank of the convective center (15° – 25°N). Here, the prime (') denotes the 10–20-day bandpass-filtered anomalous field. This southward-leading m structure suggests that the atmospheric boundary layer and lower troposphere to the south are being progressively moistened and

destabilized prior to the arrival of the convective core, effectively priming a favorable thermodynamic pathway for the equatorward migration. Budget decomposition reveals that

anomalous horizontal m advection ($-(v \cdot \frac{\partial m'}{\partial y})$; Fig. 8b) serves as the dominant contributor to this pre-moistening and destabilization process, with a robust positive cell south of 28°N (850–700 hPa).

Conversely, the anomalous vertical m advection term ($-(\omega \cdot \frac{\partial m'}{\partial p})$, Fig. 8c) exhibits a meridional dipole structure (10° – 28°N). Although a localized positive vertical advection cell operates near the southern periphery, its magnitude ($\sim 10^{-6} \text{m}^2 \text{s}^{-3}$) is an order of magnitude smaller than its horizontal counterpart (Fig. 8b). This clear scale separation confirms that vertical advection plays a passive role in building up southward-leading energy anomalies. Thus, the forward deployment of the southward QBWO branch is orchestrated overwhelmingly by low-level horizontal energy advection.

According to m tendency budget (Eq. 4), the evolution of QBWO is also modulated by net radiative heating (F_{rad} ; Figs. 9a–c) and surface heat fluxes (F_{sfc} ; Figs. 9d–f). For brevity, spatial distributions from Day 0 to Day 4 are presented to illustrate the key thermodynamic feedbacks during the propagation lifecycle. The F_{rad} term (Figs. 9a–c) exhibits significant positive anomalies on both the northern and southern flanks of the convective center. Notably, it is particularly intense on the southern side of the TP, providing critical energy that promotes localized m growth. In contrast, F_{sfc} term (Figs. 9d–f) consistently displays negative anomalies across the active convective region, acting as a turbulent damping mechanism that opposes convective development. However, positive radiative forcing (F_{rad}) effectively offsets this surface energy loss, yielding a net thermodynamic driving force. Consequently, the complete m budget analysis indicates that anomalous horizontal m advection and net radiative heating are the two primary pillars driving the positive m tendency.

To examine how these energy inputs dictate convective initiation, we analyze the evolution of moist static instability—defined as the vertical m differential ($m_{850 \text{ hPa}} - m_{400 \text{ hPa}}$; Figs. 9g–i). At Day 0, a prominent positive instability anomaly is established between 15°N and 25°N (Fig. 9g), leading the convective center (28°N) by approximately 5° – 10° in latitude. This precursory destabilization is physically anchored by low-level horizontal m advection (Fig. 8b), which acts as a thermodynamic pioneer by importing high-energy tropical air northward into the subtropics.

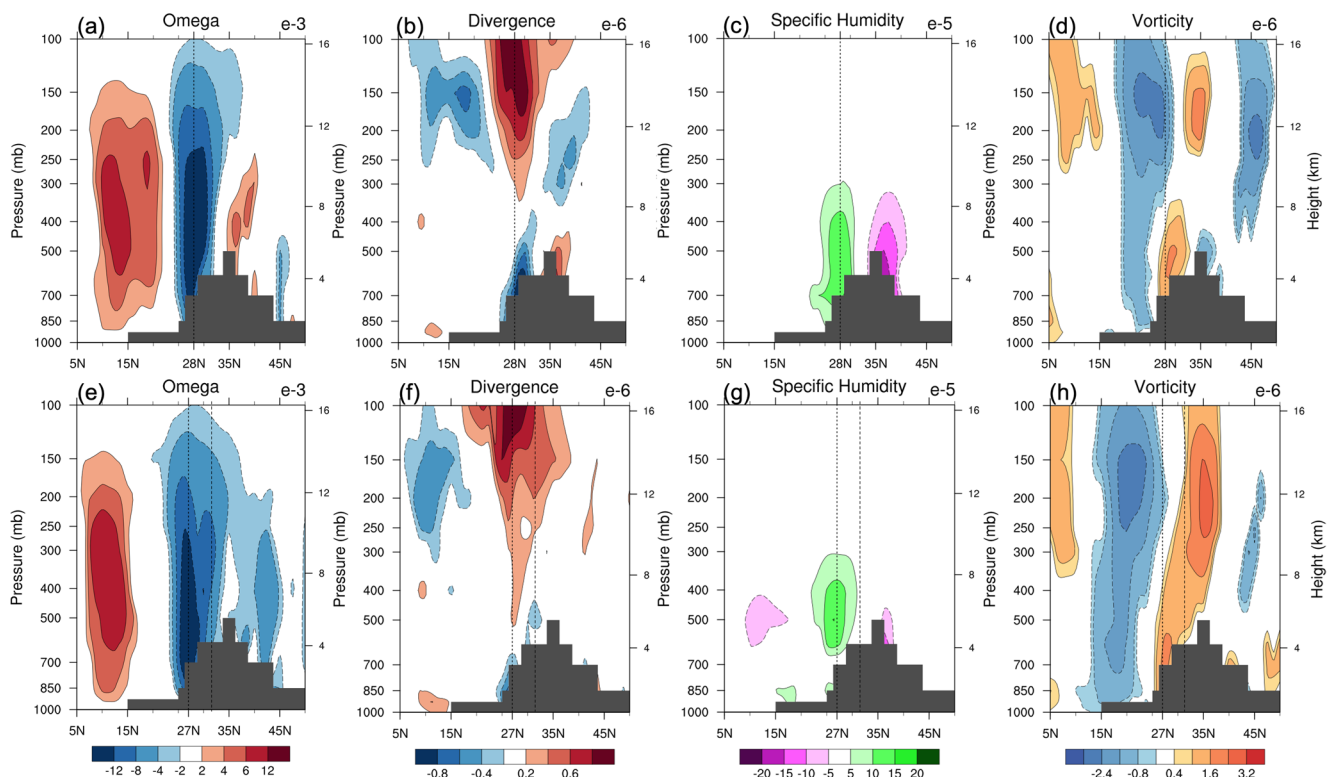


Fig. 6 Meridional-vertical structures of the bi-directional propagation of the TP QBWO cases for 10–20-day filtered **a, e** vertical velocity ($10^{-3} \text{ Pa s}^{-1}$), **b, f** divergence (10^{-6} s^{-1}), **c, g** specific humidity ($10^{-5} \text{ kg kg}^{-1}$) and **d, h** vorticity (10^{-6} s^{-1}) at **a–d** Day 0 and **e–h** Day 2.

While peak radiative heating (F_{rad} ; Figs. 9a–c) is concentrated closer to the convective core, its southern-flank extension acts synergistically with low-level moisture import to reinforce and sustain this instability zone. This spatial configuration reflects a robust thermodynamic feedback, where radiative heating seals the atmospheric column energy budget of the transitioning wave. Hence, the synergistic cooperation between horizontal m advection and radiative heating ensures that the southward-leading instability anomaly functions as a highly persistent and self-sustaining thermodynamic guide.

From Day 2 to Day 4, the instability maximum shifts progressively southward (Figs. 9h, i). Importantly, the regions previously destabilized by this thermodynamic preconditioning are subsequently captured by the southward-propagating QBWO branch. This seamless spatiotemporal transition confirms that southward branch follows the path of least resistance, migrating toward regions where the vertical m profile has been rendered most conducive to the rapid release of convective instability and deep vertical development.

To further examine the physical origin of the net radiative heating, we decompose the atmospheric column radiation budget and examine the explicit role of cloud-related

Shaded areas exceed the 90% confidence level. Vertical lines denote the maximum convection center, with 28°N at Day 0 and 27°N at Day 2 for the southward propagating QBWO and about 32°N at Day 2 for the northward propagating QBWO

processes. Figure 10 presents the evolution of the anomalous net column-integrated longwave flux and the corresponding high cloud cover from Day 0 to Day 4.

The spatial distribution of the longwave flux anomaly closely mirrors the total net radiative heating pattern observed in Fig. 9. A robust positive longwave flux anomaly is situated on the southern flank of convective center, exhibiting a systematic and well-organized southward migration over time. This localized longwave radiative heating reduces the total atmospheric column cooling, effectively acting as an internal heat source that promotes the equatorward expansion of the m maximum. In contrast, while the shortwave radiative flux anomaly also exhibits a positive signature in a similar geographical location, its magnitude is fundamentally weaker and plays a minor role in the total energy budget (Fig. S3).

Further diagnostic analysis reveals that this dominant longwave heating is intrinsically linked to the high-cloud cover. As shown in Fig. 10d–f, significant positive high-cloud cover anomalies overlap precisely with the intense longwave heating centers south of the TP. The persistent presence of these high clouds, likely consisting of deep convective anvil cirrus associated with the QBWO lifecycle,

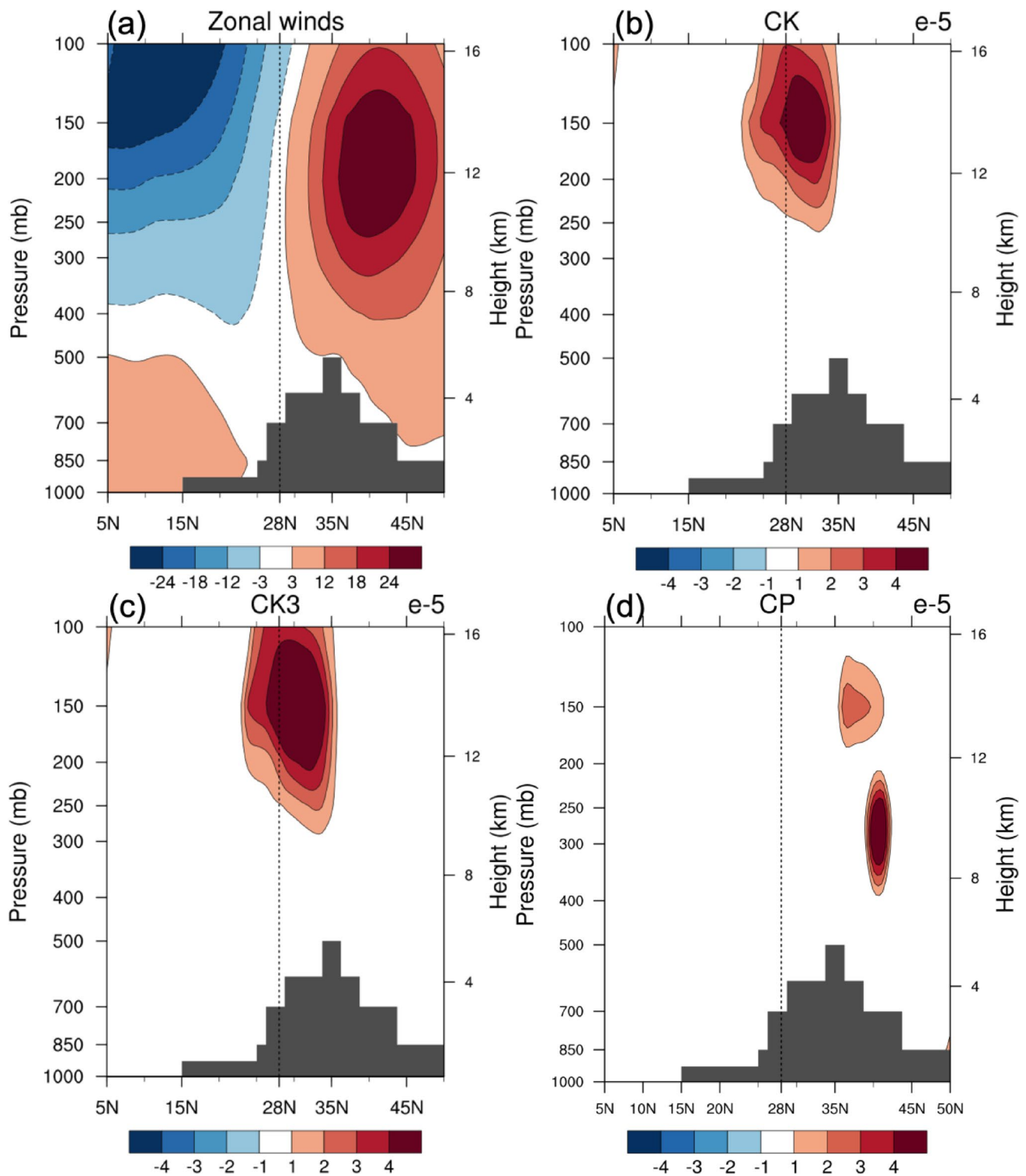


Fig. 7 As in Fig. 6, but for the meridional-vertical cross-sections of **a** climatological mean zonal winds (ms^{-1}), **b** total barotropic energy conversion (CK , $10^{-5} \text{m}^2 \text{s}^{-3}$), **c** the meridional shear term ($CK3 = -u'v' \partial \bar{u} / \partial y$, $10^{-5} \text{m}^2 \text{s}^{-3}$), and **d** total baroclinic energy conversion (CP , $10^{-5} \text{m}^2 \text{s}^{-3}$) at Day 0. In (b–d), shaded areas denote

energy conversions that are statistically significant at the 90% confidence level based on a standard two-tailed Student's t -test. The vertical dashed line indicates the latitudinal position of the maximum convective center ($\langle Q_1 \rangle$) at 28°N at Day 0

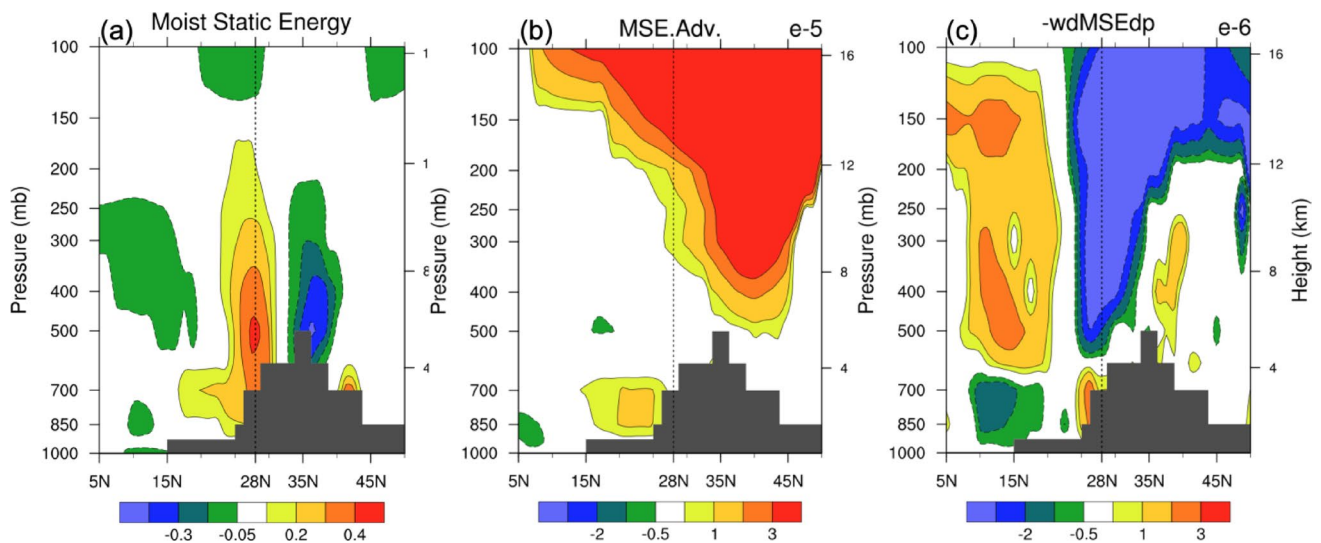


Fig. 8 As in Fig. 5, but for the 10–20-day filtered **a** moist static energy (K), **b** horizontal m advection (10^{-5} K s^{-1}), and **c** vertical m advection (10^{-6} K s^{-1}) at Day 0

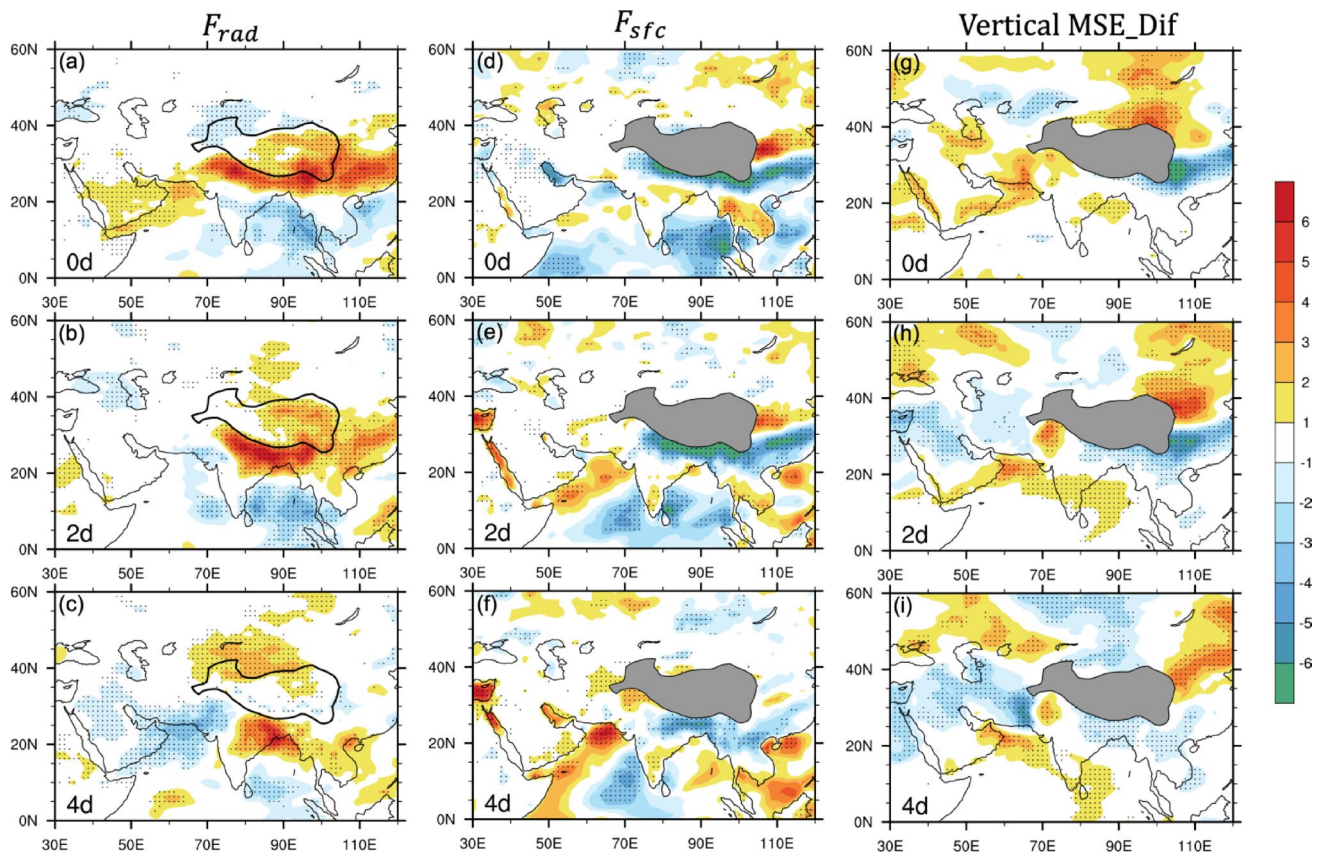


Fig. 9 Spatial distribution of 10–20-day filtered anomalies of **a–c** net column-integrated radiative fluxes (combined longwave and shortwave flux, W m^{-2}), **d–f** surface latent and sensible heat fluxes (W m^{-2}), and **g–i** moist static stability (K, calculated as $m_{850 \text{ hPa}}$ minus $m_{400 \text{ hPa}}$) at Day 0 (left column: a, d, g), Day 2 (middle column: b, e, h) and Day 4 (right column: c, f, i)

exerts a powerful greenhouse effect by trapping upward longwave radiation within the troposphere.

The southward propagation of the TP QBWO is thus governed by a robust, coupled thermodynamic chain reaction.

Initially, the low-level anomalous horizontal m advection acts as a spatial pioneer, importing high-energy tropical air northward to pre-condition and thermally destabilize the environmental column south of the TP. This environmental

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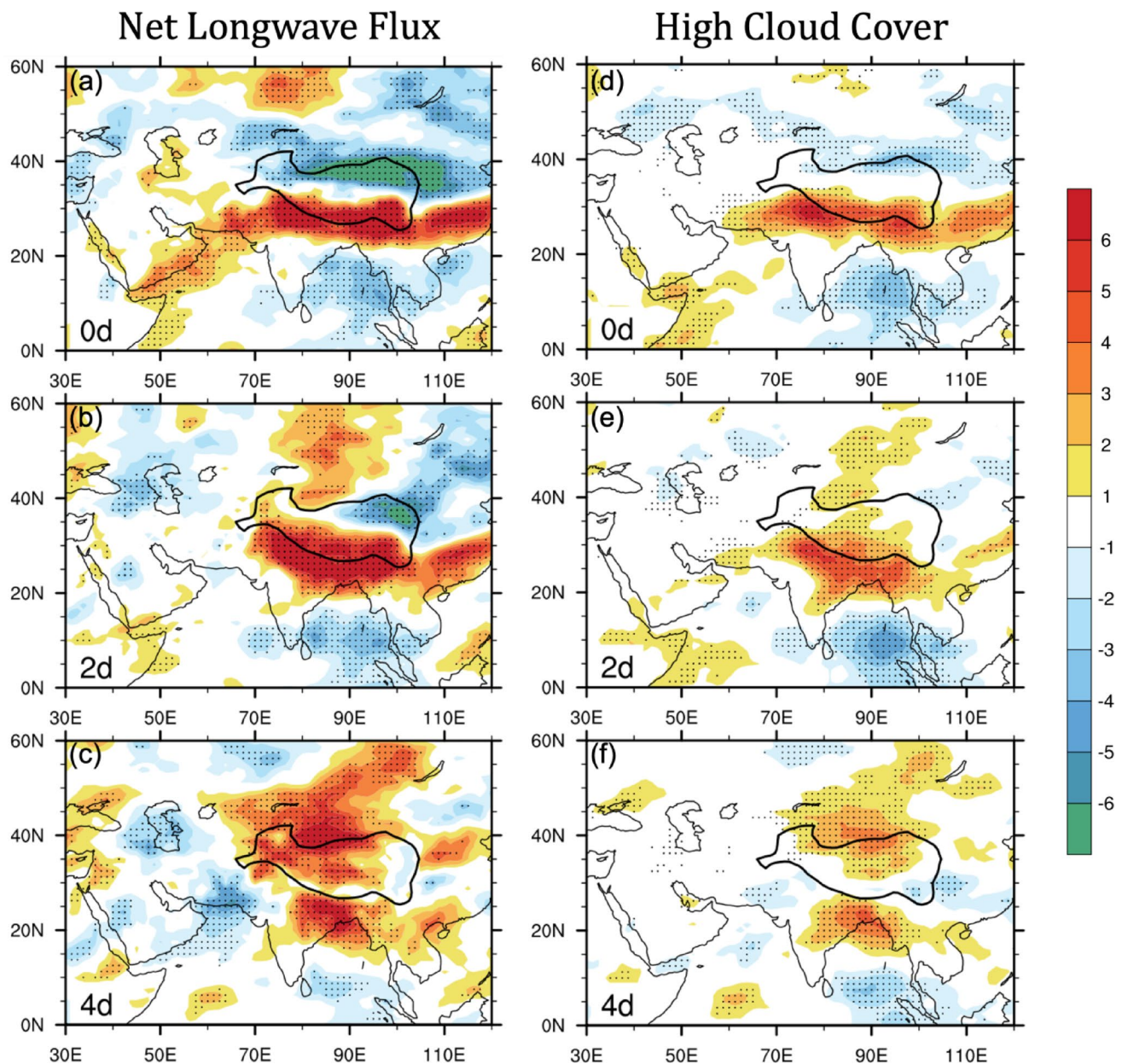


Fig. 10 As in Fig. 8, but for 10–20-day filtered anomalous **a–c** net column-integrated longwave radiative flux (W m^{-2}), and **d–f** high cloud cover (%)

destabilization effectively lowers the threshold for convective triggering, facilitating organized convection growth and the subsequent accumulation of high clouds. The resulting anomalous longwave radiative heating provides a critical positive feedback—by suppressing column cooling, it further reinforces and maintains the moist static instability in phase with the southward-advancing convective core. This synergistic interaction enables the TP-originated QBWO to continuously tap into the tropical marine energy reservoir, sustaining its long-lived lifecycle across the South Asian summer monsoon system.

4.3.2 Drivers of horizontal moisture advection

Given that the horizontal m advection is identified as the primary pioneering force for southward migration, we further decompose this term to isolate the precise underlying physical processes. Figure 11 illustrates the spatial-vertical configuration of the key decomposed components at Day 0. Among the constituent energy terms, the anomalous

horizontal latent heat advection ($-(v \cdot \frac{\partial Lq'}{\partial y})$, Fig. 11a)

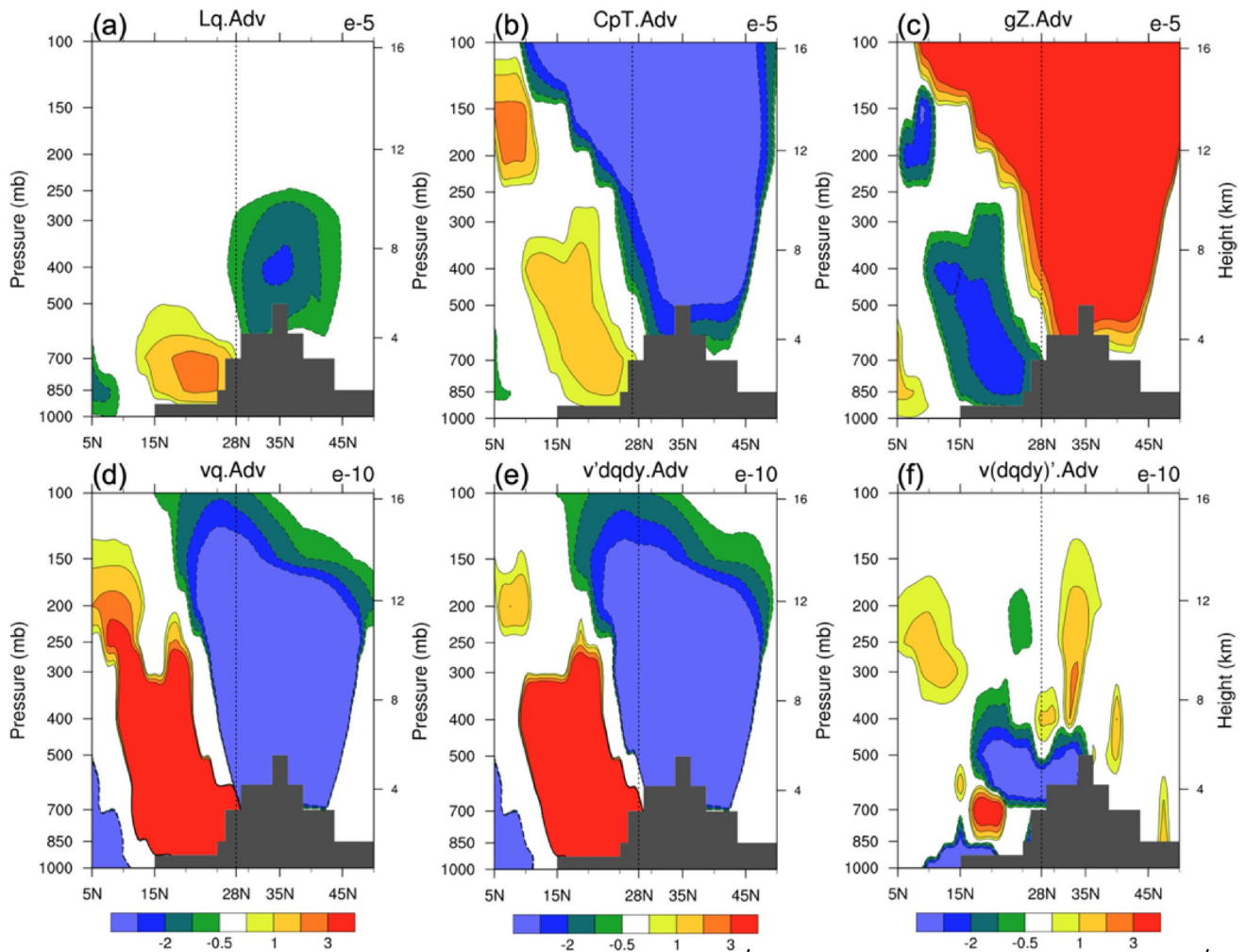


Fig. 11 As in Fig. 8, but for 10–20-day filtered decomposed **a–c** horizontal m advection terms (10^{-5} K S^{-1}) and **d–f** meridional moisture advection term ($10^{-10} \text{ kg kg}^{-1} \text{ s}^{-1}$) at Day 0: **a** horizontal latent heat advection ($-(v \frac{\partial Lq}{\partial y})'$), **b** horizontal sensible heat advection ($-(v \frac{\partial c_p T}{\partial y})'$), and **c** horizontal geopotential height advection

($-(v \frac{\partial gz}{\partial y})'$); **d** total meridional moisture advection ($-(v \frac{\partial q}{\partial y})'$), **e** advection of background moisture gradient by anomalous meridional wind ($-v' \frac{\partial \bar{q}}{\partial y}$), and **f** advection of anomalous moisture gradient by mean meridional wind ($-\bar{v} (\frac{\partial q}{\partial y})'$). The gray shading denotes the TP topography

emerges as the overwhelming contributor, capturing nearly the entire spatial structure and magnitude of the total horizontal m advection (Fig. 8b). This energetic dominance confirms that the precursory southward shift of the energy maximum is essentially a moisture-driven process

($-(v \cdot \frac{\partial q}{\partial y})'$, Fig. 11d) rather than a sensible heat-driven one.

To precisely isolate the dynamic and thermodynamic interactions within this transport, the anomalous meridional moisture advection is further mathematically expanded into its linear components:

$$-(v \cdot \frac{\partial q}{\partial y})' = -v' \frac{\partial \bar{q}}{\partial y} - \bar{v} (\frac{\partial q}{\partial y})' \quad (5)$$

where the prime () denotes the 10–20-day filtered anomalous fields and the overbar () represents the June–August climatological mean background state.

Diagnostic results reveal that this positive tendency south of the TP is almost exclusively governed by the advection of the climatological background moisture gradient

by the anomalous meridional winds ($-v' \frac{\partial \bar{q}}{\partial y}$, Fig. 11e).

Geographically, the sharp southern slopes of the TP and the broader South Asian summer monsoon region are inherently characterized by a remarkably steep, high-entropy climatological moisture gradient, with specific humidity increasing rapidly equatorward. During the initiation phases (Days 2–4), the anomalous wind field exhibits a robust anticyclonic circulation anchored over the eastern BOB and the adjacent Indochina Peninsula (Fig. 4). The anomalous southerly winds ($v' > 0$) on the western flank of this anticyclonic cell directly impinge upon this background moisture reservoir, pumping high-energy tropical moisture northward onto the southern TP slopes. This constructive interaction induces a strong positive moisture advection anomaly directly within the 15°–25°N latitudinal zone (Fig. 11e), pre-conditioning and destabilizing the local troposphere ahead of the convective core.

In summary, a comparison between the two branches reveals that the observed propagation asymmetry is driven by distinct physical mechanisms rather than passive advection by background steering flows. The northward branch relies strictly on barotropic energy conversion from the upper-level jet shear and decays rapidly due to the lack of low-level moisture support (Sect. 4.2). In contrast, the southward propagation is sustained by a robust thermodynamic-dynamic coupling process: anomalous southerly winds associated with the large-scale circulation continuously tap into the steep monsoon moisture gradient, providing the essential moisture and instability required for its long-lived persistence south of the TP.

5 Conclusions and discussions

5.1 Conclusions

In this study, the systematic meridional propagation characteristics and underlying thermodynamic-dynamic mechanisms of the TP QBWO during boreal summer are comprehensively investigated. Based on composite analysis of robust propagation cases and meticulous energy diagnostics, the primary conclusions are summarized as follows.

- (1) The TP QBWO convective anomalies exhibit a striking, asymmetric meridional propagation pattern, characterized by simultaneous northward and southward movements. While the northward-propagating branch rapidly decays into the TP interior, the southward branch successfully breaches the steep topographic barrier of the Himalayas, systematically advancing into the tropical South Asian monsoon region (15°–25°N) before finally dissipating over the Indian Ocean near 5°N.

- (2) The evolution and rapid decay of the northward-propagating branch are primarily dictated by upper-tropospheric wave-mean flow interactions associated with the mid-latitude SWJ. Diagnostic analyses reveal that while the perturbations initially grow by extracting kinetic energy from the jet's southern flank via barotropic conversion (CK), this dynamic fueling abruptly vanishes near the jet core as the background shear gradient reverses. Furthermore, the lack of low-level moisture support accelerates its rapid dissipation.
- (3) In stark contrast, moist static energy (m) budget diagnostics demonstrate that the sustained equatorward migration of the southward branch is fundamentally a moisture-driven thermodynamic process. Horizontal m advection acts as the primary pioneering force initiating and guiding this southward advance, heavily dominated by the horizontal latent heat advection term $(-v' \cdot \frac{\partial Lq}{\partial y})$ in the lower troposphere (850–700 hPa).
- (4) Mathematically, the pioneering moisture transport sustaining the southward branch is predominantly governed by the advection of the steep climatological background moisture gradient by anomalous meridional winds $(-v' \frac{\partial q}{\partial y})$. Anomalous low-level horizontal advection acts as the primary driver, pre-moistening and destabilizing the lower atmosphere between 15°N and 25°N—leading the convective core (28°N) by 5°–10° in latitude—prior to its arrival. This pre-conditioning lowers the threshold for convective triggering, facilitating organized convective growth and the subsequent accumulation of high clouds. Concurrently, the resulting anomalous longwave radiative heating provides a critical positive feedback by suppressing column cooling, which reinforces and maintains the moist static instability ahead of the convective core. This synergistic cooperation between horizontal m advection and cloud-radiative feedback establishes a highly persistent, self-sustaining thermodynamic pathway, allowing the southward branch to seamlessly migrate toward lower latitudes along the path of least resistance.

5.2 Discussions

Based on the diagnostic findings of this study, several critical aspects regarding the physical constraints, methodological robustness, and broader weather-climate implications of the TP QBWO merit further discussion.

It should be clarified first that while this study details the meridional propagation of established TP QBWO perturbations, their upstream origin and initiation mechanisms

remain outside our primary scope. As documented in previous literature (Wang and Duan 2015; Hu et al. 2016; Yang et al. 2017; Wang et al. 2018; Zhu et al. 2025, 2026), the initial excitation of the TP QBWO is a complex process driven by high-latitude wave trains, tropical convective perturbations, and localized thermal interactions. This study deliberately focuses on a more critical yet less understood question: once a robust QBWO signal is established over the TP, what thermodynamic and dynamic processes dictate its systematic off-TP meridional propagation? Unraveling these mechanisms represents a vital step toward bridging the gap between TP dynamic processes and tropical monsoon dynamics, specifically highlighting the relative contribution of TP thermal forcing versus tropical background signals.

From a methodological perspective, a potential concern when diagnosing such oscillations via band-pass filtering is whether the identified signals represent physically real weather modulations or are merely statistical artifacts. Furthermore, since the atmospheric apparent heat source ($\langle Q_1 \rangle$) over the summer TP is inherently coupled with latent heat release, the strong alignment between $\langle Q_1 \rangle$ -derived QBWO phases and precipitation fields warrants careful interpretation to avoid circular reasoning. Crucially, our analysis addresses these concerns by demonstrating that these robust precipitation signals manifest clearly and coherently in total, unfiltered daily anomalies (Fig. 5). The fact that independent, raw rainfall fields over both land (CPC, Fig. S2) and ocean (JRA-55) successfully reproduce the bifurcation lifecycle confirms that the diagnosed TP QBWO is a physically real entity that exerts substantial real-world hydrological modulation, rather than functioning as a byproduct of data processing.

In terms of the underlying mechanisms, while the southward branch exhibits remarkable scale and persistence, the rapidly decaying northward branch provides an indispensable counterpart for understanding the complete bifurcation. Crucially, the applicability of our diagnostic frameworks is dictated by the opposite ambient environments flanking the TP. Over the warm, moisture southern flank (South Asia/BOB), the southward branch operates as a moist, convection-coupled mode, governed by pioneering low-level moisture advection and reinforced and sustained by cloud-radiation feedback. Conversely, over the arid northern flank lacking boundary-layer moisture replenishment, the thermodynamic m framework is physically unwarranted. Instead, as diagnosed in Sect. 4.2, the northward branch behaves as a dry dynamical Rossby wave-guided mode, relying strictly on upper-tropospheric barotropic energy extraction (CK) from the Subtropical Westerly Jet and collapsing rapidly once it leaves the jet-shear region. Ultimately, this sharp environmental moisture contrast acts as the primary arbiter of the asymmetric bifurcation, aligning with the theoretical

consensus that background states heavily regulate the moist dynamics and wave guides of subseasonal signals (e.g., Wang and Xie 1997; Jiang et al. 2004; Li et al. 2022).

Importantly, the systematic breakthrough of the TP QBWO southward branch into lower latitudes exerts a profound downstream teleconnection on the South Asian summer monsoon region. Previous studies have long recognized the impact of tropical intraseasonal oscillations propagating northward from the equatorial Indian Ocean to modulate South Asian weather (Jiang et al. 2004; Drbohlav and Wang 2005; Goswami et al. 2006; Wang and Duan 2015; Dey et al. 2022). However, our findings highlight an alternative, top-down pathway: the southward-advancing QBWO envelopes originating from the TP provide a favorable large-scale thermodynamic background that can effectively modulate regional convective activities over Northeast India and the BOB. As the southward branch descends from the high-altitude plateau, the associated southward-leading positive m anomalies and lower-tropospheric moisture advection tend to enhance low-level southwesterly flows and moisture convergence. This top-down modulation creates highly conducive conditions for the clustering of monsoonal hydrological extremes in flood-prone regional basins (Goswami and Mohan 2001; Kulkarni et al. 2011; Misra and Jayasankar 2026). Intriguingly, during its suppressed phases, the anomalous subsidence and enhanced surface solar radiation associated with this descending wave can rapidly deplete soil moisture, thereby contributing to the triggering of regional flash droughts over South Asia. This offers a fresh, comprehensive perspective on mid-latitude-tropical interactions and disaster mitigation.

Ultimately, the low-frequency evolution and systematic southward trajectory of the TP QBWO carry profound practical implications for Sub-seasonal to Seasonal (S2S) climate prediction, potentially opening distinct subseasonal “prediction windows of opportunity” (Vitart and Robertson 2018; Mariotti et al. 2020) for downstream extreme hydrological events across East and South Asia. Specifically, once a strong QBWO thermal anomaly is established over the southern TP, this pathway offers a broad, high-skill prediction window with extended lead times for extreme precipitation over Southern China, the northern South China Sea, and South Asia (Fig. 5). Our evolutionary analysis hints that incorporating m -derived thermodynamic pre-conditioning parameters into state-of-the-art S2S numerical models offers promising prospects for extending the forecast lead time of downstream monsoonal anomalies. Due to space limitations and our strict focus on fundamental mechanisms here, a comprehensive and quantitative evaluation of these downstream predictability gains was omitted. Future research is highly warranted to systematically quantify the precise regulatory roles and operational forecast skills of

this TP-conceived southward-propagating wave on tropical monsoon extremes, which bears substantial scientific and socioeconomic significance.

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Data availability The JRA-55 reanalysis data are publicly available from the Japan Meteorological Agency (JMA) at https://www.data.jma.go.jp/jra/html/JRA-55/index_en.html. The NOAA Climate Prediction Center (CPC) global precipitation data can be accessed via the website at <https://psl.noaa.gov/data/gridded/data.cpc.globalprecip.html>.

Declarations

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

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