

Article

Relative-Humidity Decomposition of July Rainfall Anomalies over the Middle–Lower Yangtze River Basin Associated with Eastern Mediterranean–West Asian March Precipitation

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Abstract

Seasonal prediction of summer rainfall over the middle and lower reaches of the Yangtze River Basin (MLYRB) remains challenging because the linkage between preceding climate signals and regional precipitation anomalies involves complex dynamic and thermodynamic processes. This study examines March precipitation over the eastern Mediterranean–West Asia region, hereafter referred to as PE, as an upstream spring signal associated with July rainfall anomalies over the MLYRB. The central objective is to determine, through a relative humidity decomposition framework, whether the humidification accompanying PE-related July rainfall anomalies is dominated by moisture changes or by temperature-related saturation effects. The results indicate that high-PE years are associated with a significant increase in July rainfall over the MLYRB. This rainfall enhancement is accompanied by anomalous circulation patterns favourable for moisture transport and convergence over eastern China. Meanwhile, positive relative humidity anomalies extend from the lower to the upper troposphere, with the 400 and 300 hPa levels showing a particularly close spatial correspondence with the significant rainfall anomalies over the rainfall region. Although absolute water vapour content decreases with height, the coherent upper-tropospheric relative humidity response indicates the presence of a deep moist layer, which is favourable for sustained condensation, reduced dry-air entrainment, and persistent monsoon rainfall. A further moisture–temperature decomposition shows that the PE-related relative humidity response is jointly controlled by changes in atmospheric moisture content and saturation vapour pressure. Over the MLYRB, the increase in relative humidity is primarily associated with enhanced moisture content, whereas temperature-induced changes in saturation conditions are more evident in regions with more coherent temperature anomalies. These findings suggest that the PE-related July rainfall anomaly is supported by a combination of dynamic moisture supply and thermodynamic humidification of the atmospheric column. The study provides a physically consistent explanation for the potential precursor relevance of the PE signal and emphasizes the importance of vertical humidity structure in understanding and predicting summer rainfall anomalies over eastern China.



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1. Introduction

Summer rainfall over the MLYRB is one of the most important components of East Asian summer monsoon precipitation. The region is densely populated, economically developed, and highly vulnerable to hydrological extremes. Abnormal midsummer rainfall over the MLYRB can lead to severe floods or droughts, thereby affecting water-resource management, agricultural production, transportation, and disaster prevention. Previous studies have shown that summer rainfall anomalies over the Yangtze River Basin are closely related to large-scale circulation anomalies, including the western North Pacific subtropical high, tropical–extratropical interactions, and midlatitude circulation disturbances [1–3]. However, seasonal prediction of MLYRB rainfall remains challenging because precipitation variability in this region is jointly regulated by tropical oceanic forcing, western North Pacific subtropical high variability, midlatitude circulation anomalies, and regional land–atmosphere interactions [4–10]. The identification of physically meaningful cross-seasonal precursors is therefore essential for improving the understanding and prediction of midsummer rainfall anomalies over the MLYRB.

Previous studies have shown that East Asian summer rainfall is influenced not only by contemporaneous monsoon circulation but also by antecedent thermal, hydrological, and circulation anomalies over upstream regions. During boreal spring, defined here as March–May, antecedent anomalies such as Eurasian snowmelt, soil moisture, Tibetan Plateau heating, North Atlantic variability, and tropical sea surface temperature (SST) forcing can modulate downstream atmospheric circulation and moisture transport toward East Asia [11–17]. For example, spring snowmelt over Eurasia may influence subsequent East Asian summer rainfall through land–atmosphere coupling and downstream circulation adjustment [15]. The North Atlantic Oscillation (NAO) can modulate the North Atlantic–Eurasian teleconnection and affect rainfall distributions over eastern China [11,12]. Tropical SST anomalies associated with ENSO and Indian Ocean variability can further affect the western North Pacific subtropical high, the South Asian High, and East Asian rainfall through large-scale atmospheric bridges and wave-activity pathways [13,16,17]. These antecedent signals indicate that cross-seasonal rainfall predictability over the MLYRB may arise from both tropical forcing and upstream extratropical hydroclimatic anomalies.

In this context, the eastern Mediterranean–West Asia (EMWA) sector deserves attention because it is located near the upstream portion of the Eurasian subtropical jet. This sector is dynamically connected to the Eurasian waveguide, through which upper-tropospheric circulation anomalies may propagate toward East Asia. The Silk Road Pattern and related Eurasian teleconnection structures have been widely recognized as important pathways linking upstream Eurasian circulation anomalies to East Asian summer climate [18,19]. In addition, previous studies have emphasized that diabatic heating, hydrological anomalies, and thermal forcing over upstream regions can influence downstream wave trains and monsoon rainfall over China [20,21]. Therefore, spring hydroclimatic anomalies over the EMWA region may provide useful information for subsequent rainfall variability over East Asia. March precipitation over the EMWA region, hereafter referred to as PE, represents such a spring hydrological anomaly upstream of the Eurasian–East Asian circulation pathway.

Before the thermodynamic role of PE can be interpreted, its relationship with July rainfall over the MLYRB needs to be independently evaluated. A statistically meaningful

PE–MLYRB rainfall relationship would provide a basis for examining whether the associated rainfall anomalies are supported primarily by moisture changes or by temperature-related saturation changes. Such a diagnosis is important because enhanced rainfall does not depend solely on increased water-vapour supply. The formation of precipitation also requires a favourable saturation environment. Water vapour provides the direct material basis for precipitation, whereas temperature controls saturation vapour pressure and hence modulates the atmospheric capacity to hold water vapour. Previous studies have shown that water-vapour transport plays a central role in regional precipitation anomalies, especially in monsoon regions [22–25]. However, precipitation variability is also closely linked to relative humidity, which incorporates the combined effects of moisture and temperature [26–28]. Atmospheric saturation is a necessary condition for precipitation formation, which depends on both water vapour and air temperature. It has been found that the seasonal precipitation holds a very strong positive linkage to the seasonal mean relative humidity of the atmosphere [26,27]. Relative humidity can better characterize the interannual variation in the seasonal precipitation than specific humidity [28]. Therefore, temperature and vapour can both affect the formation of precipitation. The key question addressed here is whether the PE-related humidification over the MLYRB is primarily associated with enhanced moisture content or with temperature-induced changes in saturation conditions.

Relative humidity provides a useful bridge linking moisture, temperature, and precipitation. According to the definition of relative humidity, its variation can be decomposed into a moisture-related term and a temperature-related term. This framework has been used to quantitatively compare the relative contributions of water vapour and temperature to precipitation-related humidity changes [28–32]. In previous work on the influence of spring Tibetan Plateau heating on midsummer precipitation in China, this method was applied to separate the effects of water vapour and temperature and to identify the dominant contributor to regional precipitation anomalies. That study showed that water vapour generally played a more important role in major river basins, although temperature contributions were also regionally important in parts of northern China. This method is therefore suitable for diagnosing whether precipitation anomalies associated with PE are moisture-dominated or temperature-dominated.

Such a moisture–temperature decomposition is particularly relevant for the PE-related rainfall response over the MLYRB. If positive PE anomalies are accompanied by increased relative humidity and enhanced rainfall over the MLYRB, the next question is whether this humidification is mainly caused by increased moisture supply or by temperature changes that reduce saturation vapour pressure. A moisture-dominated response would indicate that PE-related rainfall anomalies are closely tied to water-vapour transport and moisture convergence. In contrast, a temperature-dominated response would suggest that local thermal conditions and cold air play a more important role. Distinguishing between these two pathways can provide a more specific thermodynamic explanation for the cross-seasonal linkage between EMWA spring precipitation and MLYRB midsummer rainfall.

The central objective is to determine, through a relative humidity decomposition framework, whether the humidification accompanying PE-related July rainfall anomalies is dominated by moisture changes or by temperature-related saturation effects. The present analysis first evaluates the statistical relationship between March EMWA precipitation and July rainfall over the MLYRB using correlation, regression, and composite analyses. The associated relative humidity, specific-humidity, and temperature responses are then examined to identify the thermodynamic characteristics of the rainfall anomaly. A relative humidity-based decomposition is applied to quantify the respective contributions of moisture and temperature, and moisture-transport diagnostics are used to interpret the circulation background supporting the dominant contribution. This framework is designed to

clarify whether the PE-related July rainfall anomaly over the MLYRB is primarily controlled by moisture supply or by temperature-related saturation adjustment.

The remainder of this paper is organized as follows. Section 2 describes the datasets and the statistical and diagnostic methods used in the analysis. Section 3 presents the relationship between PE and July rainfall over the MLYRB, followed by the associated relative humidity, specific-humidity, and temperature responses. Section 4 discusses the physical implications of the moisture-dominated response and the limitations of the diagnostic framework. The main conclusions are summarized in Section 5.

2. Data and Methods

2.1. Data

Monthly precipitation observations over China were obtained from the CN05.1 gridded observational dataset. CN05.1 is a high-resolution gridded dataset constructed from dense station observations in China and has been widely used to represent regional precipitation variability [33,34]. In this study, CN05.1 precipitation was used to define the July rainfall index over the MLYRB and to examine the spatial pattern of July rainfall anomalies associated with the precursor index. Large-scale atmospheric and surface variables were obtained from the ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [35]. The ERA5 variables used in this study include monthly precipitation, horizontal winds, air temperature, and specific humidity. Pressure-level variables, including zonal wind, meridional wind, temperature, and specific humidity, were used to diagnose the thermodynamic and moisture-transport conditions associated with July rainfall anomalies over the MLYRB. The ERA5 data used have a horizontal resolution of $1.0^\circ \times 1.0^\circ$. The pressure-level analyses include 850, 700, 600, 500, 400, 300, and 200 hPa for the humidity and thermodynamic diagnostics. For conciseness, results at four levels including 850, 500, 400, and 300 hPa are shown. ERA5 precipitation was used to define and examine the upstream precipitation precursor over the EMWA region. The common study period for CN05.1 and ERA5 was 1961–2023. All variables were converted to monthly anomalies by removing their climatological monthly means over the study period. Unless otherwise stated, anomalies were standardized before regression and correlation analyses so that the regression coefficients represent the response associated with a one-standard-deviation change in the precursor index. The first empirical orthogonal function (EOF) modes derived from the two datasets are consistent (Figure S1).

2.2. Definition of PE and MLYRB Rainfall Indices

The MLYRB is a key region of the East Asian summer monsoon and is strongly affected by Meiyu rainfall variability. July rainfall over this region was selected because it represents a mature phase of midsummer rainfall variability and is closely related to regional drought and flood risk [36]. To define the target region for prediction, an area located in the central part of the MLYRB was selected ($117\text{--}118^\circ \text{ E}$, $30\text{--}31^\circ \text{ N}$). July precipitation over this area was first averaged to obtain a reference precipitation time series. To examine the spatial coherence of July precipitation variability, the correlation coefficients between the regional mean precipitation series and July precipitation at all grid points across China are shown in Figure S2. The resulting correlation field exhibits a distinct zonal belt-shaped pattern. Within this area, many grid points show correlations above 0.8, indicating strong interannual coherence of July precipitation variability. The domain was chosen as the prediction region for subsequent analyses and is marked with a parallelogram ($113\text{--}121^\circ \text{ E}$, $28.5\text{--}31^\circ \text{ N}$ and $30.5\text{--}33^\circ \text{ N}$) in Figure S2.

The EMWA spring precipitation precursor, referred to as PE, was defined as the area-averaged March precipitation anomaly over the EMWA domain ($28\text{--}32^\circ \text{ N}$, $28\text{--}38^\circ \text{ E}$). PE

was selected based on preliminary predictor screening for July MLYRB rainfall. In that screening, March precipitation over the EMWA region emerged as one of the retained upstream hydrological predictors after multicollinearity control and cross-validated regression. The region of EMWA and the composite precipitation around there is shown in Figure S3. The present study focuses on diagnosing the thermodynamic and moisture-transport conditions associated with this specific precursor. Based on the upstream location of this region relative to the Eurasian subtropical jet and its preliminary statistical relationship with July rainfall over East Asia, the EMWA domain was selected as a candidate hydrological precursor region. The PE index was standardized before statistical analysis.

2.3. Correlation, Regression, and Composite Analyses

Linear correlation and regression analyses were used to examine the statistical relationship between PE and July rainfall over the MLYRB. The correlation coefficients between standardized PE index and July precipitation, relative humidity, specific humidity, air temperature, and moisture transport-related variables at each grid point were calculated to identify the spatial structure of PE-related anomalies. For correlation fields, statistical significance was assessed using a two-sided Student's *t*-test at the 95% confidence level. Composite analysis was further applied to compare atmospheric conditions between high-PE and low-PE years. High-PE years were defined as years in which the standardized PE index exceeded 0.8 standard deviation from mean values (1969, 1974, 1987, 1988, 1991, 2003, 2014, 2020), whereas low-PE years were defined as years below -0.8 standard deviation from mean values (1961, 1962, 1999, 2008, 2013, 2018, 2021). Composite differences were calculated as high-PE years minus low-PE years. A Welch's two-sample *t*-test was applied at each grid point to evaluate whether the means of the high-PE and low-PE samples differed significantly. Differences were considered statistically significant at $p < 0.05$. To examine whether the relationship between PE and July precipitation over the MLYRB was independent of major climate modes, partial-correlation analyses were conducted by linearly removing the effects of the monthly Niño-3.4 and NAO indices from the preceding November to the following June. The PE-moisture flux convergence (MFC) relationship over the MLYRB remained qualitatively similar after removing these indices, suggesting that the PE-related moisture-convergence signal is not solely explained by ENSO or NAO variability.

2.4. Moisture and Temperature Contribution Decomposition

The formation of precipitation depends not only on atmospheric water-vapour content but also on temperature-controlled saturation conditions. Relative humidity provides a useful framework for separating these two effects. Following the relative humidity-based decomposition method used in previous studies, variations in relative humidity can be divided into a moisture-related contribution and a temperature-related contribution. This method has been applied to quantify the relative roles of water vapour and temperature in precipitation-related humidity changes over China and other regions [26–28,37].

Relative humidity is defined as

$$RH = \frac{e}{e_s(T)}, \quad (1)$$

where e is water-vapour pressure and e_s is saturation water-vapour pressure determined by air temperature T . For high-PE and low-PE composites, the logarithmic change in relative humidity can be expressed as

$$C_{RH} = \ln\left(\frac{RH_{high}}{RH_{low}}\right). \quad (2)$$

According to the definition of relative humidity,

$$C_{RH} = C_q + C_T, \quad (3)$$

where

$$C_q = \ln\left(\frac{e_{high}}{e_{low}}\right). \quad (4)$$

represents the contribution from moisture changes, and

$$C_T = \ln\left(\frac{e_s(T_{low})}{e_s(T_{high})}\right). \quad (5)$$

represents the contribution from temperature-controlled saturation changes. A positive C_q indicates that increased water vapour favours an increase in relative humidity, whereas a positive C_T indicates that lower temperature reduces saturation water-vapour pressure and therefore favours an increase in relative humidity. The relative magnitudes of $|C_q|$ and $|C_T|$ were compared to determine whether the PE-related humidity and rainfall anomalies over the MLYRB were dominated by moisture changes or by temperature-related saturation changes.

Because ERA5 provides specific humidity rather than water-vapour pressure directly, water-vapour pressure was calculated from specific humidity and pressure as

$$e = \frac{qp}{0.622 + 0.378q}, \quad (6)$$

where q is specific humidity and p is pressure. Saturation water-vapour pressure was calculated from air temperature using a standard Clausius–Clapeyron formulation.

3. Results

3.1. PE-Related Rainfall Anomalies and Circulation Background

The relationship between March precipitation over the EMWA region and July precipitation over China is first examined to determine whether PE can be regarded as a meaningful precursor for midsummer rainfall variability over the MLYRB. As shown in Figure 1a, the correlation field exhibits a coherent positive signal over the MLYRB and its adjacent regions. This spatial structure indicates that enhanced March precipitation over the EMWA region is associated with increased July rainfall over the MLYRB rather than with an isolated grid-point response.

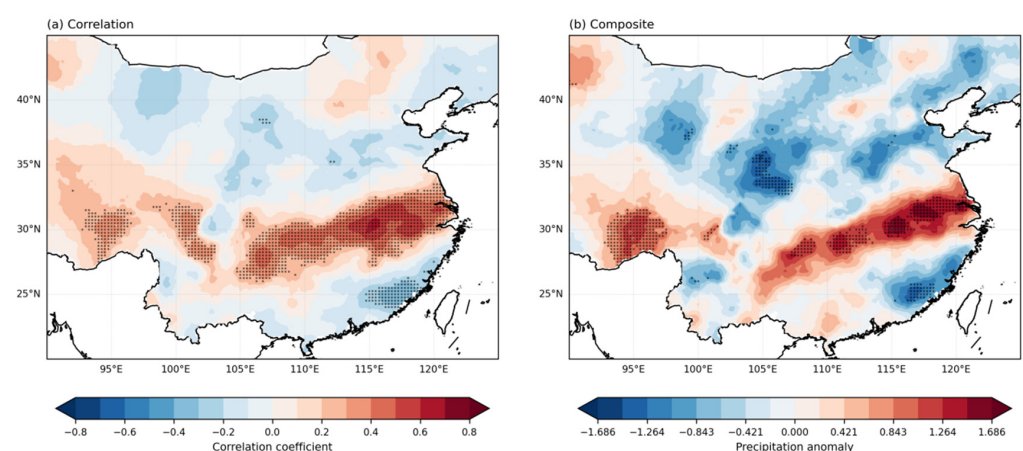


Figure 1. (a) Correlation coefficients between the standardized PE index and July precipitation. (b) Composite differences in July precipitation between high-PE and low-PE years, calculated as high minus low. Stippling denotes values significant at the 95% confidence level.

The high-minus-low PE composite further supports this relationship (Figure 1b). Positive precipitation anomalies appear over the MLYRB during high-PE years compared with low-PE years, broadly consistent with the correlation pattern. Although the rainfall response is not spatially uniform across eastern China, the enhanced precipitation belt over the Yangtze River region suggests that PE is statistically linked to the interannual variability of July rainfall in the target region. These results provide the basis for the subsequent thermodynamic diagnosis of the PE-related rainfall anomaly. The consistency between the correlation pattern and the composite difference indicates that PE is not an arbitrary index, but a physically plausible upstream hydrological signal associated with July rainfall variability over the MLYRB.

The July geopotential height (GH) anomalies associated with PE are consistent with precipitation anomalies over MLYRB (Figure 2). The high-minus-low PE composites of GH exhibit a vertically coherent meridional dipole over East Asia, with positive anomalies to the south of the MLYRB and negative anomalies over northern China, Korea, and Japan. The MLYRB lies near the transition between the positive height anomalies to the south and negative anomalies to the north. This configuration is consistent with an enhanced meridional pressure gradient and provides a dynamically favourable background for anomalous circulation and moisture convergence along the Yangtze River region. The persistence of this pattern from 850 to 300 hPa suggests that the PE-related rainfall anomaly is accompanied by a deep and organized circulation adjustment rather than a shallow local response. This circulation configuration provides a dynamically favourable background for enhanced July rainfall over the MLYRB.

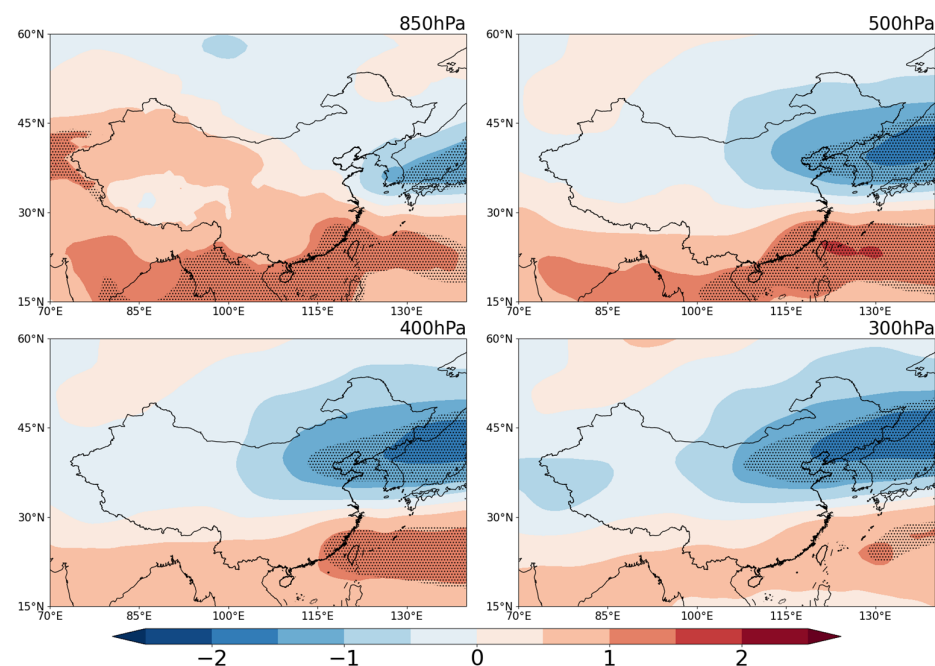


Figure 2. Composite differences in July geopotential height between high-PE and low-PE years at 850, 500, 400, and 300 hPa, calculated as high minus low. Stippling denotes values significant at the 95% confidence level.

To further examine the possible circulation bridge between the upstream PE signal and the downstream rainfall response, the evolution of the 200 hPa Takaya–Nakamura wave activity flux (WAF) [38] was analyzed from April to July (Figure S4). The monthly WAF fields exhibit eastward-shifting wave-activity centres and alternating convergence–divergence anomalies across the subtropical Eurasian sector. By July, anomalous wave activity remains evident over East Asia and its adjacent regions, suggesting that the PE-related spring

anomaly is associated with a downstream adjustment of the upper-tropospheric circulation. The monthly WAF patterns indicate an eastward-oriented sequence of PE-related wave-activity anomalies across Eurasia, providing evidence of a physically plausible downstream circulation bridge.

3.2. Relative Humidity Response Associated with PE

Precipitation formation is closely related to the degree of saturation of the air column [31]. Therefore, the PE-related relative humidity pattern provides a thermodynamic bridge between the precipitation response and the subsequent moisture–temperature decomposition. Figure 3 shows the correlation coefficients between the standardized PE index and July relative humidity anomalies at 850, 500, 400, and 300 hPa. This analysis diagnoses whether the PE-related rainfall anomalies over the MLYRB are accompanied by a favourable vertical relative-humidity structure. The positive relative humidity anomalies indicate that high-PE years tend to be associated with a more humid atmospheric column over the rainfall region. This response is favourable for precipitation formation because relative humidity reflects the combined effects of moisture availability and temperature-controlled saturation conditions. In the lower troposphere, the positive signal is closely related to the background moisture supply, whereas in the middle and upper troposphere it indicates whether the atmospheric column is sufficiently moist to support sustained condensation and precipitation development. A notable feature is that the positive relative humidity anomalies at 400 and 300 hPa show a particularly clear spatial overlap with the significant precipitation anomalies over the MLYRB. Although the absolute water vapour content decreases rapidly with height, relative humidity in the upper troposphere remains physically meaningful because it reflects the degree of saturation and the maintenance of a deep moist layer. The coherent positive RH response at 400–300 hPa therefore suggests that high-PE years are not only characterized by enhanced low-level moisture conditions, but also by a more favourable vertical humidity structure for deep condensation, latent heating, and persistent monsoon rainfall.

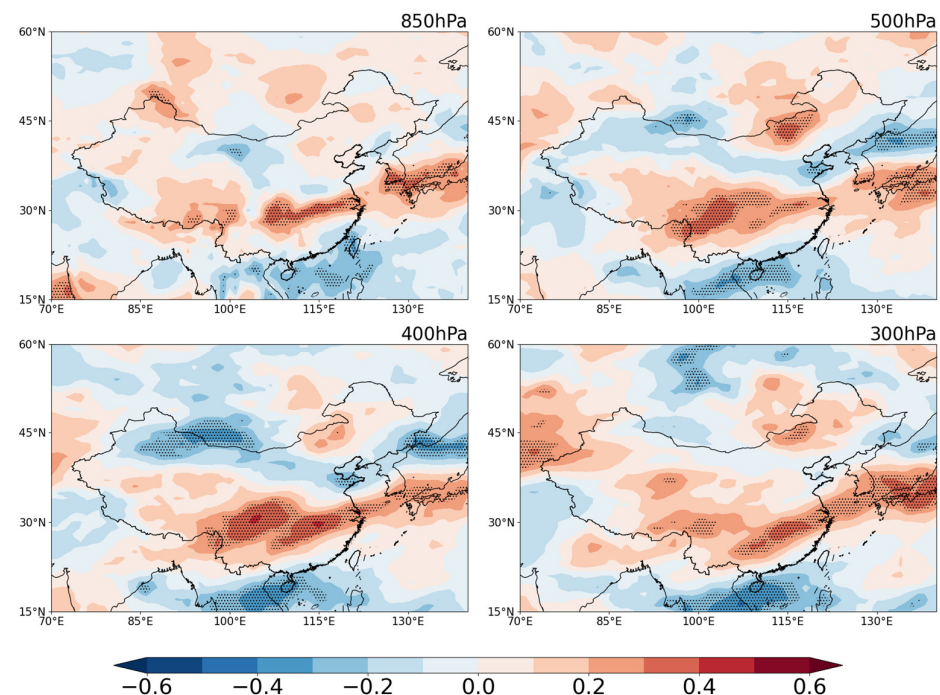


Figure 3. Correlation coefficients between the standardized PE index and July relative humidity at different pressure levels (850, 500, 400, and 300 hPa). Stippling denotes correlations significant at the 95% confidence level.

Overall, the PE-related relative humidity response suggests that the rainfall enhancement over the MLYRB is accompanied by a vertically coherent humidification, with the strongest spatial consistency appearing in the middle-to-upper troposphere. The next issue is whether this humidification is mainly caused by increased moisture content or by temperature-related changes in saturation vapour pressure.

3.3. Specific Humidity and Temperature Responses

The respective roles of moisture and temperature are first assessed using the correlations of PE with specific humidity and air temperature. Figure S5 shows the PE-related specific-humidity response at different pressure levels. Positive specific-humidity anomalies are found over parts of eastern China and along the surrounding moisture-transport pathways. Although the signal is not significant at all grid points directly over the MLYRB, the spatial distribution suggests a general moistening tendency in and around the rainfall region, particularly in the lower and middle troposphere.

In contrast, the PE-related temperature response is weaker and less spatially coherent over the MLYRB (Figure S6). Significant temperature signals are mainly displaced to surrounding regions rather than being centred over the rainfall anomaly region. This contrast between specific humidity and temperature suggests that the PE-related rainfall response is unlikely to be primarily controlled by local temperature adjustment. Instead, the rainfall anomaly appears to be more closely linked to moisture-related processes. The lack of a strong and coherent temperature signal over the MLYRB is physically meaningful. Temperature can affect relative humidity through saturation vapour pressure, but a weak temperature response implies that temperature-related saturation changes may play only a secondary role in the PE-related rainfall anomaly. However, because specific humidity alone does not fully describe saturation conditions, a quantitative decomposition of relative humidity is needed to compare the moisture and temperature contributions quantitatively and more directly.

3.4. Spatial Contrast Between Moisture and Temperature Contributions

To quantify the thermodynamic origin of the PE-related relative humidity anomalies, the relative humidity change between high-PE and low-PE years is decomposed into the moisture contribution term C_q and the temperature contribution term C_T . The spatial distributions of C_q are shown in Figure 4. Positive C_q values appear over the MLYRB and adjacent downstream regions at several pressure levels, indicating that increased water vapour contributes to higher relative humidity during high-PE years. This moisture contribution is most relevant in the lower and middle troposphere, where water-vapour variations are more directly related to monsoon rainfall formation. The distribution of C_T exhibits a different spatial structure (Figure 5). Over the MLYRB, C_T is generally weaker and less spatially coherent than C_q , suggesting that temperature-related saturation changes are not the dominant contributor to the local relative humidity increase. This result is consistent with the weak and spatially scattered temperature correlations. Therefore, the PE-related rainfall response over the MLYRB is more likely associated with moisture changes than with local cooling-induced saturation effects. A contrast is found over Northeast China. In this region, especially at the middle and upper tropospheric levels, the temperature contribution becomes more evident than that over the MLYRB. Positive C_T anomalies indicate that lower temperature can reduce saturation vapour pressure and thereby increase relative humidity. Meanwhile, the corresponding C_q signal is not always as coherent as that over the Yangtze River region. This contrast suggests that the moisture–temperature decomposition can distinguish different thermodynamic regimes. The MLYRB response is more moisture-

dominated, whereas the relative humidity response over parts of Northeast China is more closely linked to temperature-related saturation changes.

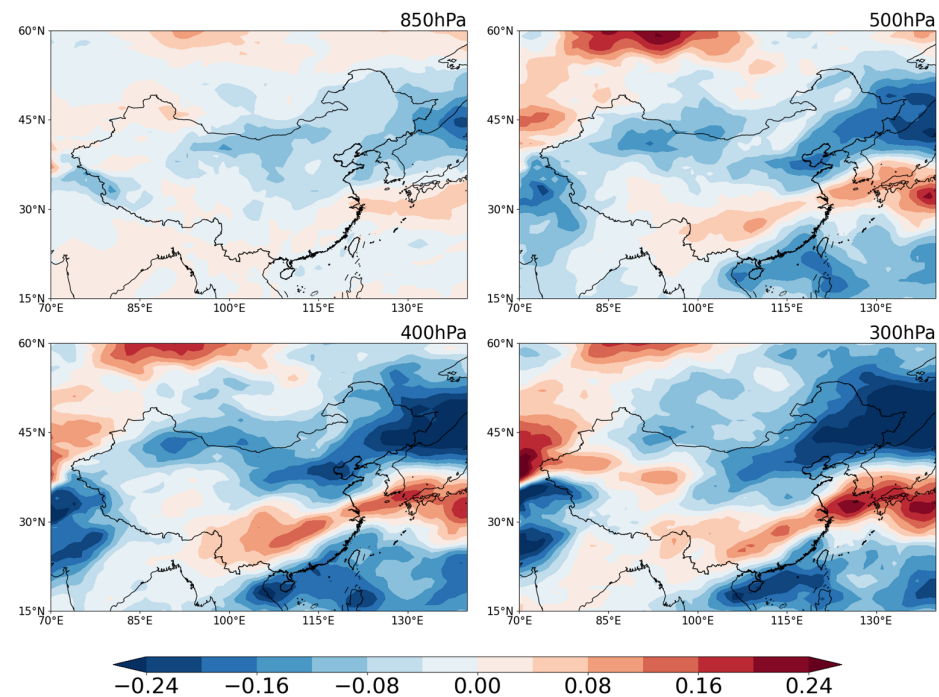


Figure 4. Spatial distributions of the moisture contribution term C_q calculated from high-PE minus low-PE composites at 850 hPa, 500 hPa, 400 hPa, and 300 hPa. Positive C_q indicates that increased (decreased) water vapour contributes to higher (lower) relative humidity.

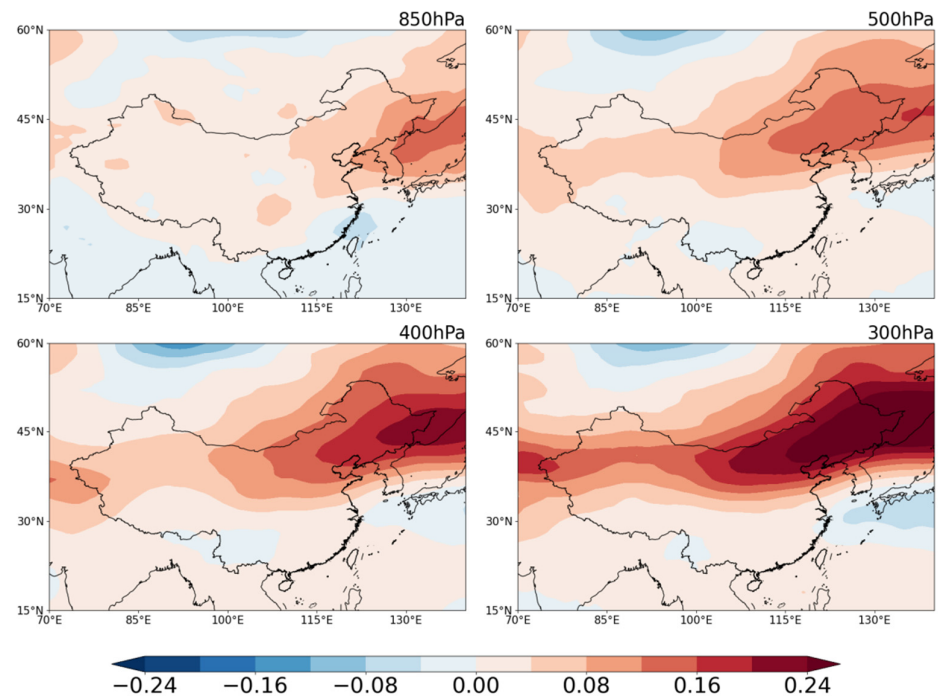


Figure 5. Spatial distributions of the temperature contribution term C_T calculated from high-PE minus low-PE composites at 850 hPa, 500 hPa, 400 hPa, and 300 hPa. Positive C_T indicates that lower (higher) temperature contributes to higher (lower) relative humidity.

This regional contrast illustrates the diagnostic capability of the decomposition framework. If the method simply reproduced the moisture field, C_T would not provide distinct regional information. Instead, the different behaviours of C_q and C_T over the MLYRB and

Northeast China indicate that the decomposition separates two physically different pathways, increased water-vapour supply and temperature-controlled changes in saturation vapour pressure. For the PE-related July rainfall anomaly, the former is more relevant over the MLYRB, while the latter becomes more apparent in regions where temperature anomalies are more organized.

3.5. Total Relative Humidity Response and Regional Interpretation

The total relative humidity change derived from the decomposition, C_{RH} , is shown in Figure 6. Positive C_{RH} anomalies appear over the MLYRB and nearby regions, indicating that high-PE years are associated with a more humid atmospheric state than low-PE years. The spatial distribution of C_{RH} over the MLYRB resembles the moisture contribution more closely than the temperature contribution, particularly in the lower and middle troposphere. This similarity further supports the interpretation that moisture changes dominate the PE-related humidification over the rainfall region. The relationship among C_q , C_T , and C_{RH} also highlights the regional dependence of the thermodynamic response. Over the MLYRB, the positive C_{RH} signal is mainly produced by the moisture term, while the temperature term is weaker and less coherent. In contrast, over parts of Northeast China, the contribution from C_T becomes more visible, indicating that the relative humidity change there may be partly related to temperature-controlled saturation effects. Thus, the same PE-related circulation background can be associated with different local thermodynamic pathways in different regions.

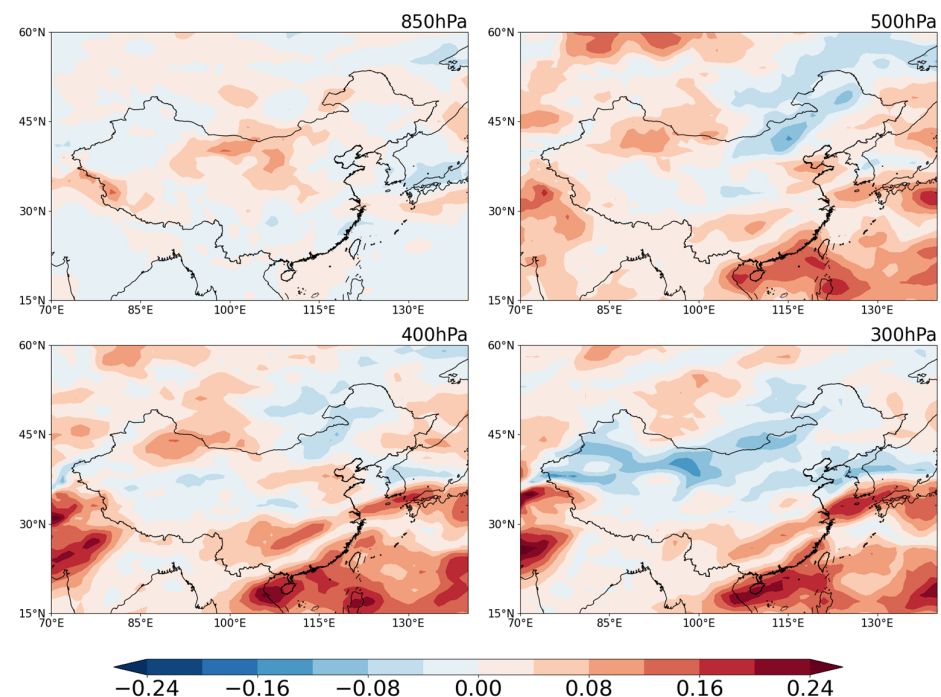


Figure 6. Spatial distributions of C_{RH} calculated from high-PE minus low-PE composites at 850 hPa, 500 hPa, 400 hPa, and 300 hPa. Positive C_{RH} indicates an increase in relative humidity in high-PE years compared with low-PE years, whereas negative C_{RH} indicates a decrease in relative humidity.

These results indicate that the MLYRB rainfall response should not be interpreted simply as a uniform humidification over eastern China. Instead, the PE-related signal contains a spatially differentiated thermodynamic structure. The Yangtze River region is characterized by a moisture-dominated increase in relative humidity, whereas higher-latitude regions show a relatively larger role of temperature-related saturation changes. This distinction is important for understanding why the PE-related rainfall response is

concentrated over the MLYRB rather than uniformly distributed over all regions with positive relative humidity anomalies.

3.6. Moisture-Flux Convergence and Moisture-Transport Support

The moisture-dominated contribution over the MLYRB requires support from anomalous moisture transport and convergence. Figure 7 shows the composite differences in standardized moisture-flux convergence and standardized horizontal moisture-flux anomalies. Positive moisture-flux convergence anomalies are found around the MLYRB and its downstream region, especially at 850 and 500 hPa. These anomalies indicate enhanced moisture accumulation in the lower and middle troposphere during high-PE years. The standardized moisture-flux vectors further indicate anomalous moisture transport toward eastern China and the Yangtze River region. Although the vectors are standardized and scaled for clarity, their directions provide useful information on the relative spatial pattern of anomalous moisture transport. The lower-to-middle tropospheric convergence signal is particularly important because July rainfall over the MLYRB depends strongly on sustained water-vapour supply, moisture convergence, and monsoon-related ascent. This result helps explain why the PE-related specific-humidity anomalies are not significant at every grid point over the MLYRB. Rainfall enhancement is not controlled solely by local moisture content. It also depends on the convergence and accumulation of moisture transported from surrounding regions. Therefore, the PE-related rainfall response is better characterized by enhanced moisture-flux convergence and a moisture-dominated relative humidity contribution than by local specific-humidity changes alone.

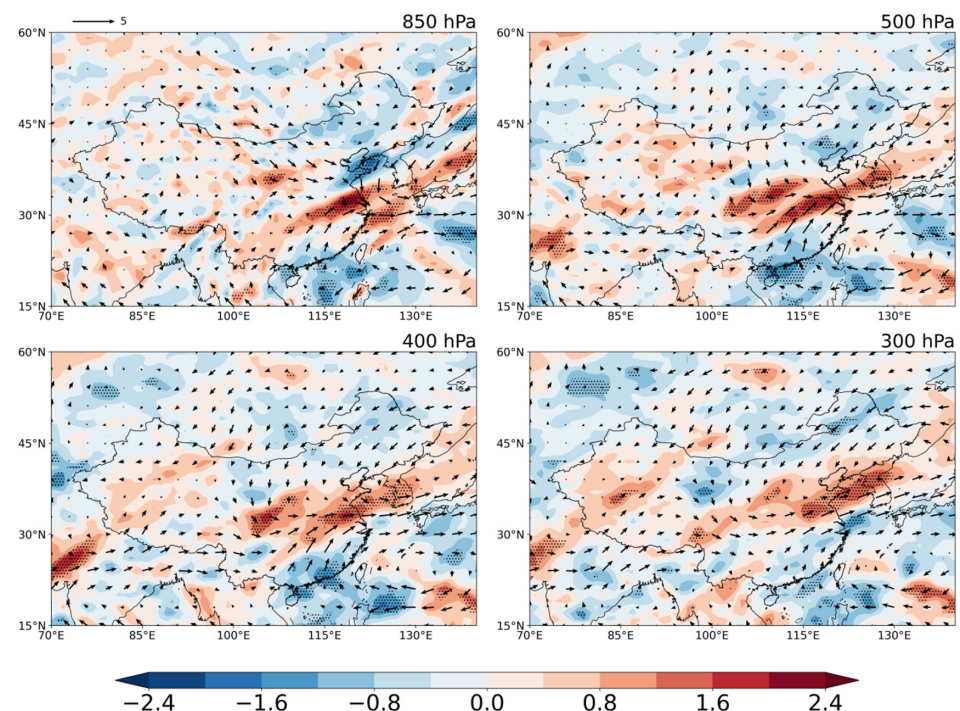


Figure 7. PE-related moisture-flux convergence and standardized horizontal moisture-flux anomalies at different pressure levels. Shading denotes high-minus-low PE composite differences in standardized moisture-flux convergence at 850 hPa, 500 hPa, 400 hPa, and 300 hPa. Positive values indicate anomalous moisture convergence, whereas negative values indicate anomalous moisture divergence. Vectors denote standardized horizontal moisture-flux anomalies, indicating the direction and relative spatial pattern of anomalous moisture transport. Stippling denotes moisture-flux convergence differences significant at the 95% confidence level. Vectors are scaled for clarity.

The moisture-flux diagnostics also provide a physical link between the thermodynamic decomposition and the rainfall response. The C_q -dominated structure over the MLYRB indicates that water-vapour changes are the primary thermodynamic contributor to the relative humidity increase, while the MFC anomalies show that such moisture changes are dynamically supported by anomalous convergence. This consistency among C_q , C_{RH} , and MFC strengthens the interpretation that PE-related rainfall anomalies over the MLYRB are primarily associated with moisture supply and convergence rather than with temperature-related saturation changes.

4. Discussion

The results reveal a coherent thermodynamic and moisture-transport pathway associated with the linkage between March precipitation over the EMWA region and July rainfall anomalies over the MLYRB. The PE index is first shown to be statistically associated with July rainfall over the MLYRB. This relationship is supported by both correlation and composite analyses, indicating that high-PE years tend to be accompanied by enhanced rainfall over the MLYRB. On this basis, the associated relative humidity, specific humidity, temperature, and moisture-flux responses are diagnosed to clarify the thermodynamic characteristics of the rainfall anomaly. A major finding is that the PE-related rainfall response over the MLYRB is more strongly connected to moisture processes than to local temperature changes. Relative humidity increases over the MLYRB and adjacent regions during high-PE years, indicating a more favourable humid environment for precipitation formation. The decomposition of relative humidity changes further shows that this increase is mainly contributed by the moisture term C_q , while the temperature term C_T is weaker and less spatially coherent over the rainfall region. This result suggests that temperature-related saturation changes play a secondary role in the PE-related July rainfall anomaly. The regional contrast between the MLYRB and Northeast China provides additional support for the physical interpretation of the decomposition. Over the MLYRB, C_q is more closely aligned with the total relative humidity response C_{RH} , indicating that water-vapour changes dominate the local humidification. Over parts of Northeast China, however, C_T becomes more evident, implying that temperature-related saturation changes may contribute more substantially to relative humidity variations there. This contrast shows that the C_q/C_T framework is not merely a restatement of moisture anomalies, but a diagnostic tool capable of separating moisture-controlled and temperature-controlled humidity responses.

The moisture-dominated response over the MLYRB is physically consistent with the characteristics of midsummer rainfall in eastern China. Under the warm and humid background state of midsummer, interannual rainfall anomalies may be more sensitive to changes in moisture supply, moisture convergence, and ascent than to local temperature anomalies. The enhanced moisture-flux convergence shown in Figure 7 therefore provides a physically consistent explanation for the C_q -dominated relative humidity response. It should also be emphasized that the PE-related moisture signal does not require a uniformly significant local specific-humidity increase over the MLYRB. Precipitation is controlled by the combined effects of moisture availability, moisture convergence, ascent, and saturation conditions. The results indicate that moisture-flux convergence and moisture-related relative humidity changes provide a more comprehensive explanation than local specific humidity alone. This distinction is important because it reduces the risk of overinterpreting weak local q anomalies and places the emphasis on the dynamical accumulation and convergence of water vapour.

The current analysis is diagnostic and does not establish strict causality between EMWA spring precipitation and MLYRB July rainfall. PE may partly reflect broader large-scale circulation conditions that also influence East Asian summer rainfall. Similar

caution is needed when interpreting statistical links between antecedent climate signals and downstream rainfall, because such relationships may partly reflect shared circulation backgrounds rather than isolated forcing pathways [11–17]. Nevertheless, the consistency among precipitation, relative humidity, moisture contribution, and moisture-flux convergence suggests that PE is a useful upstream hydrological signal associated with a moisture-favourable rainfall environment over the MLYRB.

Another limitation concerns the relative humidity decomposition method. The relative humidity decomposition provides a useful quantitative comparison between moisture and temperature contributions and has been applied to precipitation-related humidity changes in previous studies [28–32,37]. However, it does not directly represent cloud microphysical processes, precipitation efficiency, or vertical motion. Therefore, the decomposition should be interpreted as a thermodynamic diagnostic of humidity changes rather than a complete explanation of precipitation formation. Despite this limitation, the method effectively identifies whether the humidification associated with PE is mainly caused by moisture supply or by temperature-related saturation adjustment.

Overall, the present results complement circulation-based interpretations of East Asian midsummer rainfall variability by highlighting the thermodynamic contribution of moisture. The PE-related rainfall anomaly over the MLYRB appears to be supported primarily by enhanced water-vapour supply and moisture-flux convergence, while local temperature changes provide only a secondary contribution. The contrast with Northeast China further indicates that the relative roles of moisture and temperature depend on the regional thermodynamic background. This finding provides a more specific physical interpretation of the cross-seasonal association between EMWA spring precipitation and MLYRB July rainfall.

5. Conclusions

This study investigates the relative roles of moisture and temperature in the relative humidity changes accompanying July rainfall anomalies over the MLYRB associated with March precipitation over the EMWA region. The PE index was first examined as an upstream spring hydrological signal, and its statistical relationship with July rainfall over the MLYRB was evaluated using correlation and composite analyses. The results show that positive PE anomalies are associated with enhanced July rainfall over the Yangtze River region, indicating that spring precipitation variability over the EMWA sector contains useful information for subsequent midsummer rainfall anomalies over East China.

The PE-related rainfall enhancement is accompanied by increased relative humidity over the MLYRB and nearby regions, especially in the lower and middle troposphere. The responses of specific humidity and air temperature show clear differences. Specific humidity exhibits a more evident moisture-related signal around the rainfall region and along adjacent moisture-transport pathways, whereas temperature anomalies over the MLYRB are weak and spatially less coherent. This contrast suggests that the PE-related rainfall response is more closely linked to moisture processes than to local temperature adjustment. The relative humidity decomposition further clarifies the thermodynamic origin of the rainfall-related humidification. Over the MLYRB, the positive relative humidity anomalies during high-PE years are mainly contributed by the moisture term C_q , while the temperature term C_T is weaker and less spatially organized. This indicates that temperature-related saturation changes play a secondary role in the PE-related rainfall response over the Yangtze River region. In contrast, C_T becomes more evident over parts of Northeast China, suggesting that the decomposition can distinguish regional differences between moisture-dominated and temperature-influenced humidity responses.

Moisture-flux diagnostics provide additional support for the moisture-dominated interpretation. Positive PE anomalies are accompanied by enhanced moisture-flux convergence and anomalous moisture transport toward eastern China, particularly in the lower and middle troposphere. These features indicate that the PE-related rainfall response over the MLYRB is better characterized by enhanced moisture supply and convergence than by local specific-humidity changes alone. The consistency among precipitation, relative humidity, C_q , C_{RH} , and moisture-flux convergence suggests that moisture processes provide the primary thermodynamic and dynamical support for the PE-related July rainfall anomalies.

Overall, the results indicate that the cross-seasonal association between EMWA spring precipitation and MLYRB July rainfall is primarily linked to moisture supply and moisture convergence rather than temperature-related saturation adjustment. This moisture-dominated response provides a thermodynamic explanation for the potential predictive value of PE and highlights the importance of water-vapour transport in midsummer rainfall variability over the MLYRB. Since the present analysis is diagnostic, further numerical experiments are still needed to determine whether EMWA spring precipitation anomalies can actively force the downstream circulation and moisture-transport responses.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/atmos17080732/s1>: Figure S1: Map of the first EOF component of precipitation at July; Figure S2: Correlation coefficients between the July precipitation index averaged over the reference area and gridded July precipitation over China. The parallelogram-shaped domain (113–121° E, 28.5–31° N and 30.5–33° N) delineates the core prediction region; Figure S3: The composite differences in March precipitation between high-PE and low-PE years, calculated as high minus low. Stippling denotes values significant at the 95% confidence level. The black box denotes the EMWA region; Figure S4: Takaya–Nakamura wave activity flux (WAF; vectors) at 200 hPa from April to July calculated from the regressed streamfunction anomaly ψ' for a one-standard-deviation increase in PE. Shading denotes WAF convergence ($-\nabla \cdot F$). Vectors indicate the direction and relative magnitude of WAF and are thinned for clarity. Stippling indicates regions where the regressed streamfunction anomalies are significant at the 95% confidence level; Figure S5: Correlation coefficients between the standardized PE index and July specific humidity at different pressure levels (850 hPa, 500 hPa, 400 hPa, and 300 hPa). Stippling denotes correlations significant at the 95% confidence level; Figure S6: Correlation coefficients between the standardized PE index and July air temperature at different pressure levels (850 hPa, 500 hPa, 400 hPa, and 300 hPa). Stippling denotes correlations significant at the 95% confidence level.

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Data Availability Statement: ERA5 data are available from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels-monthly-means?tab=download>, accessed on 18 May 2026). As done by Xu et al. [39], the CN05.1 dataset was constructed by the “anomaly approach” during the interpolation but with more station observations

(2400) in China [33]. In the “anomaly approach”, a gridded climatology is first calculated, and then a gridded daily anomaly is added to the climatology to obtain the final dataset. Originally, CN05.1 comprised four variables of daily mean, maximum and minimum temperature, and precipitation. Then it was updated with the inclusion of daily mean humidity, wind speed, and surface evaporation [34]. Climate indices can be downloaded from the website <https://psl.noaa.gov/data/timeseries/month/>, accessed on 18 May 2026.

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