

JGR Atmospheres

RESEARCH ARTICLE

10.1029/2026JD046625

Key Points:

- Subseasonal forecast skill for drought–flood abrupt alternation events is higher during drought than during transition and flood onset
- Slowly evolving mid-tropospheric circulation anomalies link to subseasonal predictability 10–30 days before drought–flood transitions
- Forecast skill decreases during drought–flood transitions as rapidly evolving synoptic processes increase ensemble spread and uncertainty

Supporting Information:

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

Correspondence to:

W. Duan,
duanws@lasg.iap.ac.cn

Citation:

Li, C., Duan, W., & Han, Z. (2026). Assessing Subseasonal predictability and sources of drought–flood abrupt alternation over eastern china using ECMWF S2S ensemble Forecasts. *Journal of Geophysical Research: Atmospheres*, 131, e2026JD046625. <https://doi.org/10.1029/2026JD046625>

Received 9 FEB 2026

Accepted 22 SEP 2026

Author Contributions:

Conceptualization: Chunxiang Li, Wansuo Duan
Data curation: Zhe Han
Formal analysis: Chunxiang Li
Funding acquisition: Chunxiang Li
Investigation: Chunxiang Li
Methodology: Chunxiang Li, Wansuo Duan
Resources: Chunxiang Li
Software: Zhe Han
Supervision: Wansuo Duan
Validation: Wansuo Duan
Visualization: Chunxiang Li
Writing – original draft: Chunxiang Li
Writing – review & editing: Wansuo Duan, Zhe Han

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Assessing Subseasonal Predictability and Sources of Drought–Flood Abrupt Alternation Over Eastern China Using ECMWF S2S Ensemble Forecasts

Chunxiang Li¹ , Wansuo Duan^{2,3} , and Zhe Han¹ 

¹Temperate East Asia Research Center on Global Change, Institute of Atmospheric Physics, Chinese Academy of Science, Beijing, China, ²State Key Laboratory of Earth System Numerical Modeling and Application, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, ³Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science and Technology, Nanjing, China

Abstract Drought–flood abrupt alternation (DFAA) events pose major challenges for subseasonal-to-seasonal (S2S) prediction owing to their rapid hydrological transitions and complex circulation controls. Using ECMWF S2S ensemble forecasts, this study explores the subseasonal predictability of three objectively identified DFAA events over eastern China during 2022–2024. Across the analyzed cases, we find that the forecast skill tends to be higher during the drought phase than during the subsequent transition and flood onset. This tendency is associated with persistent drought conditions being linked to slowly evolving, spatially coherent large-scale circulation anomalies and relatively greater ensemble consistency at subseasonal lead times. An important source of subseasonal predictability is linked to mid-tropospheric circulation anomalies, including Rossby wave trains and subtropical–midlatitude coupling, which provide coherent precursor signals approximately 10–30 days prior to the observed transitions. In contrast, forecast skill degrades notably during the transition period and subsequent flood onset, when short-term triggering processes—particularly tropical cyclone–related circulation—introduce substantial ensemble divergence and timing uncertainty. Among the cases analyzed, the monsoon-related event is associated with relatively higher and more stable subseasonal predictability, whereas the tropical cyclone–influenced event exhibits reduced forecast reliability. These results highlight the importance of large-scale circulation precursors for extended-range monitoring of DFAA events, while underscoring the intrinsic limitations of current S2S systems in predicting the precise timing and intensity of abrupt flooding onset.

Plain Language Summary Drought–flood abrupt alternation (DFAA) events involve a rapid shift from dry conditions to heavy rainfall within a short period, often leading to serious impacts on water resources, agriculture, and society. Predicting these events several weeks in advance is difficult because they combine slowly evolving background conditions with rapidly developing weather systems. In this study, we examine three recent DFAA events over eastern China using subseasonal ensemble forecasts from the European Center for Medium-Range Weather Forecasts. The results show that forecasts tend to be more reliable during the drought stage than during the subsequent transition and flood onset. This difference is linked to the presence of large-scale atmospheric circulation patterns that evolve gradually and are more consistently represented across ensemble forecasts. As the transition approaches, forecast reliability decreases because short-lived weather systems, especially those related to tropical cyclones, introduce large uncertainty in timing and rainfall intensity. These findings suggest that monitoring large-scale circulation patterns can support early awareness of potential drought–flood transitions, while also highlighting current limitations in predicting the exact onset of abrupt flooding.

1. Introduction

Global warming has intensified the frequency and severity of extreme climate events, particularly compound events involving multiple hazards occurring in close succession or simultaneously (AghaKouchak et al., 2020; Zhang, B. et al., 2024). Among these, drought–flood abrupt alternation (DFAA)—characterized by a rapid transition from drought to heavy rainfall within days to weeks—has emerged as a critical hydroclimatic challenge under a warming climate (Gao et al., 2019; Shi et al., 2021). Recent global analyses indicate that abrupt dry–wet transitions are becoming increasingly frequent and widespread, posing growing risks to water resources and ecosystem sustainability (He et al., 2025; He & Sheffield, 2020).

DFAA events pose disproportionate risks compared to isolated droughts or floods, because impacts from both phases accumulate within a compressed time window, leaving limited opportunity for adaptation and recovery. Such rapid dry–wet transitions can severely disrupt water resources management, agricultural production, and socio-economic systems, particularly in regions with strong hydroclimatic variability (Chen et al., 2020; He & Sheffield, 2020). Recent case studies have documented that DFAA events can result in substantial economic losses and widespread societal impacts, underscoring their relevance as a high-impact compound climate hazard (Bi et al., 2020; Gao et al., 2019; Yoon et al., 2018). Importantly, the abrupt nature of these transitions amplifies forecast and early-warning challenges, as successful prediction requires capturing both slowly evolving drought conditions and rapidly developing rainfall-triggering processes.

Observational and modeling studies suggest that DFAA events, as a form of compound dry–wet extremes, are associated with increasing hydroclimatic intensity and societal impacts in many regions under a warming climate (Swain et al., 2025; Zscheischler et al., 2020), particularly in monsoon-dominated climates (Qiao et al., 2023; Wei et al., 2025). China is among the most exposed regions, especially eastern China, where dense population, intensive land use, and strong monsoon-driven climate variability converge (Bi et al., 2023; Xia et al., 2017; Yu & Zhai, 2020). Notably, recent evidence indicates a shift toward fewer but more severe DFAA events in China, highlighting the growing importance of understanding and anticipating high-impact transitions rather than their frequency alone (Qiu et al., 2024; Su et al., 2024).

Previous studies have made substantial progress in identifying and characterizing DFAA events using objective indices (Bai et al., 2023; Liu et al., 2024; Wu et al., 2006), such as the Drought–Flood Abrupt Alternation Index (DFAAI). These efforts have revealed pronounced regional and seasonal dependence, as well as close links to intraseasonal oscillations, monsoon variability, and large-scale circulation anomalies (Bai et al., 2023; Gao et al., 2019; Nie et al., 2025). However, recent work has also demonstrated that the detection and statistical characterization of short-term DFAA events are sensitive to index definitions and temporal scales (Wei et al., 2025), complicating their objective assessment. Moreover, abrupt drought–flood transitions in eastern China are often associated with interacting circulation drivers—including midlatitude wave trains, subtropical highs, monsoon surges, and tropical cyclone activity—introducing strong nonlinearity and posing inherent challenges for advance anticipation. As a result, existing studies have primarily focused on event occurrence and physical attribution, while comparatively less attention has been devoted to the predictability of DFAA events at extended lead times.

Despite growing understanding of DFAA occurrence and mechanisms, their predictability on the subseasonal-to-seasonal (S2S) time scale remains poorly quantified. The S2S range, spanning approximately 2 weeks to 2 months, represents a critical forecast gap between deterministic weather prediction and seasonal outlooks (Vitart et al., 2017). DFAA events pose a unique challenge for S2S prediction because they require the accurate representation of both slowly evolving drought conditions and the timing and intensity of rapidly developing rainfall-triggering processes, which are governed by distinct dynamical controls. The ECMWF S2S prediction system provides a widely used ensemble framework for exploring subseasonal predictability, with forecast lead times extending to several weeks (Robertson & Vitart, 2019; Vitart et al., 2017). While previous studies have demonstrated skill in predicting individual extremes such as droughts or heavy rainfall (DeFlorio et al., 2019; Masukwedza et al., 2025; Olaniyan et al., 2018; Rivoire et al., 2023), the extent to which S2S systems can anticipate the full drought-to-flood transition—particularly in monsoon-affected regions—remains largely unexplored.

In this study, we investigate the subseasonal predictability of recent high-impact DFAA events over eastern China using ensemble forecasts from the ECMWF S2S prediction system. By evaluating forecast performance across different phases of the transition and diagnosing circulation differences between successful and unsuccessful ensemble members, we aim to examine the key dynamical factors contributing to predictability and uncertainty at subseasonal lead times. This process-oriented analysis seeks to shed light on why certain DFAA events tend to exhibit higher predictability than others and to provide physically based insights to support early warning of compound hydroclimatic extremes under a warming climate.

2. Data and Methods

2.1. Data Sets

ERA5 reanalysis daily precipitation data spanning 1980–2024 are used as the observational reference for identifying and characterizing DFAA events over China (Hersbach et al., 2020). These data provide the basis for

calculating the Standardized Precipitation Index (SPI) and objectively determining the onset, duration, and termination of drought and flood phases.

Subseasonal forecasts are obtained from the ECMWF S2S ensemble prediction system (Vitart et al., 2017), which issues real-time forecasts twice weekly (Mondays and Thursdays) with lead times up to 46 days, accompanied by a consistent set of reforecasts (hindcasts). Each real-time forecast consists of one control member and either 50 or 100 perturbed members, depending on the initialization date. Specifically, forecasts initialized on 29 June 2023 include 50 perturbed members (51 members in total), whereas forecasts initialized on 3 July 2023 and thereafter include 100 perturbed members (101 members in total). The reforecast data set spans 20 years, with 11 ensemble members for each initialization date, and is used to construct the model climatology.

Both precipitation and circulation variables from the ECMWF S2S forecasts are used in the analysis. Forecast precipitation is used to compute the SPI. Circulation diagnostics include 500-hPa geopotential height (Z500), potential vorticity on the 320-K isentropic surface (PV), 850-hPa moisture flux (uq, vq), and 850-hPa relative vorticity (ROT850). Z500 and PV are directly obtained from the ECMWF S2S forecasts, while moisture flux and relative vorticity are computed diagnostically from model wind and humidity fields. These circulation variables are used to investigate the large-scale dynamical mechanisms and precursor signals associated with successful and unsuccessful DFAA predictions.

2.2. Standardized Precipitation Index and Event Identification

2.2.1. SPI Definition and Calculation

Precipitation-based indices are widely used for diagnosing drought and flood conditions, particularly for events characterized by rapid hydrological transitions (Qiao et al., 2023). Among them, the SPI provides a flexible framework for quantifying precipitation anomalies across multiple time scales (Ford et al., 2021; McKee et al., 1993). Although SPI does not explicitly represent land-surface hydrological processes such as runoff or soil moisture dynamics, it offers a practical and internally consistent metric for identifying abrupt dry–wet transitions when precipitation variability is the dominant driver, as demonstrated in recent DFAA-related studies (Gao et al., 2019; Shi et al., 2021; Wei et al., 2025).

Given that DFAA events are typically associated with short-term precipitation deficits followed by sudden excessive rainfall, a short accumulation window is required to capture their rapid evolution. Accordingly, the 7-day SPI (SPI-7) is adopted in this study as an indicator of short-term hydrological variability, consistent with recent analyses of abrupt drought–flood transitions at sub-monthly time scales (Wei et al., 2025). At such short accumulation periods, SPI computed using a standardized anomaly formulation provides a robust approximation to the canonical SPI definition and is well suited for subseasonal predictability assessment.

For observations, SPI-7 is computed using ERA5 daily precipitation based on a moving 7-day accumulation window. The accumulated precipitation P_{ERA5} is defined as the total precipitation over the current day and the preceding 6 days. The observed SPI-7 is calculated as:

$$\text{SPI}_7 = \frac{P_{\text{ERA5}} - u_{\text{ERA5}}}{\sigma_{\text{ERA5}}} \quad (1)$$

where u_{ERA5} and σ_{ERA5} denote the climatological mean and standard deviation for the corresponding calendar window, derived from the 1980–2024 ERA5 climatological record.

For forecasts, SPI-7 is computed using the same standardized anomaly approach. The 7-day accumulated precipitation $P_{\text{real-time}}$ is derived from the real-time forecast, and is standardized using the ensemble mean $u_{\text{reforecast}}$ and standard deviation $\sigma_{\text{reforecast}}$ from the corresponding reforecast data set:

$$\text{SPI}_7 = \frac{P_{\text{real-time}} - u_{\text{reforecast}}}{\sigma_{\text{reforecast}}} \quad (2)$$

This formulation allows for an objective and consistent comparison of observed and forecast SPI-7 anomalies in the subseasonal predictability assessment.

Table 1

Summary of Observed Drought–Flood Abrupt Alternation Events Over Eastern China

Case	Period	Duration (days)	Analysis domain (°E, °N)	Forecast initialization dates
1	20,221,001–1002	2	110–120°E, 30–40°N	0905, 0908, 0912, 0915, 0919, 0922, 0926
2	20,230,722–0729	8	110–120°E, 35–42°N	0626, 0629, 0703, 0706, 0710, 0713, 0717
3	20,240,619–0630	12	110–120°E, 30–36°N	0523, 0527, 0530, 0603, 0606, 0610, 0613

Note. The analysis domain refers to the region over which area-averaged precipitation and SPI-7 are calculated and may not fully coincide with the actual affected area.

2.2.2. Observed DFAA Event Identification

DFAA is conceptualized as a rapid transition from a sustained drought state to a pronounced wet anomaly within a short time window. Accordingly, three key aspects are considered in defining DFAA events: (a) the presence of a clearly identified drought phase, (b) an abrupt temporal transition from dry to wet conditions, and (c) the onset of a statistically and hydrologically meaningful wet signal (Su et al., 2024; Wang et al., 2024). Based on these considerations, DFAA events are identified from the observed SPI-7 time series using the following objective criteria:

A negative SPI-7 value must persist for at least 30 consecutive days, during which at least 80% of the days (i.e., ≥ 24 days) have $\text{SPI-7} \leq -0.5$, indicating a sustained drought condition.

The interval between the termination of the drought and the onset of significant rainfall must be no longer than 14 days, reflecting the abruptness of the transition at subseasonal time scales.

A positive wet anomaly ($\text{SPI-7} \geq 0.5$) must persist for more than 7 days following the dry phase, indicating the onset of a significant wet signal.

These thresholds are empirically chosen to balance objectivity and physical interpretability, and alternative choices may lead to some sensitivity in event identification (see Section 4.4). Based on the above criteria, three contrasting DFAA events over eastern China are identified for detailed analysis, spanning different regions, seasons, and dominant forcing mechanisms: an autumn 2022 event over the Eastern China Plain; a summer 2023 event over the North China Plain, primarily associated with Typhoon Doksuri; and an early summer 2024 event over the Huang–Huai River Basin, associated with large-scale monsoon-related circulation adjustments (Chen & Zheng, 2025) (Table 1).

The limited number of cases reflects both the strict SPI-based identification criteria and the availability of ECMWF S2S real-time forecasts, which have been operational only since 2015. Within the 2015–2024 period, these three events are the only DFAA cases over eastern China that simultaneously satisfy the objective SPI-based definition and allow consistent subseasonal predictability evaluation using real-time forecasts and corresponding reforecasts.

2.2.3. Forecast Consistency Criteria and Classification

Based on the observed DFAA events identified using SPI-7 (Section 2.2.2), forecast consistency criteria are defined to evaluate whether individual ensemble members can consistently reproduce the key characteristics of the observed drought-to-flood transition. Accordingly, the following conditions are applied to assess whether an ensemble member successfully simulates the observed transition in a manner consistent with the observational definition described above:

1. The forecast must exhibit at least five consecutive days with $\text{SPI-7} \leq -0.5$ prior to the transition point, indicating the presence of a dry phase consistent with the observed sustained drought condition.
2. The forecasted end of drought must occur within ± 3 days of the observed DFAA onset date, ensuring consistency in transition timing.
3. A forecasted wet signal ($\text{SPI-7} \geq 0.5$) appears within ± 3 days of the observed first wet anomaly, indicating successful prediction of the post-transition wet phase.

The ± 3 -day tolerance accounts for both observational and subseasonal timing uncertainties, while avoiding over-penalization of minor phase errors. Ensemble members satisfying all three conditions are classified as successful

simulations, while the remaining members are classified as unsuccessful. This event-based definition integrates the ability of ensemble members to capture both drought persistence and the subsequent transition to wet conditions. As a result, the success classification reflects a combined measure of forecast performance across these two phases. In some cases, ensemble members may reproduce one phase reasonably well but fail to satisfy all criteria simultaneously, which can lead to reduced success ratios without necessarily indicating uniformly poor forecast skill. Accordingly, the successful/unsuccessful classification should be interpreted as a diagnostic measure of event consistency rather than an absolute indicator of overall forecast quality.

2.3. Forecast Skill Measures

Forecast skill is evaluated using the Extreme Forecast Index (EFI; Lalaurette, 2003) and the Continuous Ranked Probability Skill Score (CRPSS; Hersbach, 2000), which measure ensemble signals of extreme conditions and probabilistic forecast performance relative to climatology, respectively. Both metrics are evaluated as a function of lead time to quantify the evolution of forecast skill with increasing forecast range. Here, lead time is defined as the number of days between the forecast initialization date and the end date of the observed drought-to-flood transition period, providing an event-relative temporal reference for comparing forecast performance across different initializations.

EFI is computed by comparing the real-time forecast distribution with the model climate derived from reforecasts, while CRPSS is calculated relative to a climatological ensemble constructed from ERA5-based SPI-7. Positive (negative) EFI values indicate a shift of the forecast SPI-7 distribution toward wetter (drier) conditions relative to the model climate, with larger absolute values corresponding to stronger anomalous signals. A positive CRPSS indicates that the ensemble forecast outperforms the climatological reference, while negative values indicate lower skill than climatology. Detailed formulations are provided in the Supporting Information S1.

2.4. Circulation Diagnostics and Time–Space Cross Sections

Composite analyses of large-scale circulation anomalies are performed separately for successful and unsuccessful ensemble members to diagnose dynamical differences associated with forecast skill. Horizontal composites of Z500 and 850-hPa moisture flux anomalies are examined for three stages relative to the observed transition: the pre-transition period, the transition period, and the post-transition period. The pre- and post-transition periods are generally defined as the 7-day intervals before and after the observed transition, respectively, subject to forecast availability for late initializations. Circulation anomalies in forecasts are defined as deviations from the model climatology derived from ensemble reforecasts, which accounts for systematic model biases and ensures internal consistency in the subseasonal diagnostics.

To diagnose the temporal evolution of precursor signals, latitude–time and longitude–time cross sections of circulation differences are constructed for Z500, ROT850, and PV. Statistical significance is assessed using a two-sample Welch's *t*-test, with differences exceeding the 90% confidence level highlighted. Given the relatively limited sample sizes of the successful and unsuccessful member composites, the 90% confidence level was adopted to balance statistical rigor with the identification of physically meaningful circulation differences, while avoiding an overly conservative significance criterion.

3. Results

We analyze three objectively identified DFAA events over eastern China using ECMWF S2S ensemble forecasts to evaluate subseasonal prediction skill. Forecast performance is examined as a function of lead time using EFI, CRPSS, and ensemble success ratios, while circulation composites and time–space diagnostics are used to identify dynamical features associated with forecast success. This framework provides the basis for the case-by-case analyses presented below.

3.1. Case 1: Autumn 2022 Eastern China Plain Event

Case 1 examines an abrupt drought-to-flood transition over the eastern plain region (110°–120°E, 30°–40°N) during autumn 2022. As shown in Figure 1a, regional mean daily precipitation remained persistently below normal through August and September, followed by a sharp increase at the beginning of October that marked the onset of heavy rainfall. This transition is also evident in the 7-day SPI-7 (Figure 1b), which shifted abruptly from

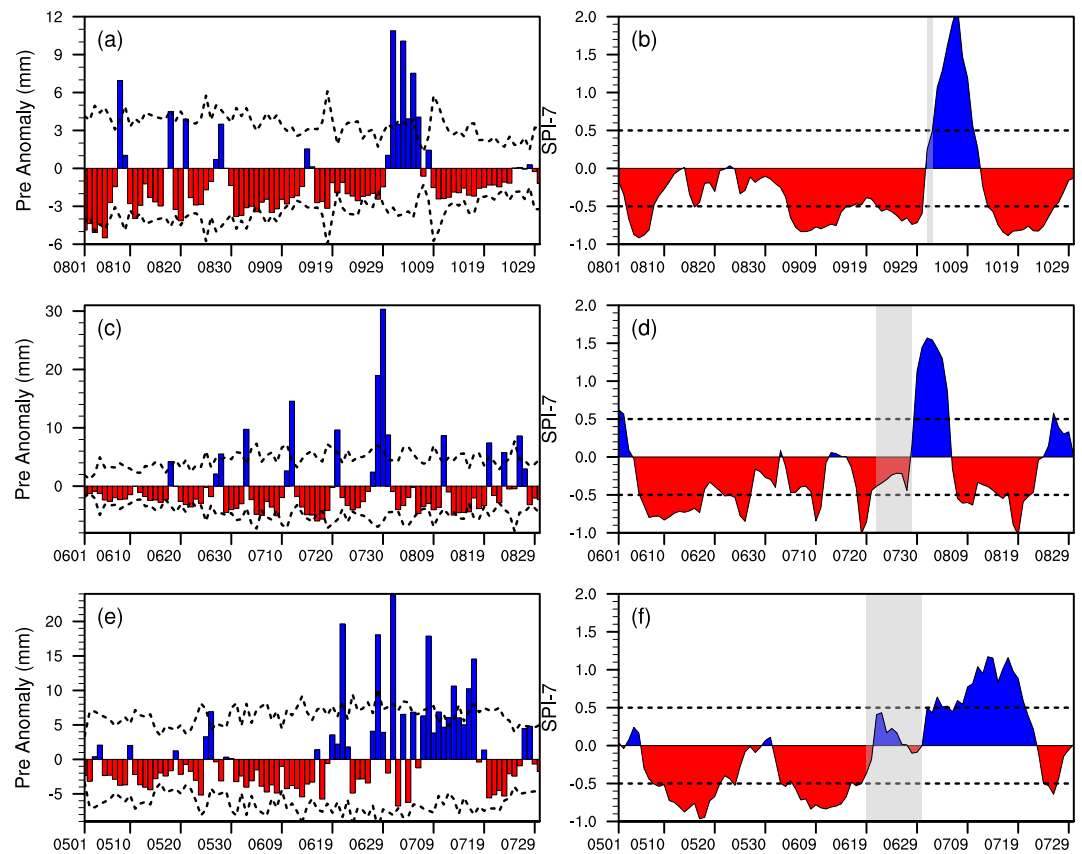


Figure 1. Time series of precipitation anomalies (left panels; units: mm) and SPI-7 (right panels) for (a, b) Case 1, (c, d) Case 2, and (e, f) Case 3, as defined in Table 1. Dashed lines denote ± 1.0 standard deviation for precipitation anomalies and ± 0.5 for SPI-7. The climatology is based on the 1980–2024 long-term mean. Gray shading highlights the Drought–flood abrupt alternation periods.

negative to positive values on 1–2 October, objectively identifying the DFAA onset. Following the SPI-7-based identification criteria described in Section 2.2.2, the transition period is defined as the interval associated with the shift from sustained dry to wet conditions.

The EFI time series (Figure 2a) exhibits pronounced negative anomalies prior to the transition across all initialization dates, with values frequently below -0.5 , indicating a strong ensemble signal associated with the persistent dry conditions. Positive EFI anomalies related to the rainfall onset emerge primarily in short-lead forecasts initialized in late September, with EFI exceeding 0.3 and reaching values above 0.5 in the 26 September forecast, closely aligned with the observed transition timing. Consistent with this behavior, CRPS values (Figure 2b) remain positive for most forecasts during the dry phase, whereas sustained positive skill during the wet phase is confined to forecasts initialized after mid-September.

Ensemble success ratios (Table 2; Figure 3) further illustrate the dependence of forecast performance on lead time. Forecasts initialized around 27 days before the transition yield moderate success ratios ($\sim 53\%$), but exhibit noticeable deviations in both amplitude and timing of SPI-7 evolution. At intermediate leads (17–24 days), success ratios drop sharply (2%–35%), accompanied by large ensemble spread and smoothed SPI-7 trajectories. A partial recovery occurs at leads of 10–13 days, when success ratios increase to 37%–51% and successful members begin to cluster more closely around the observed transition. The highest success ratio (92%) is achieved for the 26 September initialization (6-day lead), for which most ensemble members closely reproduce both the timing and magnitude of the observed SPI-7 shift.

To diagnose the circulation features associated with forecast success, Figure 4 presents composites of Z500 and 850-hPa moisture flux anomalies for the 26 September forecast, which exhibits the highest success ratio. Successful and unsuccessful members share broadly similar large-scale circulation structures but differ markedly in

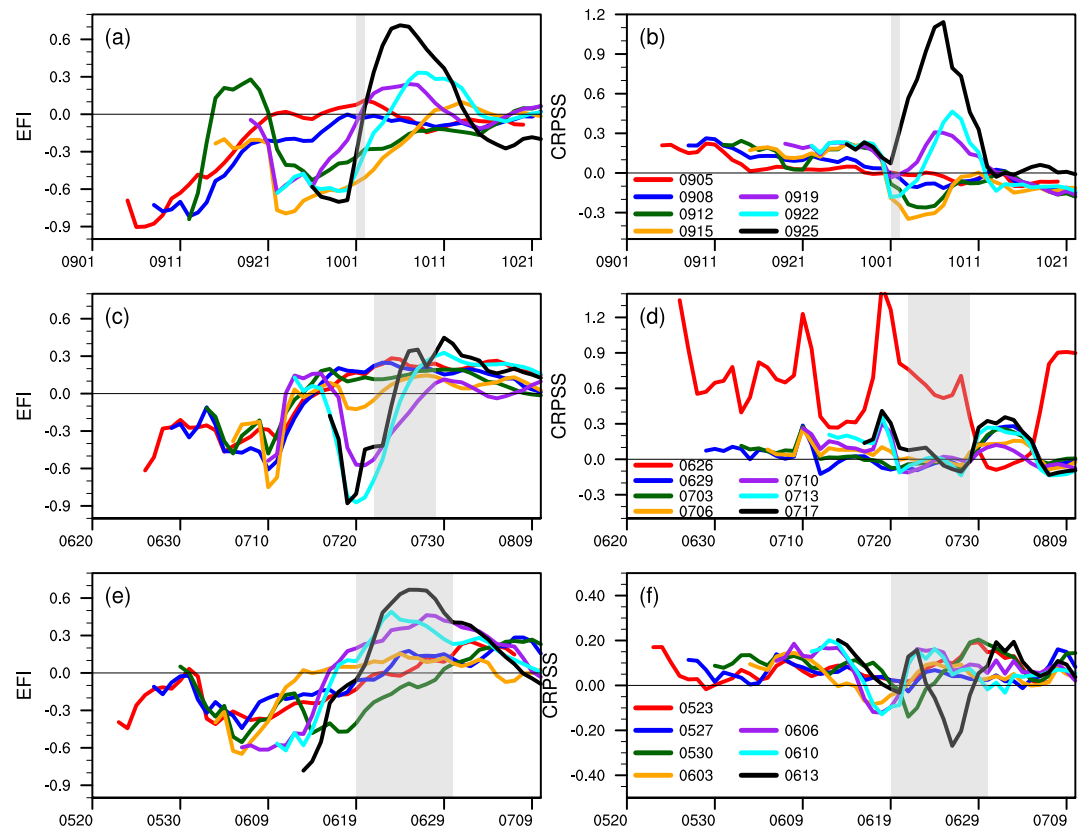


Figure 2. Time series of the Extreme Forecast Index (EFI; left panels: (a, c, e) and the Continuous Ranked Probability Skill Score (CRPSS; right panels: (b, d, f) for three selected Drought–flood abrupt alternation (DFAA) cases: (a, b) Case 1, (c, d) Case 2, and (e, f) Case 3. Each colored line represents a real-time forecast initialized on a different date, as indicated in the legend. Gray shading denotes the DFAA periods identified for each case.

anomaly amplitude. During the transition period (1–2 October), the difference composite (successful minus unsuccessful) shows a statistically significant negative Z500 anomaly over Mongolia and enhanced positive anomalies along the southeastern coast, accompanied by stronger southwesterly moisture transport into the Huang–Huai region (Figure 4f). In the post-transition stage (3–9 October), positive height anomalies further intensify and extend along eastern China, supporting sustained moisture convergence and continued wet conditions (Figure 4i).

To examine precursor signals at longer lead times, Figure 5 presents latitude–time and longitude–time cross sections of circulation differences for forecasts initialized on 5 September. This earlier initialization is used to isolate robust precursor signals that distinguish successful and unsuccessful ensemble members well in advance of the transition. The Z500 fields reveal a coherent large-scale precursor pattern emerging approximately 10–20 days before the transition. In the latitude–time section (Figure 5b), a tripole structure develops from mid-September, characterized by negative anomalies south of 15°N, positive anomalies near 25°N, and negative anomalies around 35°N, which gradually intensifies and shifts northward as the transition approaches. The longitude–time evolution (Figure 5e) shows a broad east–west dipole extending from western to eastern Eurasia (approximately 75°E–135°E), consistent with the development of a large-scale Rossby wave pattern preceding the transition. In contrast, differences in ROT850 and PV remain weak and spatially fragmented throughout most of September, with only limited areas of statistical significance. These results suggest that, for this event, successful long-lead forecasts are primarily associated with slowly evolving mid-tropospheric circulation anomalies.

3.2. Case 2: Summer 2023 North China Plain Event

Case 2 occurred over the North China Plain and adjacent regions (110°–120°E, 35°–42°N) during summer 2023 and was characterized by a prolonged drought followed by extreme rainfall associated with Typhoon Doksuri.

Table 2
Number and Percentage of Successful Ensemble Members at Different Lead Times

Case	Initial time	Lead time (days)	Successful/Total members	Success ratio (%)
1	20,220,905	27	27/51	52.9
	20,220,908	24	18/51	35.3
	20,220,912	20	6/51	11.8
	20,220,915	17	1/51	2.0
	20,220,919	13	26/51	51.0
	20,220,922	10	19/51	37.3
	20,220,926	6	47/51	92.2
2	20,230,626	33	23/51	45.1
	20,230,629	30	25/51	49.0
	20,230,703	26	10/101	9.9
	20,230,706	23	4/101	4.0
	20,230,710	19	17/101	16.8
	20,230,713	16	38/101	37.6
	20,230,717	12	25/101	24.8
3	20,240,523	38	56/101	55.4
	20,240,527	34	48/101	47.5
	20,240,530	31	49/101	48.5
	20,240,603	27	54/101	53.5
	20,240,606	24	84/101	83.2
	20,240,610	20	54/101	53.5
	20,240,613	17	18/101	17.8

Note. Lead time is calculated relative to the end of the drought-to-flood transition period. Ensemble size varies with initialization date: forecasts initialized on 29 June 2023 consist of 51 members (1 control and 50 perturbed), whereas those initialized on 3 July 2023 and thereafter consist of 101 members (1 control and 100 perturbed).

The drought phase persisted from early June to late July under suppressed precipitation and recurrent heatwaves. The abrupt transition was triggered by the northward migration of Doksuri's remnant circulation following its landfall on 28 July, producing widespread flooding over North China between 29 July and 1 August (Figures 1c and 1d). The transition period is defined as 22–29 July.

The EFI and CRPSS time series (Figures 2c and 2d) indicate marked variability in forecast performance across lead times. Negative EFI anomalies are present in all forecasts prior to the transition, with stronger signals appearing in mid-July initializations, consistent with the observed drought. In contrast, positive EFI anomalies associated with the rainfall phase remain weak across most forecasts, indicating an underestimation of the rainfall extremity. The CRPSS shows sustained positive values at long leads (e.g., 29 June) for much of the drought period, but drops toward zero around the transition. Partial recovery of CRPSS occurs in mid-July forecasts, with local maxima exceeding 0.3 near 31 July.

Success ratios (Table 2; Figure 6) exhibit a pronounced non-monotonic dependence on lead time. Forecasts initialized at long leads (~30–33 days) achieve the highest success ratios (45%–49%), primarily reflecting reasonable representation of drought persistence. Skill degrades sharply at intermediate leads (~23–26 days), with success ratios falling to 4%–10% and ensemble members showing muted or delayed transitions. At shorter leads (~12–19 days), success ratios partially recover (17%–38%) as a subset of members captures both the drought phase and the subsequent rainfall onset.

Circulation diagnostics based on the 29 June forecast (30-day lead; Figure 7) provide insight into the sources of predictability. During the week preceding the transition (Figures 7a–7c), both successful and unsuccessful members simulate a pronounced positive Z500 anomaly over Northeast Asia, accompanied by anomalous southward moisture flux into the North China Plain. This large-scale circulation pattern suppresses moisture transport and supports drought persistence. Differences between the two groups emerge during and after the

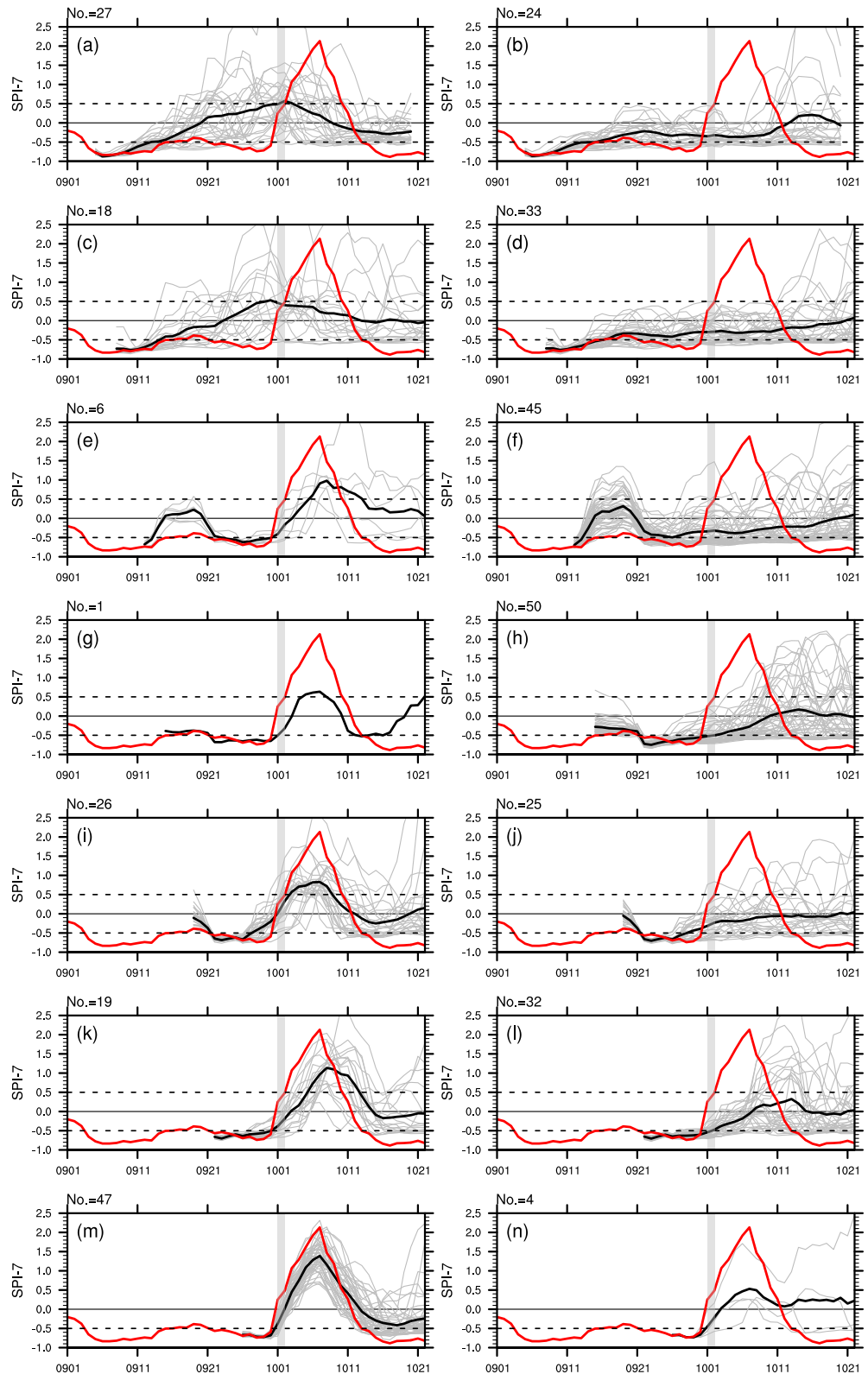


Figure 3. Evolution of the SPI-7 index for Case 1 at different forecast lead times. Rows correspond to forecasts initialized on 5, 8, 12, 15, 19, 22, and 26 September, respectively. The left and right columns show successful and unsuccessful ensemble members. The red line denotes observations, the black line the ensemble mean, and gray lines individual ensemble members.

Evolution of Z500 and 850hPa moisture flux anomalies (20220926)

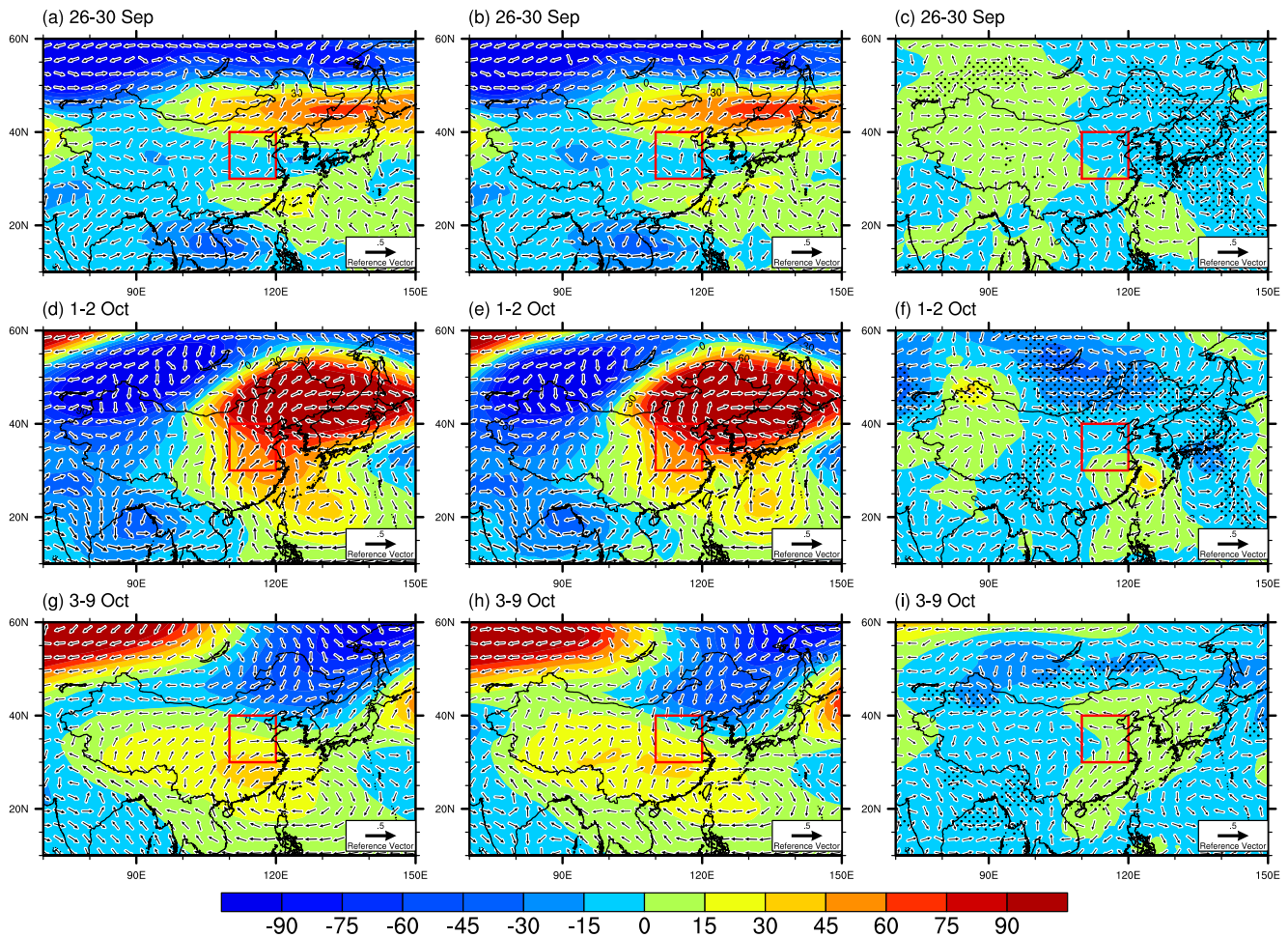


Figure 4. Case 1 composites of Z500 anomalies (shading; gpm) and 850-hPa moisture flux anomalies (vectors; m s^{-1}) for the forecast initialized on 26 September 2022 (47 successful and 4 unsuccessful members). Results are averaged over three periods: (a–c) the pre-transition period (26–30 September), (d–f) the transition period (1–2 October), and (g–i) post-transition period (3–9 October). The left, middle, and right columns show the ensemble means of successful members, unsuccessful members, and their difference (successful minus unsuccessful), respectively. The red box denotes the eastern plain region ($110\text{--}120^\circ\text{E}$, $30\text{--}40^\circ\text{N}$). Dots indicate regions where Z500 differences are statistically significant at the 90% confidence level based on Welch's *t*-test.

transition. Successful members reproduce a stronger mid-tropospheric high over central–eastern China together with a low-level cyclonic anomaly over southeastern China associated with Typhoon Doksuri (Figures 7d and 7g), whereas unsuccessful members substantially underestimate both features (Figures 7e and 7h). The difference field (Figure 7i) highlights the combined influence of enhanced anticyclonic anomalies aloft and stronger typhoon-related circulation in successful forecasts.

Despite this improvement, even successful ensemble members fail to reproduce the full vertical structure of Typhoon Doksuri. Notably, the typhoon-related cyclonic signal is evident primarily in the 850-hPa moisture-flux field, while a corresponding deep negative Z500 anomaly is largely absent. This vertically shallow representation implies a weakened coupling between the typhoon remnant, the subtropical high, and the midlatitude flow, which likely contributes to the underestimation of rainfall intensity and the relatively weak EFI signals during the flooding phase.

In addition, ensemble-mean composites tend to smooth localized typhoon-related circulation features, reflecting both the nonlinear nature of tropical cyclone dynamics and substantial structural diversity among ensemble members. Such sensitivity may also be related to rapid structural adjustments of landfalling tropical cyclones associated with land–sea thermal and surface roughness contrasts, which can further enhance forecast uncertainty

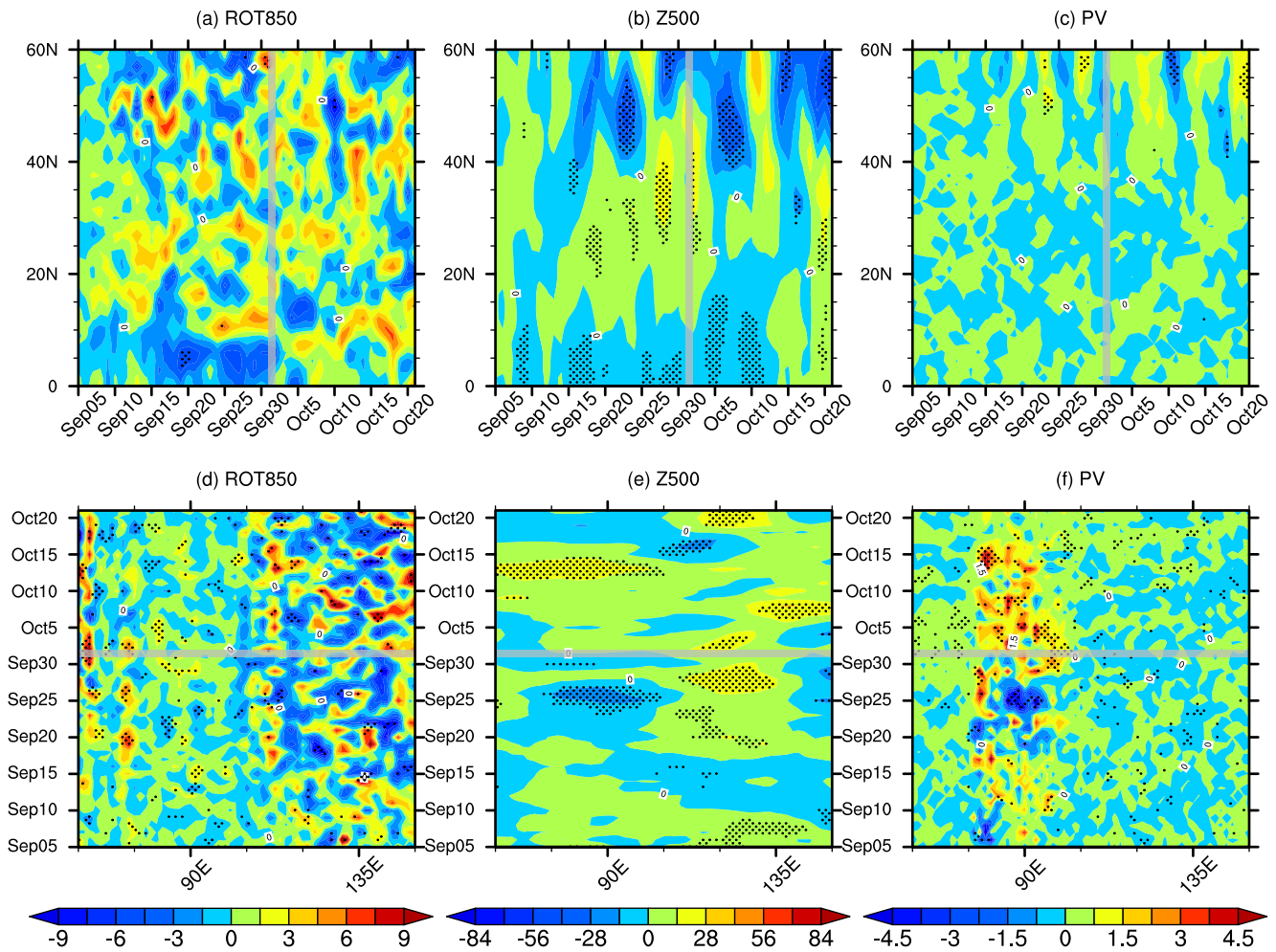


Figure 5. Latitude–time (top row; averaged over 110°E–120°E) and longitude–time (bottom row; averaged over 32°N–34°N) composite cross sections of differences between successful and unsuccessful ensemble members (successful minus unsuccessful) for Case 1, based on the forecast initialized on 5 September 2022. Shown are ROT850 (left), Z500 (middle), and PV (right). The gray shading denotes the Drought–flood abrupt alternation period (1–2 October). Dots indicate regions where differences in the corresponding variables are statistically significant at the 90% confidence level based on Welch's *t*-test.

in post-landfall precipitation evolution (Zhong et al., 2026). As a result, the predictability of the extreme rainfall phase is highly member-dependent and sensitive to small differences in typhoon track, intensity, and interaction with the background circulation.

Long-lead precursor signals are further examined using latitude–time (top row) and longitude–time (bottom row) evolution diagnostics (Figure 8). Compared with Cases 1 and 3, Case 2 exhibits much weaker and less coherent precursor signals. Although statistically significant Z500 differences appear intermittently during July, they mainly indicate a favorable large-scale circulation background rather than a direct precursor of the subsequent extreme rainfall. By contrast, PV anomalies remain weak and spatially fragmented, with limited statistical significance prior to the transition, suggesting that upper-level PV forcing does not provide a robust subseasonal precursor for this event. These results indicate that drought persistence is primarily associated with the slowly evolving large-scale circulation, whereas the abrupt flood transition depends strongly on the later evolution of Typhoon Doksuri and its interaction with the background circulation.

3.3. Case 3: Early Summer 2024 Huang–Huai Basin Event

Case 3 examines a prolonged DFAA event over the Huang–Huai Basin and adjacent regions (110°–120°E, 30°–36°N) during June 2024, a key transition period of the East Asian summer monsoon characterized by strong intraseasonal variability. The drought–flood transition extended from 19 to 30 June (Figure 1f), lasting

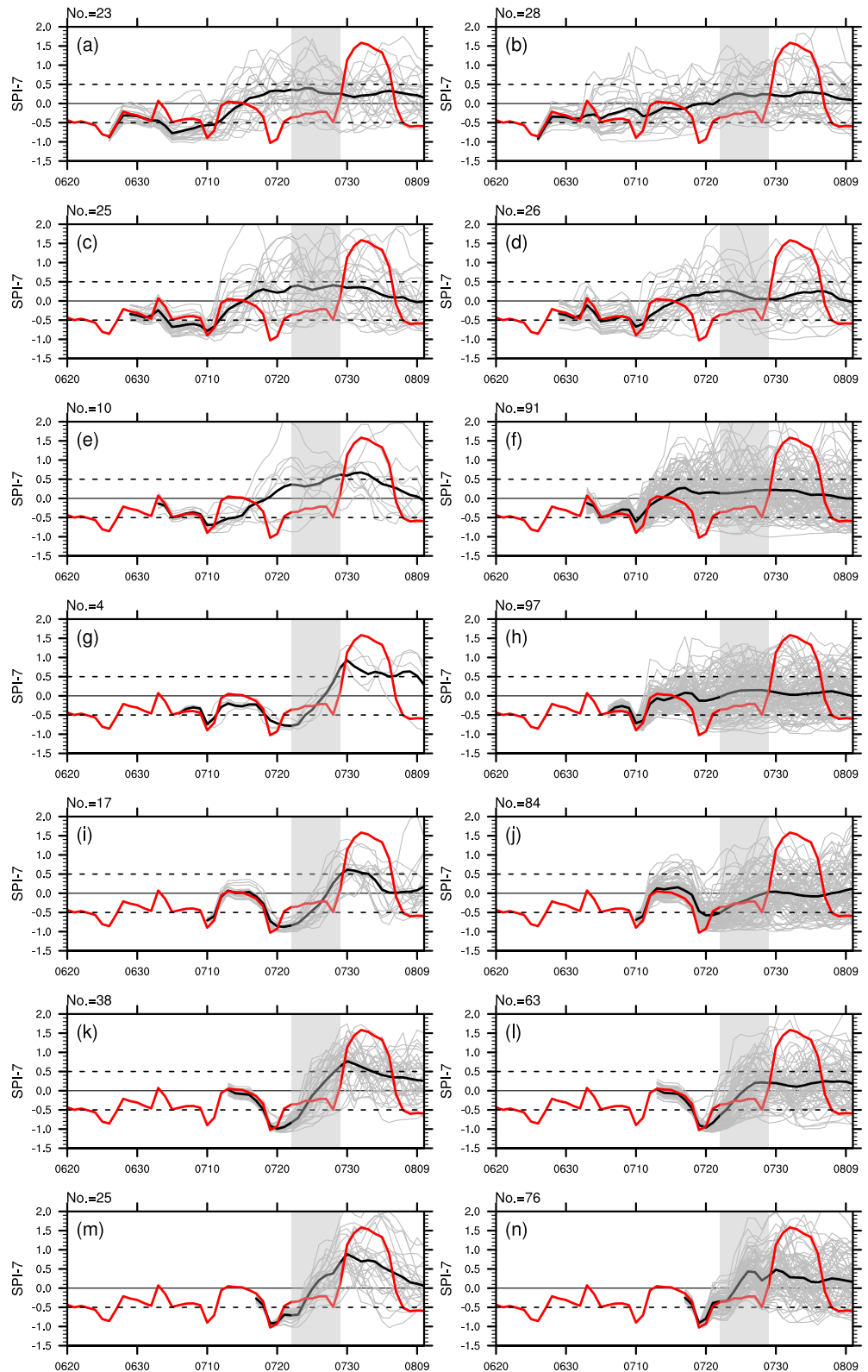


Figure 6. Evolution of the SPI-7 index for Case 2 at different forecast lead times. Rows correspond to forecasts initialized on 26 June, 29 June, 3 July, 6 July, 10 July, 13 July, and 17 July, respectively. The left and right columns show successful and unsuccessful ensemble members. The red line denotes observations, the black line the ensemble mean, and gray lines individual ensemble members.

Evolution of Z500 and 850hPa moisture flux anomalies (20230629)

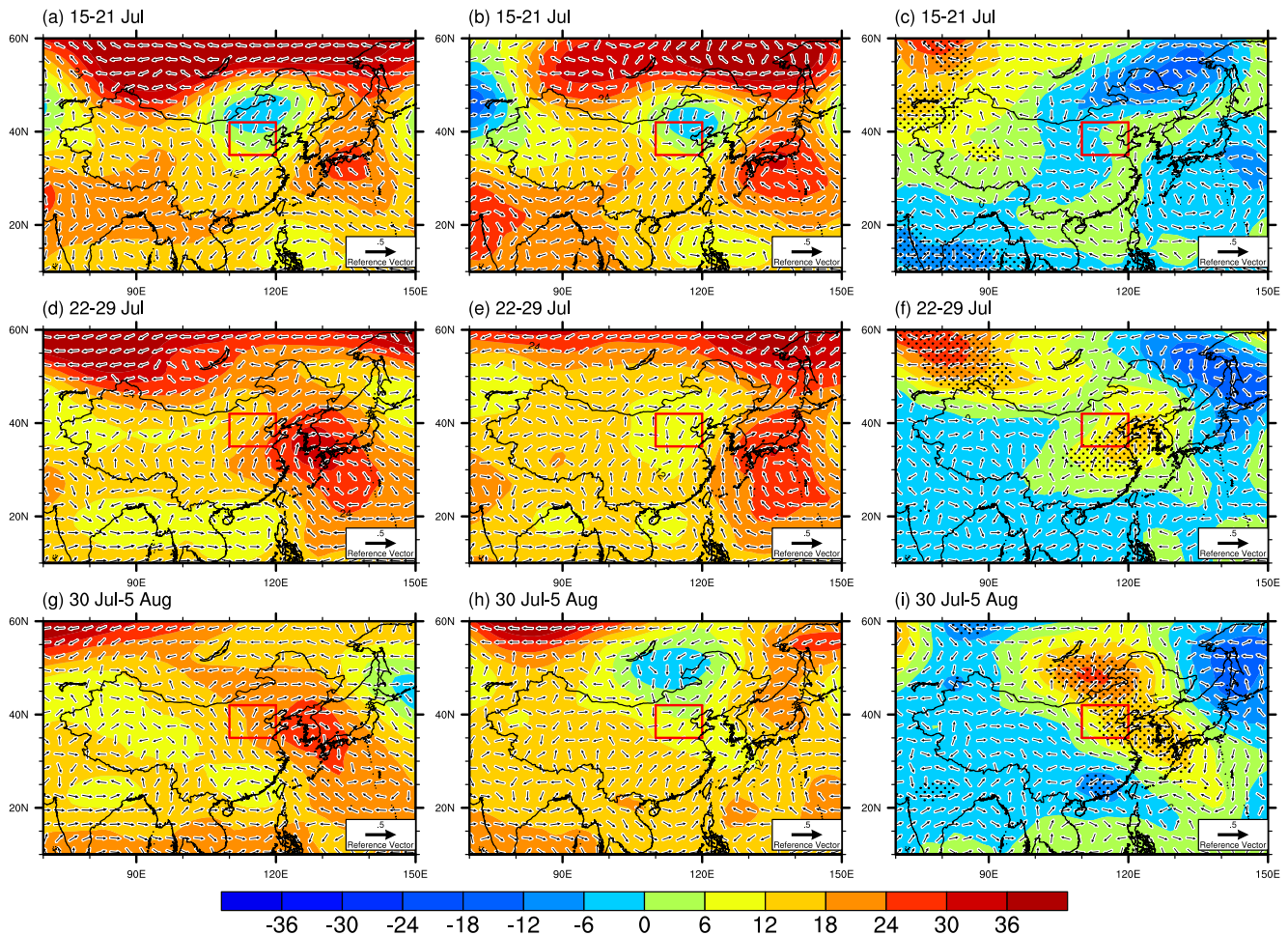


Figure 7. Same as Figure 4, but for Case 2. Composites are shown for the forecast initialized on 29 June 2023 (25 successful and 26 unsuccessful members), averaged over three periods: (a–c) the pre-transition period (15–21 July), (d–f) the transition period (22–29 July), and (g–i) the post-transition period (30 July–5 August). The red box denotes the North China Plain (110–120°E, 35–42°N). Dots indicate regions where Z500 differences are statistically significant at the 90% confidence level based on Welch's *t*-test.

approximately 12 days and thus representing a more gradual but sustained transition compared with the other two cases.

The EFI and CRPSS time series (Figures 2e and 2f) reveal a clear contrast between the two phases of the event. Prior to the transition, EFI values are persistently negative across nearly all forecasts, indicating a coherent dry signal that is consistently detected at both long and short lead times. Positive EFI anomalies associated with the flooding phase emerge only in short-lead forecasts (e.g., initializations on 6, 10, and 13 June), but these signals tend to appear earlier than observed and remain relatively weak, reflecting a combination of timing errors and underestimation of rainfall intensity. In contrast, CRPSS values remain positive throughout most of the drought phase, indicating robust probabilistic skill for the persistent dry conditions, while skill decreases markedly during the transition period.

The ensemble success ratios (Table 2) further illustrate the lead-time dependence of forecast performance. Forecasts initialized between 23 May and 3 June (27–38-day leads) maintain moderate success ratios ranging from 47.5% to 55.4%, suggesting that a substantial fraction of ensemble members capture the overall evolution of the event. The forecast initialized on 6 June (24-day lead) achieves the highest success ratio among all cases (83.2%), with successful members closely reproducing both the prolonged drought and the subsequent abrupt flooding onset (Figures 9g–9j). By contrast, the forecast initialized on 13 June (6-day lead) exhibits a much lower

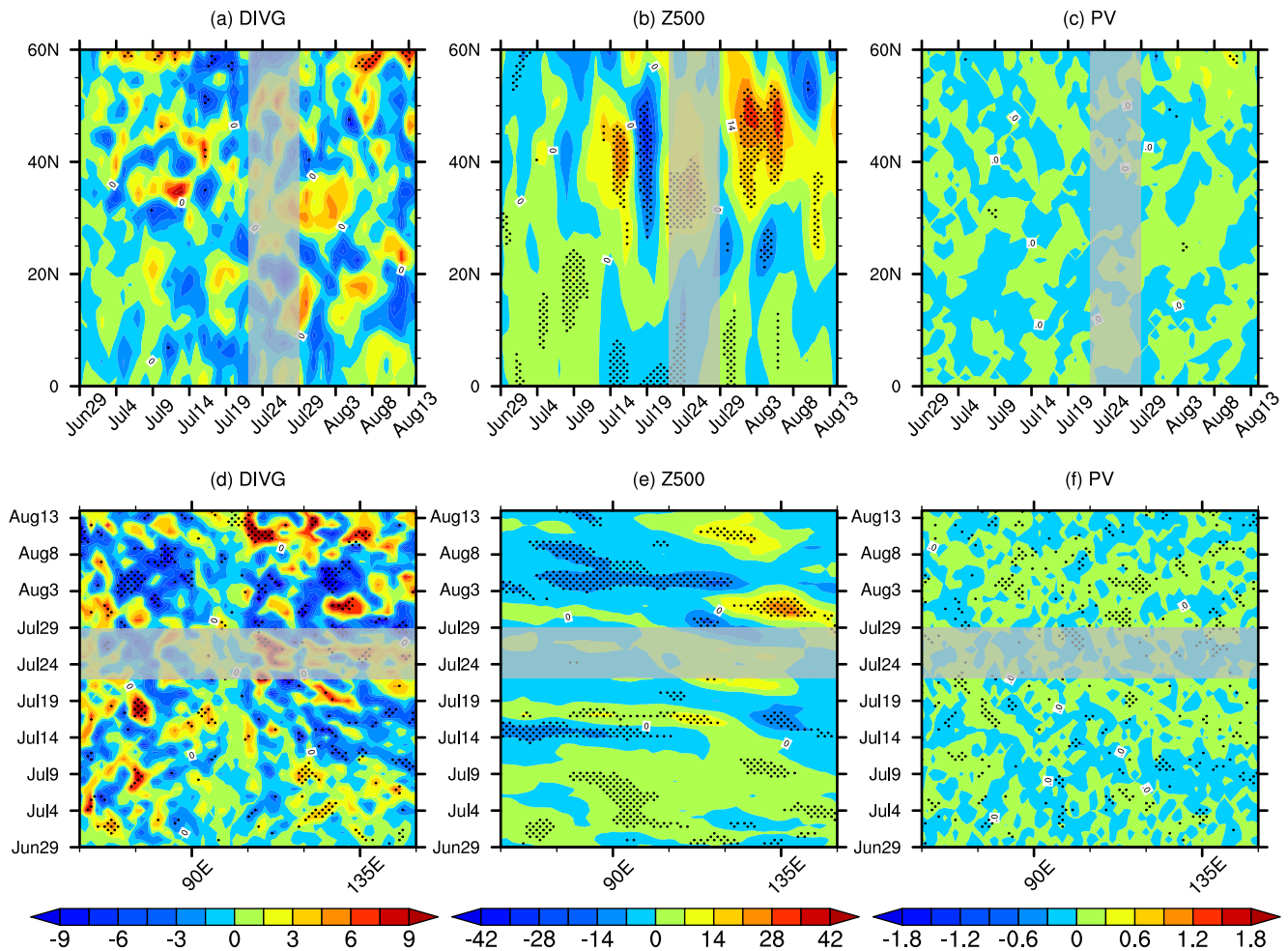


Figure 8. Same as Figure 5, but for Case 2. Latitude–time (top row; averaged over 110°E–120°E) and longitude–time (bottom row; over 25°N) composites of differences between successful and unsuccessful ensemble members (successful minus unsuccessful) are shown for the forecast initialized on 29 June 2023. Variables shown are ROT850 (left), Z500 (middle), and PV (right). The gray shading denotes the Drought–flood abrupt alternation period (22–29 July). Dots indicate regions where the differences in the corresponding variables are statistically significant at the 90% confidence level based on Welch's *t*-test.

success ratio (17.8%). This reduction mainly reflects the event-based success criteria requiring sufficient antecedent dry conditions prior to transition. Because this initialization occurs very close to the observed flooding onset, some ensemble members capture the wet transition reasonably well but do not provide sufficient lead time to satisfy the minimum dry-phase requirement, rather than indicating a fundamental loss of forecast skill.

Circulation composites for the 6 June initialization (Figure 10) show that prior to the transition, both successful and unsuccessful members simulate a low-level cyclonic moisture-flux anomaly over the East China Sea and the adjacent southeastern coast. Northeasterly anomalies on the western flank of this circulation suppress moisture transport into the Huang–Huai Basin, favoring the persistence of dry conditions. During the transition period (19–30 June; Figures 10d–10f), this cyclonic circulation weakens substantially and is replaced by a pronounced anticyclonic anomaly at 500 hPa over central–eastern China, which enhances southwesterly moisture transport into the Huang–Huai region and triggers the abrupt shift to wet conditions. The difference composite (Figure 10i) highlights stronger positive Z500 anomalies and enhanced low-level southerly moisture transport in successful members, together with compensating negative anomalies to the northeast, indicating that a more robust mid-tropospheric high and intensified monsoonal flow are critical for reproducing the observed transition.

The circulation evolution shown in Figure 10 also explains the relatively stable forecast performance during the drought phase. Prior to the transition, successful and unsuccessful members exhibit highly consistent large-scale circulation patterns, characterized by suppressed moisture transport and limited ensemble spread. This spatially

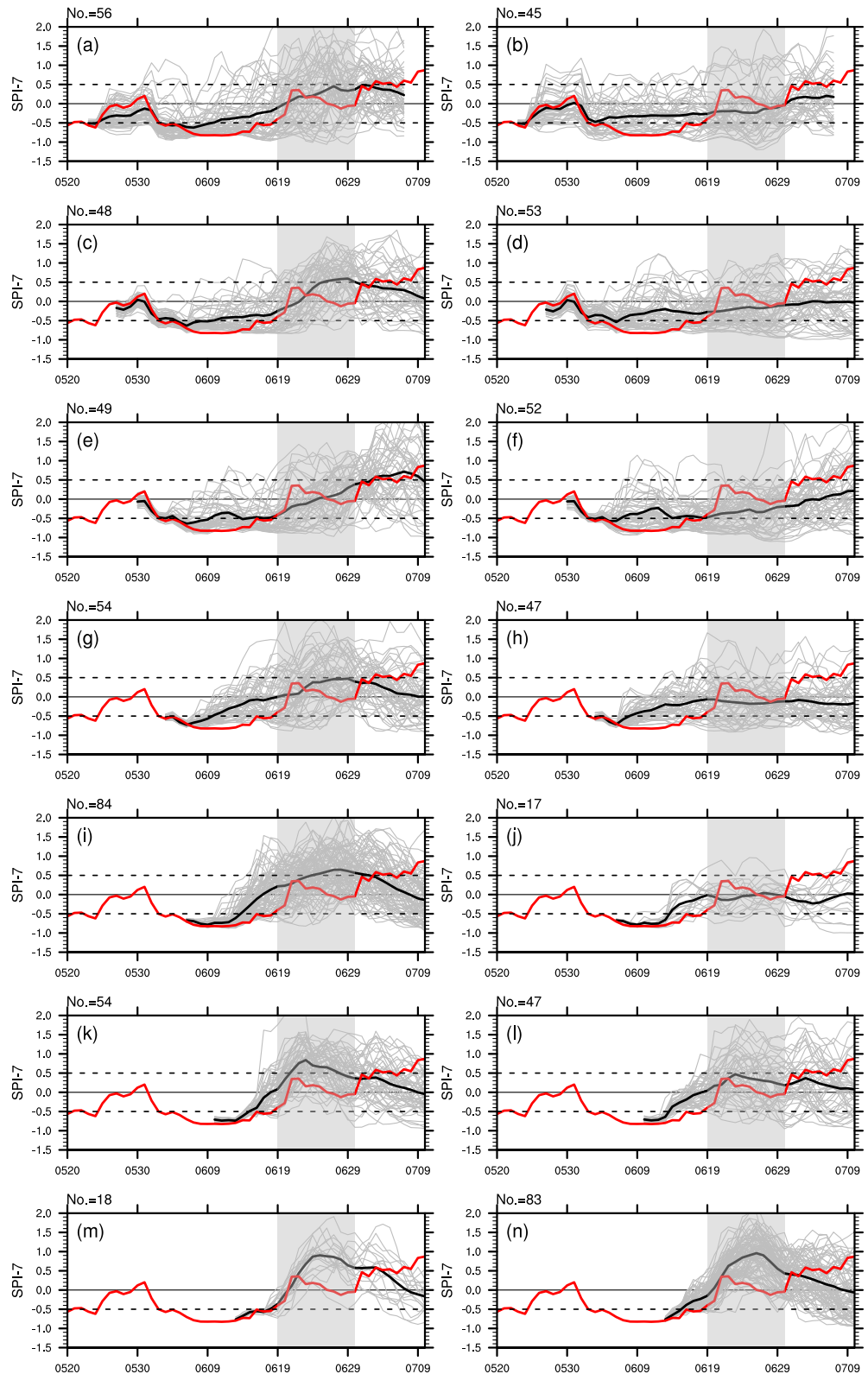


Figure 9. Evolution of the SPI-7 index for Case 3 at different forecast lead times. Rows correspond to forecasts initialized on 23 May, 27 May, 30 May, 3 June, 6 June, 10 June, and 13 June, respectively. The left and right columns show successful and unsuccessful ensemble members. The red line denotes observations, the black line the ensemble mean, and gray lines individual ensemble members.

Evolution of Z500 and 850hPa moisture flux anomalies (20240606)

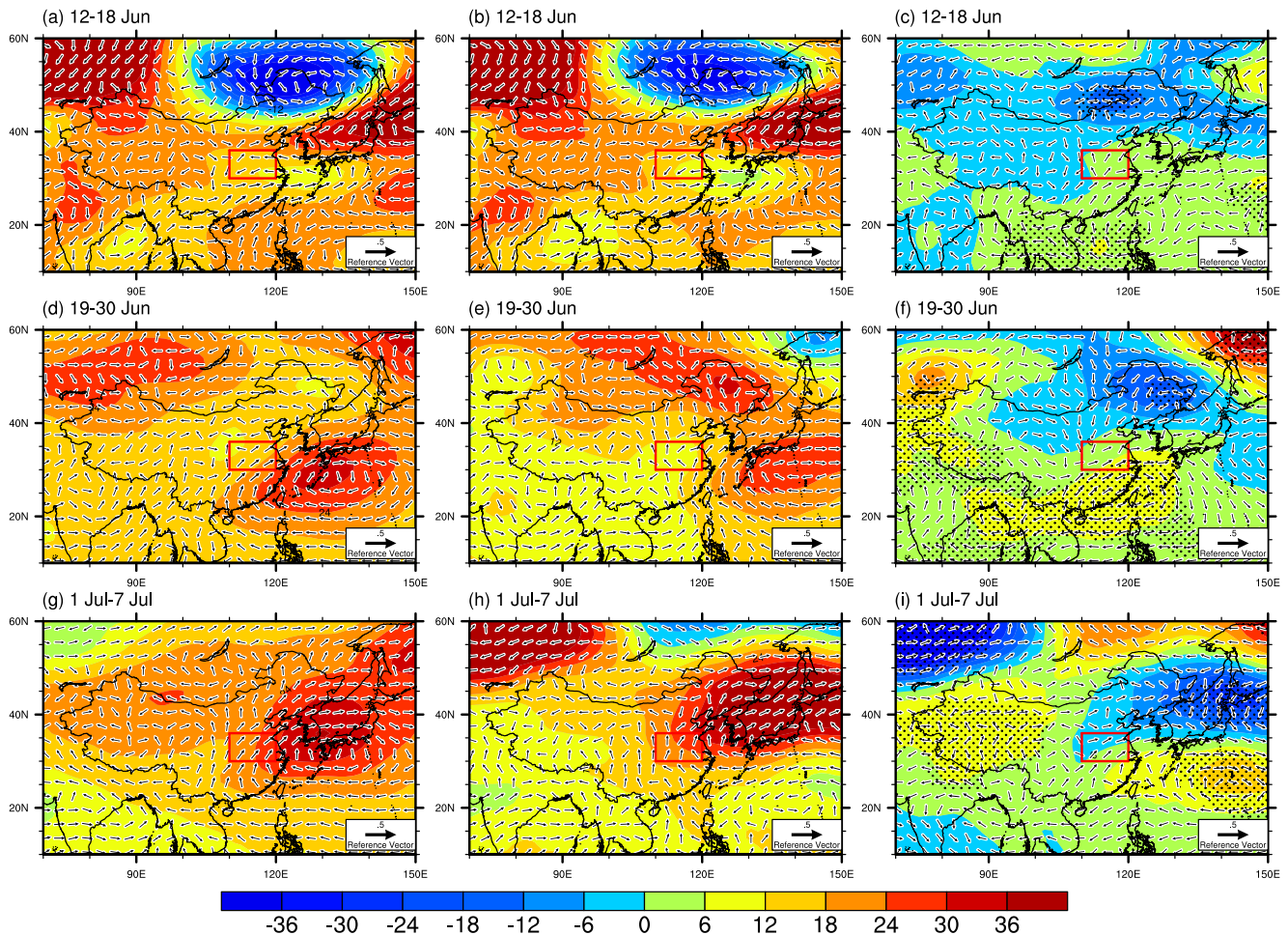


Figure 10. Same as Figure 4, but for Case 3. Composites are based on the forecast initialized on 6 June 2024 (84 successful and 17 unsuccessful members), averaged over three periods: (a–c) the pre-transition period (12–18 June), (d–f) the transition period (19–30 June), and (g–i) the post-transition period (1–7 July). The red box denotes the Huang–Huai Basin region (110–120°E, 30–36°N). Dots indicate regions where Z500 differences are statistically significant at the 90% confidence level based on Welch's *t*-test.

coherent and slowly evolving circulation regime supports stable ensemble behavior, as reflected by persistent negative EFI values and positive CRPSS. In contrast, the transition to flooding requires a rapid reorganization of the mid-tropospheric circulation and an abrupt strengthening of monsoonal moisture transport, processes that are highly sensitive to amplitude and timing errors and therefore more difficult to predict.

Further insight into the sources of predictability is provided by the latitude–time and longitude–time cross sections in Figure 11. Differences in Z500 reveal significant large-scale anomalies emerging as early as 6 June, forming a meridional dipole with negative anomalies over northern East Asia and positive anomalies to the south. This dipole intensifies and shifts westward and equatorward as the transition approaches, reflecting the development of a Rossby wave train and the westward extension of the western Pacific subtropical high. These slowly evolving mid-tropospheric circulation anomalies constitute the dominant long-lead precursor that distinguishes successful from unsuccessful forecasts. In contrast, differences in ROT850 exhibit more localized and westward-propagating features, while PV anomalies remain weak and spatially fragmented. These results indicate that upper-level PV forcing plays a secondary role compared with mid-tropospheric circulation and monsoon-related processes in Case 3.

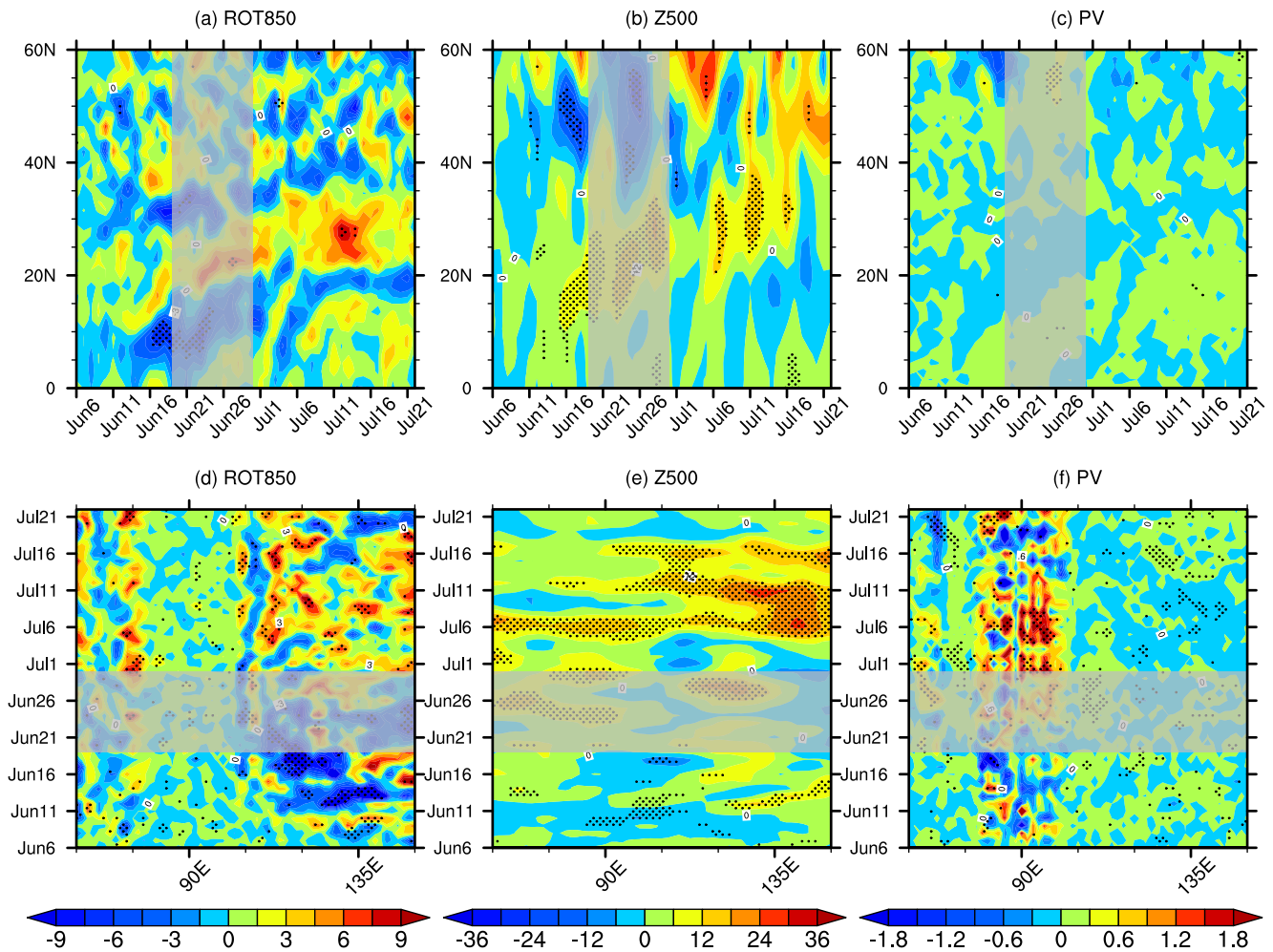


Figure 11. Same as Figure 5, but for Case 3. Latitude–time (top row; averaged over 110°E–120°E) and longitude–time (bottom row; over 32°N) composites of differences between successful and unsuccessful ensemble members (successful minus unsuccessful) are shown for the forecast initialized on 6 June 2024. Variables shown are ROT850 (left), Z500 (middle), and PV (right). The gray shading denotes the Drought–flood abrupt alternation period (19–30 June). Dots indicate regions where the differences in the corresponding variables are statistically significant at the 90% confidence level based on Welch's *t*-test.

4. Discussion

This section provides a physical interpretation of the subseasonal predictability features identified in Section 3, with emphasis on the roles of large-scale circulation evolution and drought-to-flood transition mechanisms. It synthesizes common characteristics across the three events, examines how differences in dominant transition processes modulate forecast skill, and discusses implications for subseasonal prediction of compound drought–flood events, together with key limitations and future directions.

4.1. Common Subseasonal Predictability Characteristics Across the Three DFAA Events

Despite pronounced differences in seasonality, transition duration, and dominant forcing mechanisms, the three DFAA events analyzed in this study share several common features in their subseasonal predictability. These shared characteristics provide a useful basis for interpreting how different stages of drought–flood evolution are represented in the ECMWF S2S ensemble forecasts, before considering case-specific differences.

Across all three cases, forecasts exhibit greater subseasonal skill during the drought phase than during the subsequent drought-to-flood transition. This contrast can be understood in terms of the underlying circulation evolution. Persistent drought conditions tend to be associated with slowly evolving, spatially coherent large-scale circulation anomalies, for which error growth is relatively gradual compared to rapidly evolving synoptic-scale

processes. As a result, ensemble forecasts exhibit greater internal consistency at subseasonal lead times during the drought phase, as reflected by more sustained negative EFI signals and comparatively positive CRPSS values over a broad range of lead times.

Another common feature is the role of mid-tropospheric circulation anomalies in shaping subseasonal predictability. Successful ensemble members are typically characterized by more coherent and better-amplified Z500 anomaly patterns than unsuccessful members. These anomalies are frequently linked to Rossby wave trains and subtropical–midlatitude coupling and tend to emerge approximately 10–30 days prior to the observed transitions. The timing of these signals suggests that large-scale circulation evolution provides useful information on drought persistence and the evolving background state preceding abrupt transitions, rather than directly determining the occurrence or intensity of extreme rainfall. These circulation precursors should therefore be interpreted as indicators of enhanced probabilistic predictability rather than deterministic predictors of DFAA occurrence.

Consistent with these results, ensemble members exhibiting stronger and more coherent Z500 anomaly patterns generally show improved representation of precipitation evolution, including more realistic timing and spatial organization of rainfall. This correspondence suggests that mid-tropospheric circulation anomalies provide a dynamically consistent large-scale framework within which precipitation anomalies develop, thereby supporting enhanced subseasonal forecast skill.

In contrast, forecast skill consistently decreases during the transition period and flood onset, when accurate prediction depends on the timing and intensity of rapidly evolving triggering processes. This reduction in skill is manifested by increased ensemble spread, weaker EFI signals for wet extremes, and reduced CRPSS across all three cases, indicating heightened sensitivity to short-term dynamical uncertainties. The increase in ensemble spread during the transition period reflects not only reduced predictability but may also indicate physically meaningful uncertainty arising from differences in the evolution of key circulation features among ensemble members, particularly in cases influenced by rapidly evolving synoptic processes. Because successful classification requires both drought persistence and the subsequent transition to satisfy the event criteria simultaneously, the event-based success ratio should not be interpreted as an isolated measure of forecast skill for either phase or as an absolute measure of overall forecast quality. Some ensemble members may reproduce one phase more successfully than the other while failing to satisfy the complete event criteria. Instead, the higher predictability during the drought phase is supported jointly by EFI, CRPSS, and circulation diagnostics.

4.2. Key Contrasts Among the Three Cases: Role of Transition Mechanisms

Despite these shared predictability characteristics, the three cases exhibit notable differences in forecast behavior that are closely related to their dominant transition mechanisms. In particular, the degree to which large-scale circulation predictability translates into usable subseasonal forecast skill varies depending on whether the drought-to-flood transition is governed by gradual large-scale adjustments or by rapidly evolving synoptic forcing.

The early summer 2024 Huang–Huai Basin event exhibits relatively higher subseasonal predictability compared to the other cases. Its drought-to-flood transition is primarily associated with gradual monsoon-related circulation adjustments, including the westward extension of the western Pacific subtropical high and enhanced large-scale moisture transport. The relatively slow and organized nature of this transition allows ensemble members to converge toward a broadly consistent circulation evolution, leading to higher success ratios even at longer lead times.

By comparison, the summer 2023 North China Plain event shows markedly reduced predictability during the transition period. Although drought persistence is reasonably captured at extended leads, the subsequent flooding is triggered by member-dependent typhoon forcing associated with Typhoon Doksuri. The representation of the typhoon-related circulation is mainly confined to the lower troposphere and is highly sensitive to small-scale structural differences, with limited expression in mid-tropospheric height fields. Consequently, ensemble forecasts display weak and spatially inconsistent EFI signals for wet extremes, accompanied by large internal divergence, indicating strong dependence on short-lead initialization.

The autumn 2022 Eastern China Plain event represents an intermediate regime. Its transition is influenced by coherent mid-tropospheric circulation precursors without strong tropical cyclone involvement, allowing for

moderate predictability at intermediate lead times. However, the relatively abrupt nature of the transition still constrains forecast skill compared to the more gradually evolving 2024 case.

Together, these contrasts suggest that the dominant transition mechanism—gradual large-scale adjustment versus rapid synoptic forcing—modulates the extent to which large-scale predictability can be translated into usable forecast skill.

4.3. Implications for Subseasonal Prediction of Compound Drought–Flood Events

The cross-case synthesis provides several process-oriented implications for subseasonal prediction of DFAA and related compound events. Across the three cases, predictability at subseasonal lead times is most consistently associated with slowly evolving mid-tropospheric circulation anomalies, which offer physically interpretable information on drought persistence and the evolving background state prior to abrupt transitions.

However, the degree to which this large-scale predictability is reflected in precipitation forecasts depends strongly on the nature of the transition process. The monsoon-related event is associated with relatively higher and more stable forecast skill, whereas the tropical cyclone-influenced event exhibits greater ensemble divergence and reduced reliability during the transition period. This contrast highlights the importance of distinguishing between background circulation precursors and short-term triggering processes when interpreting ensemble forecasts.

These interpretations are broadly consistent with previous studies emphasizing the roles of large-scale circulation and background thermodynamic conditions in DFAA evolution (e.g., Ding et al., 2025; Wang et al., 2025), as well as the inherent predictability limitations associated with typhoon-related extreme rainfall (Yin et al., 2025). The present results extend these findings by placing them within a subseasonal prediction framework and demonstrating how different physical processes govern forecast skill at different stages of DFAA evolution.

From an operational perspective, the results suggest that interpretation of subseasonal ensemble forecasts should place greater emphasis on slowly evolving large-scale circulation signals, which may provide useful guidance for real-time subseasonal monitoring of favorable background conditions for DFAA development, while explicitly accounting for the increased uncertainty associated with rapidly evolving transition processes. Such a process-oriented perspective may facilitate the interpretation of probabilistic forecasts, support early warning of elevated DFAA risk, and contribute to future improvements in the operational prediction of DFAA events over eastern China.

4.4. Limitations and Outlook

Several limitations of this study should be acknowledged. The analysis is based on three objectively identified events, reflecting both the rarity of well-defined DFAA cases and the limited availability of ECMWF S2S real-time forecasts. While the consistency of circulation-related signals across these cases supports the proposed physical interpretations, the findings should be regarded as case-informed rather than statistically comprehensive.

The three cases examined here were selected to represent distinct types of DFAA transitions, including monsoon-related large-scale adjustment, typhoon-induced rapid forcing, and intermediate regimes influenced primarily by midlatitude circulation. Although not exhaustive, these cases span a range of dominant transition mechanisms and therefore provide a physically meaningful basis for interpreting subseasonal predictability across different DFAA regimes.

Additional uncertainty arises from the objective identification of DFAA events. The detection of short-term drought–flood transitions is sensitive to the choice of indices, thresholds, and temporal scales, particularly regarding the definition of transition timing (Zhao et al., 2025). Although the SPI-based criteria used here are designed to capture high-impact events relevant for subseasonal analysis, alternative definitions may yield different samples. Modest adjustments to the event-identification thresholds may influence the precise timing of transitions and the number of successful ensemble members; however, such changes are unlikely to qualitatively alter the principal conclusions of this study. This is because the main findings are supported jointly by EFI, CRPSS, and circulation diagnostics rather than by the event-based success ratio alone. In particular, the conclusion that forecast skill is generally higher during the drought phase than during the subsequent transition period is expected to remain robust.

Within this event-based verification framework, forecasts initialized very close to the observed transition may underestimate event consistency because the available forecast window may not fully encompass the antecedent drought phase required by the event definition. Consequently, some ensemble members that reproduce the transition reasonably well may nevertheless fail to satisfy the complete event-based criteria. This methodological limitation should therefore be considered when interpreting success ratios at the shortest lead times.

Finally, the focus on a single S2S prediction system limits the generality of the results. Future work should extend this framework to multi-model S2S ensembles and longer hindcast records, enabling a more systematic evaluation of predictability sources across different climatic backgrounds and transition types. Further progress will also require improved diagnostics of tropical–extratropical interactions and other rapidly evolving synoptic processes that currently constrain forecast skill during drought-to-flood transitions. Recent studies have also highlighted the potential influence of large-scale inter-basin teleconnections and evolving Atlantic–Pacific interactions on subseasonal-to-interannual climate variability (e.g., Ding et al., 2023; Tian et al., 2025), suggesting that broader climate background states may further modulate the predictability of DFAA events. Incorporating these factors into future multi-model analyses may further improve our understanding of the physical sources of subseasonal predictability for DFAA events.

5. Conclusions

This study examined the subseasonal predictability of three objectively identified DFAA events over eastern China using the ECMWF S2S ensemble prediction system. By analyzing forecast performance across different stages of DFAA evolution, the study highlights how predictability varies between drought persistence and subsequent drought-to-flood transitions.

Across the analyzed cases, forecast skill is generally higher during the drought phase than during the transition and flood onset. This contrast suggests that different stages of DFAA evolution are associated with differing levels of predictability, likely reflecting differences in the governing atmospheric processes and their characteristic error-growth behavior. In particular, slowly evolving large-scale circulation anomalies tend to support more consistent ensemble forecasts at subseasonal lead times.

The analysis further indicates that extended-range predictability is closely linked to the evolution of mid-tropospheric circulation. Coherent Z500 anomaly patterns emerge approximately 10–30 days prior to the observed drought-to-flood transitions and are more clearly expressed in ensemble members with higher forecast skill. These signals provide useful information on drought persistence and the broader circulation environment preceding abrupt transitions, although they do not directly determine the timing or intensity of extreme rainfall.

In contrast, forecast skill tends to decrease during the transition period and flood onset, when prediction depends on rapidly evolving triggering processes. Tropical cyclone–related circulation and associated moisture transport, in particular, introduce substantial ensemble spread and timing uncertainty, limiting subseasonal forecast reliability even when large-scale conditions are reasonably captured.

Taken together, the results emphasize the value of monitoring large-scale mid-tropospheric circulation as part of extended-range early-warning efforts for DFAA events, while also highlighting the intrinsic limitations of current S2S systems in predicting the precise timing and magnitude of abrupt flooding onset. Although based on a limited number of cases and a single prediction system, the findings offer a process-informed perspective on subseasonal predictability of compound drought–flood extremes in monsoon-affected regions.

Conflict of Interest

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

Availability Statement

The ECMWF subseasonal-to-seasonal (S2S) ensemble forecast data used in this study are available from the S2S Prediction Project database (Vitart et al., 2017). ERA5 reanalysis data are publicly available from the Copernicus Climate Change Service (C3S) Climate Data Store (Hersbach et al., 2023). The derived indices and diagnostics generated during this study are available from the corresponding author upon reasonable request.

Acknowledgments

This research was supported by the National Key R&D Program of China (2024YFC3012401), the National Natural Science Foundation of China (42330111; 42175051), Fundamental Research Funds of Institute of Atmospheric Physics, Chinese Academy of Sciences, and the National Key Scientific and Technological Infrastructure project "Earth System Numerical Simulation Facility" (EarthLab).

References

- AghaKouchak, A., Chiang, F., Huning, L. S., Love, C. A., Mallakpour, I., Mazdiyasn, O., et al. (2020). Climate extremes and compound hazards in a warming world. *Annual Review of Earth and Planetary Sciences*, 48(1), 519–548. <https://doi.org/10.1146/annurev-earth-071719-055228>
- Bai, X., Zhao, C., Tang, Y., Zhang, Z., Yang, B., & Wang, Z. (2023). Identification, physical mechanisms and impacts of drought–flood abrupt alternation: A review. *Frontiers in Earth Science*, 11, 1203603. <https://doi.org/10.3389/feart.2023.1203603>
- Bi, W., Li, M., Weng, B., Yan, D., Dong, Z., Feng, J., & Wang, H. (2023). Drought–flood abrupt alteration events over China. *Science of the Total Environment*, 875, 162529. <https://doi.org/10.1016/j.scitotenv.2023.162529>
- Bi, W., Weng, B., Yan, D., Wang, M., Wang, H., Wang, J., & Yan, H. (2020). Effects of drought–flood abrupt alternation on phosphorus in summer maize farmland systems. *Geoderma*, 363, 114147. <https://doi.org/10.1016/j.geoderma.2019.114147>
- Chen, H., Wang, S., & Wang, Y. (2020). Exploring abrupt alternations between wet and dry conditions on the basis of historical observations and convection-permitting climate model simulations. *Geophysical Research Letters*, 47, e2020GL087356. <https://doi.org/10.1029/2020GL087356>
- Chen, Z., Li, X., Zhang, X., Xu, L., Du, W., Wu, L., et al. (2025). Global drought–flood abrupt alternation: Spatiotemporal patterns, drivers, and projections. *The Innovation Geoscience*, 3, 100113. <https://doi.org/10.59717/j.xinn-geo.2024.100113>
- Chen, Z., & Zheng, Z. (2025). The strongest early-summer drought–flood abrupt alternation event over the Huang–Huai–Hai River Basin in 2024 since the 1980s: Perspective of anomalous subseasonal circulation evolution. *Atmospheric and Oceanic Science Letters*, 18(5), 100648. <https://doi.org/10.1016/j.aosl.2025.100648>
- DeFlorio, M. J., Waliser, D. E., Guan, B., Ralph, F. M., & Vitart, F. (2019). Global evaluation of atmospheric river subseasonal prediction skill. *Climate Dynamics*, 52(5–6), 3039–3060. <https://doi.org/10.1007/s00382-018-4309-x>
- Ding, R., Nnamchi, H. C., Yu, J. Y., Li, T., Sun, C., Li, J., et al. (2023). North Atlantic oscillation controls multidecadal changes in the North Tropical Atlantic–Pacific connection. *Nature Communications*, 14(1), 862. <https://doi.org/10.1038/s41467-023-36564-3>
- Ding, T., Xie, T., Gao, H., & Zhang, S. (2025). Alternation between the extreme drought–flood event in the North China Plain in summer 2024. *International Journal of Climatology*, 45(8), e8831. <https://doi.org/10.1002/joc.8831>
- Ford, T. W., Chen, L., & Schoof, J. T. (2021). Variability and transitions in precipitation extremes in the Midwest United States. *Journal of Hydrometeorology*, 22(3), 533–545. <https://doi.org/10.1175/JHM-D-20-0216.1>
- Gao, Y., Hu, T. S., Wang, Q., Yuan, H. W., & Yang, J. W. (2019). Effect of drought–flood abrupt alternation on rice yield and yield components. *Crop Science*, 59(1), 280–292. <https://doi.org/10.2135/cropsci2018.05.0319>
- Handwerger, A. L., Huang, M.-H., Fielding, E. J., Booth, A. M., & Bürgmann, R. (2019). A shift from drought to extreme rainfall drives a stable landslide to catastrophic failure. *Scientific Reports*, 9(1), 1569. <https://doi.org/10.1038/s41598-018-38300-0>
- He, N., Yin, J., Liu, P., Fu, X., Zhang, Q., Cheng, L., et al. (2025). Global increases in dry–wet abrupt alternation events under climate change. *Geophysical Research Letters*, 52(18), e2025GL117322. <https://doi.org/10.1029/2025GL117322>
- He, X., & Sheffield, J. (2020). Lagged compound occurrence of droughts and pluvials globally over the past seven decades. *Geophysical Research Letters*, 47(14), e2020GL087924. <https://doi.org/10.1029/2020GL087924>
- Hersbach, H. (2000). Decomposition of the continuous ranked probability score for ensemble prediction systems. *Weather and Forecasting*, 15(5), 559–570. [https://doi.org/10.1175/1520-0434\(2000\)015<0559:DOTCRP>2.0.CO;2](https://doi.org/10.1175/1520-0434(2000)015<0559:DOTCRP>2.0.CO;2)
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2023). ERA5 hourly data on single levels from 1940 to present [Dataset]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. <https://doi.org/10.24381/cds.adbb2d47>
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999–2049. <https://doi.org/10.1002/qj.3803>
- Huang, Z., Tan, X., Gan, T. Y., Liu, B., & Chen, X. (2023). Thermodynamically enhanced precipitation extremes due to counterbalancing influences of anthropogenic greenhouse gases and aerosols. *Nature Water*, 1(7), 614–625. <https://doi.org/10.1038/s44221-023-00107-3>
- Lalauette, F. (2003). Early detection of abnormal weather conditions using a probabilistic extreme forecast index. *Quarterly Journal of the Royal Meteorological Society*, 129(594), 3037–3057. <https://doi.org/10.1256/qj.02.152>
- Liu, G., Xiang, A., Wan, Z., Zhang, L., Wu, J., & Xie, Z. (2024). Quantitative characterization, spatiotemporal evolution, and analysis of driving factors of daily dry–wet abrupt alternation: A case study of the Ganjiang River Basin. *Journal of Hydrology: Regional Studies*, 56, 102030. <https://doi.org/10.1016/j.ejrh.2024.102030>
- Masukwedza, G. I. T., Lazenby, M., Mwangi, E., & Todd, M. C. (2025). Assessing the subseasonal forecasting skill of extreme agro-meteorologically relevant dry spells over Southern Africa. *Climate Dynamics*, 63(4), 199. <https://doi.org/10.1007/s00382-025-07674-z>
- McKee, T. B., Doesken, N. J., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. In *Proceedings of the 8th conference on applied climatology* (pp. 179–183). American Meteorological Society.
- Nie, W., She, D., & Xia, J. (2025). Five-century monthly streamflow reconstruction of the upper Brahmaputra River reveals historically frequent and intense drought–flood abrupt alternation events. *Journal of Hydrology*, 658, 133195. <https://doi.org/10.1016/j.jhydrol.2025.133195>
- Olaniyan, E., Adefisan, E. A., Oni, F., Afiesimama, E., Balogun, A. A., & Lawal, K. A. (2018). Evaluation of the ECMWF subseasonal to seasonal precipitation forecasts during the peak of West Africa Monsoon in Nigeria. *Frontiers in Environmental Science*, 6, 4. <https://doi.org/10.3389/fevs.2018.00004>
- Qiao, Y., Xu, W., Meng, C., & Zhao, D. (2023). Review of study on dry–wet abrupt alternation: Progress and challenges. *Journal of Catastrophology*, 38(3), 131–138. <https://doi.org/10.3969/j.issn.1000-811X.2023.03.021>
- Qiu, J., He, C., Liu, X., Gao, L., Tan, C., Wang, X., et al. (2024). Projecting dry–wet abrupt alternation across China from the perspective of soil moisture. *npj Climate and Atmospheric Science*, 7(1), 269. <https://doi.org/10.1038/s41612-024-00808-w>
- Rivoire, P., Martius, O., Naveau, P., & Tuel, A. (2023). Assessment of subseasonal-to-seasonal ensemble extreme precipitation forecast skill over Europe. *Natural Hazards and Earth System Sciences*, 23(8), 2857–2871. <https://doi.org/10.5194/nhess-23-2857-2023>
- Robertson, A. W., & Vitart, F. (2019). Subseasonal to seasonal prediction: The gap between weather and climate forecasting. *Bulletin of the American Meteorological Society*, 100, 151–153.
- Shi, W., Huang, S., Liu, D., Huang, Q., Han, Z., Leng, G., et al. (2021). Drought–flood abrupt alternation dynamics and their potential driving forces in a changing environment. *Journal of Hydrology*, 597, 126179. <https://doi.org/10.1016/j.jhydrol.2021.126179>
- Su, J., Ding, Y., Liu, Y., Wang, J., & Zhang, Y. (2024). China is suffering from fewer but more severe drought to flood abrupt alternation events. *Weather and Climate Extremes*, 46, 100737. <https://doi.org/10.1016/j.wace.2024.100737>
- Sun, W., Zhu, C., Jiang, N., Liu, B., Wang, J., Hu, Z., et al. (2025). A super cluster of extreme rainfall event over North China in July 2023: Role of typhoon–monsoon interaction. *Environmental Research Communications*, 7(5), 051007. <https://doi.org/10.1088/2515-7620/add654>
- Swain, D. L., Prein, A. F., Abatzoglou, J. T., Albano, C. M., Brunner, M., Diffenbaugh, N. S., et al. (2025). Hydroclimate volatility on a warming Earth. *Nature Reviews Earth and Environment*, 6(1), 35–50. <https://doi.org/10.1038/s43017-024-00624-z>

- Tang, S., & Luo, J.-J. (2025). Towards understanding the extreme flood–drought abrupt alternation over Southeast China in late summer 2019. *Atmospheric Research*, 319, 108024. <https://doi.org/10.1016/j.atmosres.2025.108024>
- Tian, Q., Yu, J. Y., Nnamchi, H. C., Li, T., Li, J., Li, X., & Ding, R. (2025). Unraveling the mystery of recent shortened response time of ENSO to Atlantic forcing. *Nature Communications*, 16(1), 5884. <https://doi.org/10.1038/s41467-025-61130-4>
- Vitart, F., Ardilouze, C., Bonet, A., Brookshaw, A., Chen, M., Codorean, C., et al. (2017). The subseasonal to seasonal (S2S) prediction Project database. *Bulletin of the American Meteorological Society*, 98(1), 163–173. <https://doi.org/10.1175/BAMS-D-16-0017.1>
- Wang, C., Li, K., & Santisirisomboon, J. (2021). Wave activities characteristics during a sudden sharp drought–flood turn event in 2011 in East China. *International Journal of Climatology*, 41(6), 3469–3480. <https://doi.org/10.1002/joc.7030>
- Wang, H., Wang, S., Shu, X., He, Y., & Huang, J. (2024). Increasing occurrence of sudden turns from drought to flood over China. *Journal of Geophysical Research: Atmospheres*, 129(3), e2023JD039974. <https://doi.org/10.1029/2023JD039974>
- Wang, L., Yuan, Z., Shi, X., Yin, J., Qin, T., & Zhang, J. (2025). A driving force analysis method for drought–flood abrupt alternation events. *Ecological Informatics*, 90, 103214. <https://doi.org/10.1016/j.ecoinf.2025.103214>
- Wei, Y., Li, H., Zhou, Y., Commey, N. A., Jin, J., & Zhou, P. (2025). Study on the evolution of regional future drought–flood abrupt alternation events. *Journal of Hydrology: Regional Studies*, 59, 102459. <https://doi.org/10.1016/j.ejrh.2025.102459>
- Wu, Z., Li, J., He, J., & Jiang, Z. (2006). Large-scale atmospheric singularities and summer long-cycle droughts–floods abrupt alternation in the middle and lower reaches of the Yangtze River. *Chinese Science Bulletin*, 51(16), 2027–2034. <https://doi.org/10.1007/s11434-006-2060-x>
- Xia, J., Duan, Q.-Y., Luo, Y., Xie, Z. H., Liu, Z. Y., & Mo, X. G. (2017). Climate change and water resources: Case study of Eastern monsoon region of China. *Advances in Climate Change Research*, 8(2), 63–67. <https://doi.org/10.1016/j.accre.2017.03.007>
- Yin, J., Li, F., Li, M., Xia, R., Bao, X., Sun, J., & Liang, X. (2025). The unique features in the 4 d widespread extreme rainfall event over North China in July 2023. *Natural Hazards and Earth System Sciences*, 25(5), 1719–1735. <https://doi.org/10.5194/nhess-25-1719-2025>
- Yoon, J.-H., Wang, S.-Y. S., Lo, M.-H., & Wu, W.-Y. (2018). Concurrent increases in wet and dry extremes projected in Texas and combined effects on groundwater. *Environmental Research Letters*, 13(5), 054002. <https://doi.org/10.1088/1748-9326/aab96b>
- Yu, R., & Zhai, P. (2020). More frequent and widespread persistent compound drought and heat event observed in China. *Scientific Reports*, 10(1), 14576. <https://doi.org/10.1038/s41598-020-71312-3>
- Zhang, B., Wang, S., & Slater, L. (2024). Anthropogenic climate change doubled the frequency of compound drought and heatwaves in low-income regions. *Communications Earth and Environment*, 5(1), 715. <https://doi.org/10.1038/s43247-024-01894-7>
- Zhang, B., Wang, S., Zscheischler, J., & Moradkhani, H. (2023). Higher exposure of poorer people to emerging weather whiplash in a warmer world. *Geophysical Research Letters*, 50(21), e2023GL105640. <https://doi.org/10.1029/2023GL105640>
- Zhao, L., Aiyub, K., Ata, F. M., Lam, K. C., & Sun, M. (2025). A systematic review of methods for identifying drought–flood abrupt alternation: Advances and future directions. *Frontiers in Environmental Science*, 13, 1590613. <https://doi.org/10.3389/fenvs.2025.1590613>
- Zhong, Q., Chan, J. C. L., Duan, W., Li, J., Gan, J., & Ding, R. (2026). Landfalling tropical cyclones accelerate due to land–sea thermal and roughness contrasts. *Nature Geoscience*, 19(2), 159–164. <https://doi.org/10.1038/s41561-025-01891-1>
- Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., et al. (2020). A typology of compound weather and climate events. *Nature Reviews Earth and Environment*, 1(7), 333–347. <https://doi.org/10.1038/s43017-020-0060-z>

References From the Supporting Information

- Buizza, R., & Leutbecher, M. (2015). The forecast skill horizon. *Quarterly Journal of the Royal Meteorological Society*, 141(693), 3366–3382. <https://doi.org/10.1002/qj.2619>
- Dai, G., Mu, M., Li, C., Han, Z., & Wang, L. (2021). Evaluation of the forecast performance for extreme cold events in East Asia with subseasonal-to-seasonal data sets from ECMWF. *Journal of Geophysical Research: Atmospheres*, 126(1), e2020JD033860. <https://doi.org/10.1029/2020JD033860>
- Zsoter, E. (2006). Recent developments in extreme weather forecasting. *ECMWF Newsletter*, 107, 8–17.
- Zsoter, E., Pappenberger, F., & Richardson, D. (2015). Sensitivity of model climate to sampling configurations and the impact on the Extreme Forecast Index. *Meteorological Applications*, 22, 236–247. <https://doi.org/10.1002/met.1453>