Moisture transport of extreme rainfall events and remote influences of traveling disturbances

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Keywords：Beijing Rainstorm, Tropical Cyclones, Marine heatwave, Backward trajectories

1. Research Background

In late July 2025, North China, including Beijing and its surrounding areas (BSA), experienced a series of record-breaking rainstorms (Fig. 1). This event persisted over 6 days (~147 hours) from July 23 to 29 with an area-averaged accumulated precipitation reaching 210.4 mm—equivalent to 38% of the annual mean, and many regions in the BSA recorded over 500 mm of accumulated rainfall.

Rainfalls over the BSA during the boreal summer are often due to the topographic blocking and low-level convergence of the monsoon-related southerly flows, and extreme events also frequently occur with substantial moisture supplies from the synoptic-scale disturbances. However, moisture during this event may be contributed differently, as it experiences unique circumstances involving four remote tropical cyclones, including Wipha, Co-may, Francisco, and Krosa. The large-scale circulation influenced by these tropical cyclones likely led to a favorable condition for long-distance moisture transport from the tropical Pacific and Indian Ocean to the BSA and contributed to the record-breaking event.

In addition to the atmospheric influences, oceanic contributions should also be considered. During the rainstorm, abnormally high sea surface temperature (SST) anomalies were observed across the Northwest Pacific, including the Bohai and Yellow Seas (BYS) near the BSA (Fig. 1f), exhibiting a prolonged marine heatwave in the BYS region (Fig. 2b). This heatwave event may enhance the local evaporation and further intensify the moisture transport towards the BSA.

Overall, it is conjectured that the sequential generation of tropical cyclones and the BYS marine heatwave jointly established favorable conditions for the development and maintenance of the recent BYS rainstorm event in July 2025. Following that, this study aims to provide a review of this recent event and evaluations of the roles of tropical cyclones and the BYS marine heatwave.

2. Experiment Designs and Model Settings

To evaluate the atmospheric conditions during the event, we used hourly data from the 0.25° ERA5 reanalysis, which also served as the initial and lateral boundary conditions for the numerical experiments. The 1/10° IMERG satellite precipitation was obtained for validation and comparison. For analyzing marine heatwaves and the model lower boundary, we utilized the U.K. Met Office 0.05° OSTIA SST, which was also employed in

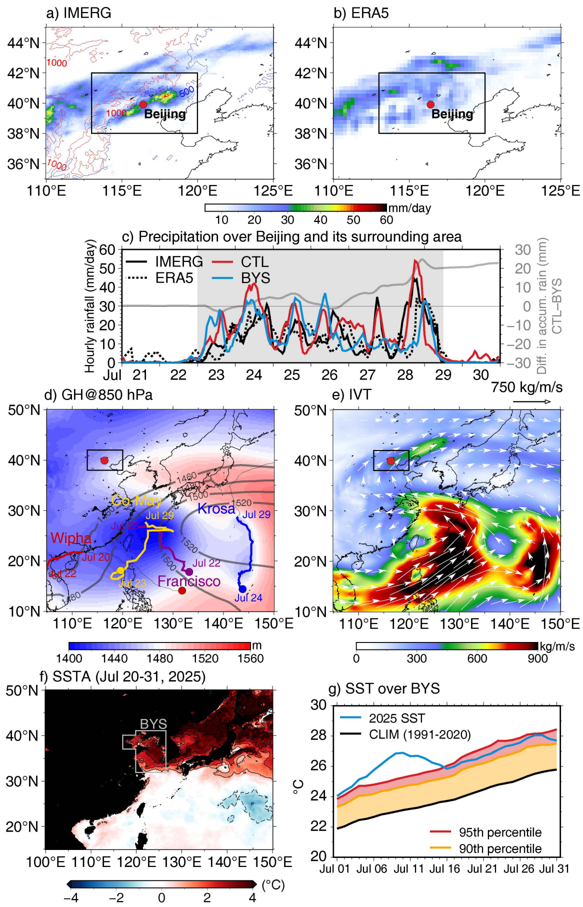

Fig. 1: Overview of the July 2025 rainstorm. Rainfall averaged during the event based on (a) satellite observation, (b) ERA5, (c) their time series averaged over the BSA with the difference of accumulated rainfall between CTL and BYS runs (gray line), the averaged (d) the mean 850-hPa geopotential height and (e) moisture transport (IVT), the SST anomaly in late July, and the time series of SST anomalies.

ERA5. Specifically, we used the reprocessed OSTIA to calculate the baseline daily climatology (1991-2020) of SST and the related thresholds.

To obtain finer atmospheric fields for trajectory experiments and to investigate the role of marine heatwaves over the BYS region, we conducted a pair of numerical experiments from July 20 to July 30, 2025, based on the WRF Model (V4.4.2). The control run (CTL) used the observed OSTIA SST in July 2025 as its lower boundary conditions, while the sensitivity experiment (BYS) used the same data, except for the BYS region (Fig. 1f), which was replaced with the baseline daily climatology. Both experiments were conducted with a resolution of 9 km and 60 vertical sigma layers from the surface to 50-hPa, which covers the entire East Asia region (see Fig. 1f). The major schemes and moisture diagnostics were applied following Zhao et al. (2023).

3. Heavy rainfalls over the BSA

Figure 1 illustrates the characteristics of the rainstorms over BSA in late July 2025. In general, the rainfall zone exhibits a distinct southwest-northeast orientation, displaying two rainbands associated with the wind channel between large-scale low- and high-pressure systems (i.e., southerly moisture conduit) and mountainous topography in North China. Particularly, the orography-related rainband exhibited the maximum precipitation intensity, concentrated over the BSA, which eventually led to the record-breaking rainstorm event. Notably, although the ERA5 precipitation aligns spatially with IMERG's maximum center over the study area, its intensity is much weaker. Such a discrepancy may stem from the coarser resolution of ERA5, which cannot resolve the complex topography-related rainfalls.

While the rainfall represented a general image of the BSA rainstorm event, the large-scale circulation also qualitatively reveals moisture transport for this event. In the regions south of 30°N, the cyclonic circulations dominated, exhibiting the influences of tropical cyclones (Fig. 1d), which transport the moisture from the tropics, with pronounced maximum vertically Integrated Vapor Transport (IVT) near their centers. Results indicate that moisture transported northeastward from the Philippines diverged into two branches: one turned northwestward near the Ryukyu Islands under the influence of Wipha, Francisco, and Co-may, while the other, steered by Krosa, turned northwestward around 145°E and merged with the former branch. This merged flow was then taken over by the anticyclonic winds induced by the high-pressure system, passing through the BYS region before reaching BSA, which likely formed the stable moisture channel from the lower latitudes to the BSA and supported the long-lasting rainstorm.

Besides the rainstorm itself, the SST over the BYS region was over 2°C warmer than the climatology before July (Fig. 1g), exhibiting a pronounced marine heatwave event. Given the southeasterly wind over the BYS, the SST-induced enhanced latent heat fluxes may, therefore, influence moisture transport, supplying additional moisture to the BSA.

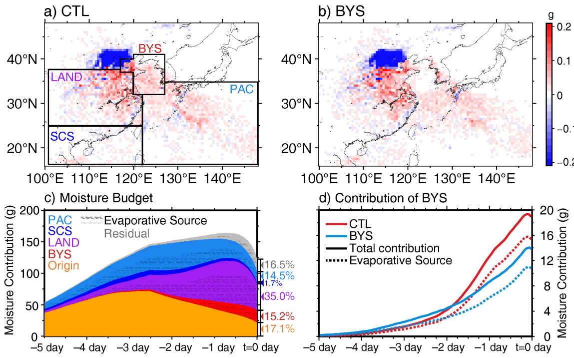

Fig. 2: Moisture contributions to the event. Net surface freshwater fluxes based on moisture gain/loss of rainfall-related particles forced by (a) CTL and (b) BYS experiments, and (c) the temporal variations of contributions from individual regions, including BYS, land, the South China Sea, and the Pacific. The evaporative source is defined as the moisture gain within the planetary boundary layer (Zhao et al., 2023).

4. Moisture source and Role of MHW

The net surface freshwater flux based on the rainfall-related particles showed that the transported moisture absorbed substantial additional moisture during the transport from the Pacific to eastern China (Fig. 2a). Notable moisture uptake (~35%) was found over the land, suggesting the importance of the terrestrial evaporative and/or local moisture recycling. Compared to that, oceanic moisture sources played secondary roles, with the Pacific and the BYS contributing 14.5% and 15.2%, respectively.

Then, to isolate the impact of the MHW, we conducted a sensitivity experiment (BYS run) wherein the BYS's SST was replaced with its climatological baseline. Compared to the CTL run, although the BYS run maintained similar spatial precipitation patterns (Fig. 1), it exhibited markedly reduced rainfall over the BSA region, primarily stemming from the pronounced weakening of the peaks during July 27~29 (Fig. 1). The cumulative area-mean precipitation was reduced by 22 mm (16.2%) during this critical 3-day period. In other words, the anomalous warm SST in the BYS did enhance moisture supply to the BSA region, which eventually helped the record-breaking rainfall there.

Overall, this study provides an overview of the recent Beijing rainstorm and a quantitative analysis of its moisture sources, and it also highlights the unignorable role of the concurrent marine heatwave nearby (Yang et al. 2026). Future work will further investigate the regulation of vapor transport pathways by air-sea coupling processes and evaluate the potential risks posed by similar extreme events under the changing climate scenarios, which enhance the predictability of the increasing heavy rainfalls.

References

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