Moisture source, transport, and moisture-related initiation mechanisms of extreme rainfall events

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Keywords : **moisture source, heavy rainfalls, numerical simulation, backward trajectories, Tohoku region**

1. Research Background

Due to global warming, extreme rainfall events have become more and more common during the past several decades. Particularly, previous studies suggest most of these severe events in Japan could be related to the highly accumulated moisture in the troposphere [1]. Therefore, this study focuses on the moisture in specific heavy rainfall events that occurred in Japan and attempt to reveal its source, transport processes, and moisture-related mechanisms of the heavy rainfalls by using numerical simulations and Lagrangian backward trajectories.

2. Tohoku heavy rainfalls in August 2022

In recent years, while record-breaking rainfall events were reported in almost every rainy season of Japan (i.e., the 'Baiu-Meiyu' season), severe events in other seasons also became more frequent. In August 2022, some extreme rainfall events occurred in The Tohoku region (Figure 1). According to the Japan Meteorological Agency (JMA), the precipitation increased by over 70% in the whole Tohoku region, especially in Aomori (> 300%), while the heavy rainfalls were mainly induced by a quasi-stationary front. Unlike the famous 'Baiu-Meiyu' front, this front was in the north which is far from the moist-rich regions south of Japan, while the Japanese archipelago may block the usual low-level moisture transport from south. Meanwhile, since two tropical storms vanished over the East China Sea (ECS) just one day before the Tohoku rainfalls, one may expect the highly accumulated moisture was carried by those storms.

This paper is published in Geophysical Research Letters on September 7, 2023 [2].

3. Experiment Designs and Model settings

To answer the above questions, we conducted numerical simulations based on the Weather Research and Forecasting (WRF) model and performed the trajectory experiments based on the FLEXPART-WRF model following our previous study [3]. Our model has a resolution of 9 km and 60 vertical sigma layers from surface to 50-hPa, with a two-way nested 3-km domain was embedded over Japan (Figure 1a). The initial and boundary

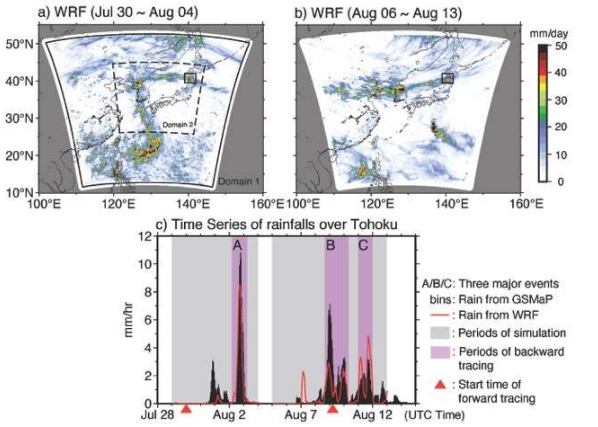

Figure 1: Mean precipitation averaged from two periods: (a) July 30~August 4, and (b) August 6~August 13 based on WRF model. (c) Time series of area-averaged observed (black bins) and simulated (red lines) precipitation over Tohoku (black boxes in panels a and b).

conditions were obtained from the 6-hourly ERA5 dataset and the 0.25° daily OISSTv2.1. For model validation, we used the 0.1° hourly precipitation from the Global Satellite Mapping of Precipitation (GSMaP). Two simulations were conducted for the periods of July 29~August 4 and August 5~13 to represent the anti-cyclone and the 'Baiu-like' quasi-stationary front, respectively (Figure 1c).

During the trajectory experiment, we released 2500 particles every 6 hours during three heavy rainfall events (purple shadings in Figure 1c). All particles were originally located over Tohoku from the surface to 300-hPa and were traced backward for three days. To evaluate the influences of tropical storms, three forward trajectory experiments were also conducted for storms Songda, Trases, and Meari. We released 5000 particles from a 9°×9° column (surface to 300-hPa) near the centers of Songda, Trases, and Meari (see white boxes in Figure 3). The moisture diagnostic methods are following our previous study [5].

4. Moisture Transport during Tohoku events

As shown in Figure 2, beside the common dry air masses in upper levels, routes of moisture and the regional moisture contributions showed fundamental differences among the three events.

During Event A, moist air masses were mainly transported from the subtropical western Pacific (WP) before entering the Sea of Japan (JS) but can be separated into two different groups. The first group was transported along the edge of the anti-cyclone south of Japan, while the Japanese archipelago did not block the particles (and hence moisture) from the south as we expected before because they were transported by the low-to-mid-level wind. Meanwhile, the second group was transported northward to the ECS at first and then eastward to the JS, which was later confirmed to be the air masses of tropical storms Songda and Trases (see Section 5).

After August 8, the 'Baiu-like' front and the associated easterly wind created a stable moisture channel for Events B and C, guiding the air masses from Southeast China (SEC) and the ECS to the front and Tohoku. Some trajectories originated from Siberia north of JS, which subducted from the mid-troposphere to lower levels before entering the JS and also gained a certain amount of moisture over the land. Particularly, in Event C, in addition to the front-transported transport, part of the moisture was from the WP (e.g., Figures 2e and 2f).

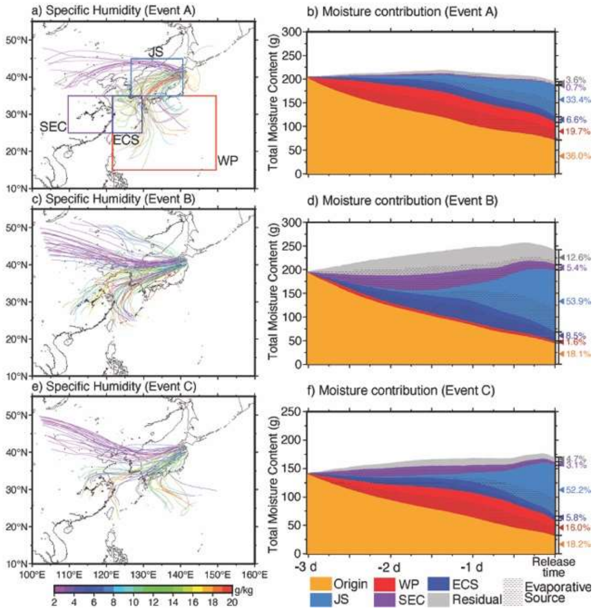

Figure 2: (Left) Three-day trajectories of backward traced particles, which were released during three events, and (Right) temporal variations of moisture contributions over specific regions shown as boxes in panel a.

By summarizing the moisture changes of particles, we calculated contributions of each region shown in Figure 2a. Particularly, the JS contributed over 30% in Event A and more than 50% in the others, and over one-third of those were provided by the evaporation which may be related to the along-front wind and the warm SST. Moreover, much of the moisture was supplied within one day before the rainfalls, suggesting the importance of moisture gains nearby. The ECS and the WP also supplied a certain amount of moisture, but their contributions varied among the events. Like the ECS, the SEC also provided a certain amount of moisture via surface evaporation, but over half of them were lost during the transport (e.g., Figures 2d and 2f). Note that moisture from Siberia also contributed to Event B, which caused a large residual.

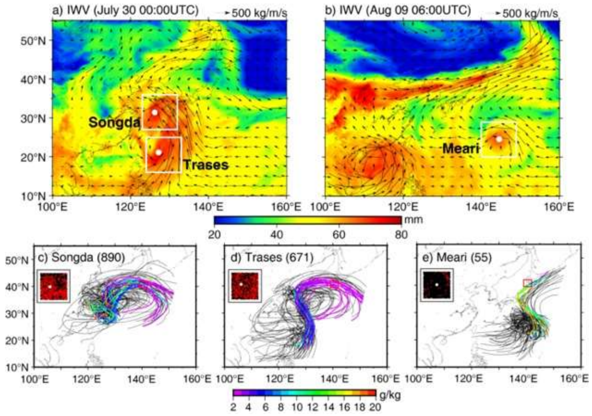

Figure 3: (Upper) Moisture transport on (a) July 30 at 00 UTC and (b) August 9 at 06 UTC based on the ERA5. (Lower) Trajectories (black lines) of particles released around the centers of tropical storms, while those that reached Tohoku were colored by their specific humidity. To avoid overcrowding, trajectories were plotted every 50 particles (every 10 for Meari). In the embedded figures, black dots represent the locations of particles when they were released, and the dots are marked red if the particle finally reached Tohoku. Numbers in the brackets show how many particles reached Tohoku.

5. Experiments on Influences of Tropical Storms

As shown in Figure 3, particles from Songda and Trases spread over entire East Asia after they were released. Among them, only 17.8% and 13.4% of particles finally reached Tohoku, respectively. Moreover, only one-third of the moisture remained in those particles when they reached Tohoku. Although we did not estimate the step-by-step moisture changes as we did for the backward trajectories, the above results demonstrated that moisture that was carried by Songda and Trases played a minor role in Event A. Compared to them, even fewer particles (and hence moisture) reached Tohoku during Event C from Meari (~1.1%).

6. Future Plan

The current study revealed the direct contributions of tropical cyclones to moisture accumulation over the Tohoku region were relatively small. On the other hand, it also suggests the important role played by these cyclones in controlling the paths of moisture transport. Future studies will be conducted to quantitatively evaluate the direct and indirect contributions of cyclones based on more cyclone-related heavy rainfall events, including the potential roles of cyclones that were far away from the rainfall regions.

Acknowledgment

This work is partially supported by JSPS KAKENHI (JP19H05697, 20K14560, and 23K11403) and is also supported by JAMSTEC through its sponsorship for the JICore project.

References

[1] Tsuji, H., Takayabu, Y. N., Shibuya, R., Kamahori, H., Yokoyama, C. The role of free-tropospheric moisture convergence for summertime heavy rainfall in western Japan. *Geophys. Res. Lett.,* 48, e2021GL095030, (September 2021)
[2] Zhao, N., Wu, P., Manda, A., Guo, X., & Wang, B. (2023). Moisture sources of the Tohoku heavy rainfalls in August 2022 and the influences of tropical storms. *Geophys. Res. Lett.*, 50, e2023GL104166, (September 2023)
[3] Zhao, N., Manda, A., Guo, X., Kikuchi, K., Nasuno, T., Nakano, M., et al. A Lagrangian view of moisture transport related to the heavy rainfall of July 2020 in Japan: Importance of the moistening over the subtropical regions. *Geophys. Res. Lett.*, 48, e2020GL091441, (February 2021)