A Lagrangian View of Moisture Transport Related to the Heavy Rainfall of July 2020 in Japan: Importance of the Moistening Over the Subtropical Regions

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Abstract The transport and accumulation of moisture played an essential role in the extremely heavy rainfall of July 2020 in Japan. To better understand this event in terms of moisture sources and transport routes, backward particle trajectory analysis was conducted. We found two major moisture sources: transport from the tropics and uptake from the subtropics. A narrow moisture channel was found along the edge of the western Pacific Subtropical High (WPSH), transporting the moisture to the Baiu front. However, most moisture from the tropics was lost due to precipitation, and their contributions were reduced to about 15%. In contrast, the subtropical regions contributed over 80% moisture via evaporation and lower tropospheric convection. Among those regions, the western Pacific contributed the most (>33%). This study highlights the role of WPSH in moisture transport and demonstrated the importance of moisture uptake during transport.

Plain Language Summary Heavy rainfalls hit Japan in July 2020, and the related atmospheric river was found to be accumulated by the moisture from tropics and subtropics. The moisture was transported by a narrow moisture channel along the edge of western Pacific Subtropical High. But, due to the precipitation during the transport, the moisture from the tropics decreased. On the other hand, when the air flows passed over the subtropical regions, they were moistened by evaporation and lower troposphere convection. Thus, our results suggest that the moisture from subtropical regions contributed the most to the moisture accumulation during the heavy rain event.

1. Introduction

Extremely heavy rain fell over Japan in July 2020 (hereafter, 20HR). The rainfall continued during this whole period and included several severe rainfall events. As reported by the Japan Meteorological Agency (JMA), during this event, the 48 h precipitation exceeded 1,300 mm in many regions of western Japan (e.g., Kyushu, Gifu, Kochi, and Nagano). Specifically, some records indicate that the total precipitation was equal to nearly half of the historical annual mean (e.g., Fukuoka, Kagoshima; JMA, 2020). It was reported that 82 fatalities occurred, and 18,380 buildings were destroyed or damaged during the heavy rains (EOCI, 2020).

Kamae (2020), based on a series of early analyses, showed that a narrow plume of water vapor transport (i.e., the atmospheric river, AR; also see Figure 1a) played a key role in 20HR. According to the results in Kamae (2020) and JMA (2020), this AR started from the South China Sea (SCS) and passed through the southeast China mainland, before turning west along the Baiu front. It was also reinforced by the low-level flows from the south, similar to previous events in Japan (e.g., Hirota et al., 2016; Tsuguti et al., 2019). Meanwhile, it is likely that the westward extension of the western Pacific Subtropical High (WPSH) also enhanced the northward moisture transport from the SCS to Japan (e.g., Naoi et al., 2020).

To date, the relationship between moisture transport and heavy rainfall during the Baiu season has been extensively studied (e.g., Kamae et al., 2017; Zhou & Yu, 2005). Previous studies demonstrated that the strong precipitation is primarily related to the local moisture convergence, accompanied by the low-level southerly
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moisture fluxes (e.g., Kamae et al., 2017; Sekizawa et al., 2019). Recent studies indicated that strong moisture transport in the free troposphere provided a favorable environmental condition for extreme rainfalls (e.g., Hamada & Takayabu, 2018). Moreover, some studies demonstrated the moisture in the mid-to-low levels played a key role in those extreme events (e.g., Hirota et al., 2016; Manda et al., 2014; Yokoyama et al., 2017).

Although the importance of moisture transport was well documented in previous studies (e.g., Guan & Waliser, 2019; Kamae et al., 2017; Sampe & Xie, 2010), few of them paid attention to where the moisture came from and how moisture was transported. Previous studies suggested that moisture sources and transport of AR-related heavy rainfalls may depend on the related atmospheric phenomena (e.g., Eiras-Barca et al., 2017; Ramos et al., 2019). For example, during the wintertime, the moisture transport is often related to the extratropical cyclones, in which the warm conveyor belt and cold fronts provide the fundamental forces for the local moisture convergence (e.g., Dacre et al., 2019). Meanwhile, some studies revealed the occurrence of moisture gain/loss processes during the transport (e.g., Bao et al., 2006; Ramos et al., 2016). Therefore, it is necessary to evaluate how moisture was accumulated and transported to Japan during 20HR, especially considering that it was preceded by the heavy rainfalls (hence, the great moisture loss) over southeastern China where the AR likely passed (e.g., Liu et al., 2020).

This study addresses two scientific topics: (1) the moisture sources of AR and transport routes and (2) moisture gain/loss processes along the routes. Since an Eulerian point of view has limitations to clarify the moisture sources and processes affecting moisture accumulation (see Gimeno et al., 2012, and references therein), we performed a Lagrangian backward trajectory experiment, which has proven to be computationally efficient and useful in similar studies (e.g., Sodemann et al., 2008; Langhammer et al., 2018). We used a numerical hindcast to obtain high-resolution atmospheric fields for backward tracing and to evaluate physical details. Due to the complexity of multiple events during the 20HR, this study was based on one major event (July 3–4 in Kyushu; hereafter 20HRK) that caused a flooding disaster (JMA, 2020).

Figure 1. The IVT (a and b) and vertical cross-section (c and d) along the 130 E on July 3, 12 UTC based on ERA5 and WRF. Yellow boxes show the region for particle releasing, and red lines show the location of the cross-section.
2. Materials and Methods

2.1. Numerical Hindcast

The numerical hindcast started from June 27 to July 5 based on the Weather Research and Forecasting model (WRF V4.1.5), covering the East Asian region (Figure 1), with 9-km mesh grids and 60 sigma layers from the surface to 50 hPa. The boundary and initial conditions were interpolated from the 0.25° 6-hourly NCEP GDAS/FNL dataset (NCEP, 2015) with the sea surface temperature (SST) from the daily GHRST MultiProduct Ensemble (Martin et al., 2012). The output was saved every 30 min, and the first day was for spin-up and not used. We used the WSM6 microphysics scheme (Hong & Lim, 2006), the Yonsei University PBL scheme (Hong et al., 2006), the Revised MM5 surface layer scheme (Jimenez et al., 2012), the United Noah Land Surface Model (Tewari et al., 2004), the RRTMG Shortwave and Longwave Schemes (Iacono et al., 2008), and the Grell-Freitas Ensemble cumulus scheme (Grell & Freitas, 2014).

To represent moisture transport, we calculated the integrated water vapor transport (IVT; e.g., Lavers et al., 2012; Zhang et al., 2019):

\[
\text{IVT} = \sqrt{\left(\int_{1,000\text{ hPa}}^{200\text{ hPa}} qu \, dp\right)^2 + \left(\int_{1,000\text{ hPa}}^{200\text{ hPa}} qv \, dp\right)^2}
\]  

(1)

where \( g \) is the gravitational acceleration, \( q \) is the specific humidity, \( p \) is the pressure, \( u \) and \( v \) are the zonal and meridional wind, respectively.

We used the ERA5 reanalysis (Hersbach et al., 2020) for model validation and comparison. As shown in Figure 1, our hindcast well reproduced the extremely high IVT, with strong water vapor fluxes below the 500-hPa level. It also well simulated the localized heavy rain over Kyushu (Figure S1). Note that our model showed approximately 1° northward shift of the front and a lesser northward tilt with height (Figure 1), which were probably caused by the schemes we used in WRF (Figure S4); however, the extraexperiment demonstrated that our results were not sensitive to these mismatches and parameterizations we chose (see Text S1 in supporting information).

2.2. Backward Trajectories

To identify the moisture source and transport route, we applied a backward trajectory analysis based on WRF output and the FLEXPART-WRF model (Version 3.3.2; Brioude et al., 2013), which has been widely used in studies on moisture transport (e.g., Langhamer et al., 2018). We used the snapshot wind and the Hanna scheme for the turbulence parameterization, with the convection scheme on.

Particles were released from July 3, 00 UTC to July 4, 12 UTC during 20HRK with a 12 h interval. Considering the importance of lower-to-mid-level moisture on the Baiu heavy rainfalls (e.g., Hirota et al., 2016; Yokoyama et al., 2017), we released the particles from 950 to 550-hPa height level over Kyushu where the strong IVT located (129–132°E and 31.5–33.5°N; boxes in Figure 1). Each particle represented an air parcel with specific mass, and 10,000 particles (with a total mass of 20 kg) were released (Figure S2). All particles were backward traced to June 28, and their locations and properties would not change again when they reached the lateral boundaries of our model. Because this study focused on moisture transport, we excluded particles originated north of 30°N, which are generally dry and cold particles. As a result, 8,868 particles remained for further analyses. Note that our results were not greatly changed if particles were released by 6 h interval and within the entire troposphere (Figure S3).

2.3. Diagnostic variables

Moisture changes of a specific particle \( i \) (\( \Delta Q_i \)) predominantly reflect the effects of precipitation (p) and evaporation (e) processes within the air parcel (e.g., Stohl and James, 2004):

\[
\Delta Q_i = p_i - e_i
\]
where $m_{i,t}$ is the mass of particle, $q_{i,t}$ is the specific humidity, $t$ is time ($t=0$ is the release time), and $\Delta t$ is the time interval (30 min). For simplicity, the moisture uptake is regarded as $\Delta Q_{i,t} > 0$, and precipitation is defined when $\Delta Q_{i,t} < 0$. Specifically, a bulk “evaporative” source is defined if moisture uptake occurred within the planetary boundary layer (PBL; obtained from WRF), while we adopted a factor of 1.5 for the PBL to account for potential underestimations and small-scale variations. Accordingly, the “nonevaporative” source can be estimated when moisture uptake occurred above the PBL.

To evaluate the contributions of moisture sources, we applied the “source attribution” method as introduced by Sodemann et al. (2008). The general conception is: (a) once moisture uptake is detected, its weighted contribution would be determined ($f_{i,t} = \Delta Q_{i,t} / Q_{i,t}$), and all previous contributions will be diluted; and (b) if precipitation is detected, all previously gained moisture will be reduced according to the weighted contributions. In simple terms, moisture uptake at previous times would be “filtered” by precipitation occurred later (e., “rain-off”). Readers may refer to Text S2 for an example and Sodemann et al. (2008) for detailed descriptions.

The “rain-off” filtered moisture uptake ($\Delta Q_{i,t,rain-off}$) for all particles in a specific atmospheric column at a time $t$ yield the contribution for the accumulated moisture content:

$$\Delta Q_{tot,t} \approx \sum_i^N \left( \frac{\Delta Q_{i,t,rain-off}}{A} \right),$$

where $\Delta Q_{tot,t}$ is the total “rain-off” filtered moisture change, $N$ is the number of particles within the atmospheric column over a unit area $A$ (0.5° mesh grid). Contrastingly, moisture changes for all particles, that ever passed the column during the whole period, yield the net surface freshwater flux (Ramos et al., 2016):

$$E - P \approx \sum_{t=5-day}^{t=0} \sum_i^{M(t)} \left( \frac{\Delta Q_{i,t}}{A} \right),$$

where $E$ is the evaporation rate, $P$ is the precipitation rate, and $M$ is the number of particles passed the column.

3. Results

3.1. Moisture Transport Route

Figure 2a shows the horizontal trajectories of particles (e., air parcels). The air parcels of the 20HRK mainly came from two tropical regions (Figure 1). Among the 8,868 particles, 6,380 (71.9%) of them came from the regions west of 122 E (the central longitude line of our domain), including the tropical Indian Ocean (IO) and the regions south of SCS, and 2,285 (25.8%) of particles came from the east (e., the tropical Pacific). The amount of water vapor carried by each particle from the west was lower than those particles from the east when they reached Kyushu (e., the release time). Moreover, our results showed that all air parcels became moister during transport (Table S1).
The trajectories show that most particles traveled along the periphery of the WPSH, exhibiting a narrow moisture channel (i.e., the AR). This moisture channel varied from time to time, which is likely caused by the changing WPSH. For instance, particles released on July 3 mainly passed over the East China Sea (ECS) (red curves in Figure 2a), while other trajectories shifted westward due to the westward extension of the WPSH in early July (see contours Figure 2a). The particles traveling along the edge of WPSH distributed within the whole mid-to-lower troposphere (Figure 2b), while the particles in the east subducted and became moister simultaneous to the dominant WPSH (Figure 2c).

The moisture transport route of 20HRK can be summarized as follows. In the first stage, air parcels from the IO were transported eastward (and/or northeastward) to the SCS, while other air parcels were transported westward from the tropical Pacific. After merging at approximately 20°N, the air parcels from these two tropical regions went farther north, guided by the WPSH, passing over southeastern China and the WP (and the marginal seas) in the next few days. During the northward transport, some air parcels were subducted under the strengthening of WPSH. Within 1 or 2 days, the air parcels encountered the Baiu front at approximately 30°N and turned east along the front before reaching Japan. Readers may refer to an animation that shows the backward tracing of released particles (Video S1; see Data Availability section).

3.2. Moisture Evolution During Transport

To further understand the moisture changes shown in Figure 2, we examined the temporal evolutions of particles during transport. For simplicity, we consider the particles in three layers: Lower (>800 hPa), Mid-Lower (800–600 hPa), and Mid (600–400 hPa). As shown in Figure 3a, the variation trends of the particle numbers of Lower and Mid-Lower layers were quite different, although the numbers of particles were almost the same at both the release time and the end of tracing. More particles were subducted into the Lower layer, which facilitated gains of moisture from the sea surface. As a result, the net water vapor content of particles in the Lower layer increased about 20% during transport (dashed lines in Figure 3a).
Contrastingly, while the particles kept entering the model domain, the particles in the Mid (Mid-Lower) layers decreased (changed only slightly) in numbers with slight changes in moisture content, suggesting air parcels more likely subducted into lower levels, which is quite different from the ARs formed by WCB-like processes (Bao et al., 2006).

Figure 3b shows the time evolution of the “rain-off” filtered moisture contributions of different regions. The total moisture content continuously increased until the parcels reached Japan; however, the causes of the increase were different. During the first 2 days (day −5 and day −4), the increase was mainly due to the greater number of particles (hence, the air parcels) that entering the domain, especially the low-level air flows (see black lines in Figure 3a). On day −3, after the particle numbers reached the maximum, the amount of moisture from the tropics started decreasing due to the precipitation (the “rain-off”), and it declined almost linearly during the next 2 days. By contrast, more moisture was gained from the SCS and the WP, of which more than half was gained by the evaporation (see masked parts in Figure 3b). Especially, after day −1, the WP played the most important role in the moisture accumulation and finally contributed 33.7% moisture at day 0. Meanwhile, the moisture contributed by southeast China and Baiu front was highly related to the heavy rainfalls there, which was likely caused by the “recycling of moisture” within the air parcel and the convective moistening (see section 3.3).

To further show the horizontal distributions of moisture gain/loss processes along with the transport, we evaluated the net surface freshwater fluxes (E−P). The strongest downward freshwater fluxes (hence, moisture loss) were found around 30°N, indicating heavy rainfalls along the Baiu front (Figure 4a). Moreover, negative values were also found along the periphery of the WPSH and the coastal region where most of the Mid and Mid-Lower particles traveled (Figure 2b), suggesting that the moisture loss continued due to precipitation along the transport routes. On the other hand, widely distributed positive freshwater fluxes over the SCS and the WP suggested a large amount of moisture was gained over those regions, which are consistent with the results of “rain-off” filtered contributions (Figure 3b).

### 3.3. Moistening Processes

As shown in Figure 3b, about half of the moisture was gained from “nonevaporative” sources over the subtropics. To reveal what processes helped such moistening, we examined the temporal variations in humidity and apparent moisture sink (−Q2, positive means moisture increase) with meridional geopotential height anomalies (contours) over the region (122.5–127.5°E, 20–25°N; black box in panel a).

Figure 4. (a) The net freshwater fluxes (E−P, upward positive; Equation (4)), while contours show the mean geopotential height at 850 hPa (dashed) and 500 hPa (solid). (b) Time and height diagram of the area-averaged specific humidity and (c) apparent moisture sink (−Q2, positive means moisture increase) with meridional geopotential height anomalies (contours) over the region (122.5–127.5°E, 20–25°N; black box in panel a).
“back-building” and orography-related processes and, therefore, the heavy rain in Kyushu (e.g., Miyajima & Fujibe, 2011; Schumacher & Johnson, 2005; see Text S3).

4. Conclusions

This study investigated the moisture sources and transport processes of the high accumulation of moisture associated with the 20HRK, based on numerical hindcast and backward trajectory analyses. Ten thousand particles with random masses were released from July 3, 00 UTC to July 4, 12 UTC, and 8,868 particles that originated south of 30°N were used for the analyses.

The backward trajectories exhibit a narrow moisture channel that started from the SCS at 20°N where most particles merged. This channel was located along the periphery of the WPSh before encountering the Baiu front. Our findings of moisture sources and transport are summarized schematically in Figure 5. There were two kinds of sources: (a) the moisture transported from tropical regions, including the IO, south of SCS and tropical Pacific, and (b) the moisture gained in subtropics during the transport. The moisture from tropical regions was continuously lost due to precipitation, resulting in a smaller contribution to the final moisture accumulation of 20HRK. Besides the evaporation, our analyses suggest that the air parcels acquired half of the moisture via the lower tropospheric convection, especially over the WP where they subducted. Finally, the moisture from tropics (15%) and subtropics (80%) were accumulated as the form of AR along the Baiu front and contributed to the heavy rainfall over Kyushu.

The current study demonstrates that, rather than the moisture from the tropics, subtropical regions played the most important role in moisture accumulation and heavy rain. Moreover, unlike the ARs formed by the WCB-like ascending background airflows (e.g., Bao et al., 2006), the nonevaporative moistening in subtropical regions of the AR in 20HRK was mainly induced by the self-constructed convection, even under the WPSh.

Although we revealed how was the moisture accumulated and transported to Japan, this study was mainly based on one major event during the 20HR; multi-casts and longer simulations could reduce the potential uncertainties. On the other hand, recent studies have revealed that AR activities and related extreme precipitation events were enhanced during the past decades due to the warming climate (e.g., Algarra et al., 2020; Payne et al., 2020 and references therein). Therefore, our study also suggests the potential impacts of recent increasing SSTs over the subtropical WP (e.g., Bulgin et al., 2020) on the recorded heavy rainfall in Japan by enhancing the local evaporation and convection. Further analyses of the influence of warmer SSTs in subtropical regions will be the next step of this study.

Data Availability Statement

The data used in this study were listed as follows: GSMaP (https://sharaku.eorc.jaxa.jp/GSMaP), GDAS/FNL (https://rda.ucar.edu/datasets/ds083.3), ERA5 (https://cds.climate.copernicus.eu/), GHRSST (http://data.nodc.noaa.gov/ghrsst/), and TRMM (https://gpm.nasa.gov/data). The trajectories and animation are available on Zenodo.org (https://doi.org/10.5281/zenodo.3986631 and https://doi.org/10.5281/zenodo.4027542, respectively).

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