Moisture Supply, Jet, and Silk-Road Wave Train Associated with the Prolonged Heavy Rainfall in Kyushu, Japan in Early July 2020

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Abstract

A prolonged heavy rainfall event occurred in Kyushu in early July 2020. Its large-scale environmental factors are investigated with observational and reanalysis data. Seven-day precipitation and moisture flux convergence around Kyushu were the greatest among the last 30 years. This pronounced convergence was maintained by nearly steady moisture influx, and the persistent upper-level trough to the northwest enhanced the ratio of moisture convergence to the influx. The magnitude of instantaneous moisture flux, however, was not particularly large among those along the subtropical jet axis or the Meiyu-Baiu rainband. What made this event unique is the persistence of the moisture flux peak anchored around Kyushu under the influence of the Silk-Road teleconnection. In June 2020, three upper-level troughs, whose easternmost one corresponding to the aforementioned trough, tend to form along the subtropical Asian jet. This wave train was persistent in the month and lasted until mid-July, 2020. Our analysis suggests that, prior to the rainfall event, the Silk-Road teleconnection was intensified through an interaction with a wave train at subpolar latitudes, which involves nonlinear processes including trough cut-off.

(Citation): Horinouchi, T., Y. Kosaka, H. Nakamigawa, H. Nakamura, N. Fujikawa, and Y. N. Takayabu, 2021: Moisture supply, jet, and Silk-Road wave train associated with the prolonged heavy rainfall in Kyushu, Japan in early July 2020. *SOLA*, **17B**, 1–8, doi:10.2151/sola.2021-019.)

1. Introduction

Kyushu, the westernmost of the four major islands of Japan, has repeatedly suffered from heavy rainfall events during Baiu (e.g., Matsumoto et al. 1971; Ogura et al. 1985; Kato 2006), which is a part of the East Asian Summer Monsoon. In early July 2020, a series of heavy rainfall occurred over Kyushu, whose mesoscale features were documented in Hirockawa et al. (2020) and Akaki et al. (2020). Rainfall increased from 25 June, and it was particularly intense over 3–11 July (Figs. 1a and 1b); 7-day mean precipitation in this period was the greatest among the latest 40 years (Fig. 1a). In this period the accumulated precipitation averaged over the 150 weather stations in Kyushu was 610 mm, which is 5 times as much as its climatology, and it exceeded 1000 and 1500 mm at 20 and 2 stations, respectively (Fig. 1b). The long duration and the extent of the affected area suggest the potential importance of large-scale environmental factors. Climatologically, the Baiu period ends in mid-July around Kyushu, but it lasted until around 29 July in 2020.

Takaya et al. (2020; T2020) conducted ensemble experiments with an atmosphere-ocean coupled model. They showed that the enhanced Meiyu-Baiu precipitation over June and July, 2020, can

be explained by the increased sea-surface temperature (SST) over the Indian Ocean, which originated from the super Indian Ocean Dipole event in 2019. The effect of the warm Indian Ocean on Meiyu-Baiu was partly realized by increasing SST over the South China Sea. Their study explains the precipitation enhancement over the early summer of 2020, but explaining the heavy rainfall event in Kyushu over a ~10-day period requires investigation at finer scales.

This paper provides an overview of the prolonged heavy rainfall event in early July 2020 to promote further studies. Here, we examine its large-scale environmental conditions and the factors associated with their formation, with a focus on upper-level conditions. The characteristics of the 2020 summer are examined through comparison among past summers in several years. We show that the meridional position of the Asian jet and the Silk-Road teleconnection were particularly important.

The Asian jet, a mid- to upper-tropospheric subtropical jet, is an important factor that affects summertime weather and climate over East Asia (e.g., Kodama 1993; Sampe and Xie 2010; Kosaka et al. 2011; Horinouchi 2014, hereinafter H14; Horinouchi and Hayashi 2017, hereinafter HH17). The Silk-Road teleconnection found by Enomoto et al. (2003; E2003) affects summertime low-frequency variability over East Asia (e.g., E2003; Wakabayashi and Kawamura 2004; Kosaka et al. 2009; Chen and Huang 2012; Thompson et al. 2019; Shimpo et al. 2019). This teleconnection is often regarded as a spatial variability pattern on monthly or inter-annual time scales, referred to as the Silk-Road “pattern”. Here, we rather employ its original physical interpretation as stationary Rossby-wave trains that occur along the summertime Asian jet with enhanced potential-vorticity gradients, which increases the effective beta effect (E2003; Fig. S1).

The rest of the paper is organized as follows. After describing basic features in Section 3, we compare the atmospheric features during the early summer of 2020 with those during the same period in the preceding eight years in Section 4. We also briefly revisit the extreme rainfall event on 4–8 July 2018 (Shimpo et al. 2019; Sekizawa et al. 2019; Takemura et al. 2019; Tsuji et al. 2020). The time evolution of the Silk-Road wave train associated with the 2020 event is investigated in Section 5.

2. Data and method

We used the 6-hourly 1.25° data from the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015). The variables used are horizontal winds, temperature, and geopotential height at pressure levels, Ertel’s potential vorticity (EPV) at isentropic surfaces, column moisture (water vapor) flux and precipitable water. Climatological data are derived from the reanalysis as the 31-day (± 15 -day) running mean for each of the 4 times of day (0, 6, 12, 18 UTC) from 1990 to 2019 (30 years). We also used precipitation from automated weather stations of Japan Meteorological Agency called AMeDAS stations over 1981–2020.

Quasi-geostrophic potential vorticity (QGPV) q is defined

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Fig. 1. (a) 7-day running-mean of daily precipitation rate averaged over the 150 AMeDAS weather stations in Kyushu including near-by islands (Yakushima, Tanegashima, Tsushima, and Gotou) from 1981 to 2017 (thin black solid lines), 2018 (black dashed line), 2019 (black dotted line), and 2020 (thick red solid line). The solid cyan line shows the mean over the 40 years, and the dotted cyan lines show the mean plus/minus the interannual standard deviation. Time is based on Japan standard time (JST), and the values are assigned to 12 o'clock of the days. (b) Total precipitation from 25 June to 14 July (JST) in 2020 at individual AMeDAS stations. (c) As in (a) but for column moisture flux convergence in a region enclosing Kyushu (the cyan box in (g); 30°N–33.75°N and 128.75°E–132.5°E) from 1991 to 2020. (d) as in (c) but for the influx from the western and southern sides of the cyan box, which is defined as convergence by setting the moisture flux at the northern and eastern sides to zero. (e) zonal component of the column moisture flux averaged along the western side of the cyan box. (f) as in (e) but for the meridional component averaged along the southern side of the cyan box. (g) Horizontal map of quantities averaged over 7 days centered around 12 UTC, 5 July 2020 (00 UTC, 2 July to 00 UTC, 9 July): precipitable water (color shading), column moisture flux (arrows; scale in $\text{kg m}^{-1} \text{s}^{-1}$ shown on the right margin), 250-hPa geopotential height (black contours; interval: 50 m), 1485-m contour of 850-hPa geopotential height (blue contour). The cyan line shows the 1485-m contour of the climatology of 850-hPa geopotential height. The red line shows the 2-PVU contour of the 7-day-mean EPV at the 350-K isentropic surface. (h) as in (g) but for zonal wind (color shading), meridional wind (blue contours; interval: 10 m s^{-1} ; solid/dotted for positive/negative values; zero contours omitted), and geopotential height (black contours; interval: 50 m) at 250 hPa. The cyan line shows the climatological jet axis as the local peak of zonal wind in the meridional direction.

spherically as $q = f + \frac{\partial^2 \psi}{a^2 \cos^2 \varphi \partial \lambda^2} + \frac{\partial}{\partial a^2 \cos \varphi \partial \varphi} \left(\cos \varphi \frac{\partial \psi}{\partial \varphi} \right) + \frac{\partial}{\partial \rho_0 \partial z} \left(\frac{\rho_0 f^2}{N^2} \frac{\partial \psi}{\partial z} \right)$, where ψ is the quasi-geostrophic stream function, a is the Earth's radius, λ is longitude, φ is latitude, f is the Coriolis parameter, z is log-pressure height, and N is the log-pressure buoyancy frequency defined as its horizontal mean poleward of 10°N. The stream function is defined as $\psi \equiv \frac{\Phi - \Phi_{\text{ref}}}{f}$,

where Φ is geopotential and Φ_{ref} is its reference vertical profile defined as the horizontal mean Φ poleward of 10°N.

The phase-independent wave activity flux (WAF) of Takaya and Nakamura (2001; TN2001) is computed from ψ averaged over 7 days, which is divided into the background defined as its zonal running mean over $\pm 60^\circ$ and the deviation from it. This background definition alleviates a problem to apply WAF to waves propagating along a jet; a detailed method description and its rational are available in the supplementary document.

3. Moisture supply to the 2020 event and its large-scale environment

Figure 1c shows the 7-day running-mean column moisture flux convergence in a $3.75^\circ \times 3.75^\circ$ domain covering Kyushu (cyan box in Fig. 1g). Around 5–6 July 2020, it was greater than 40 mm/day, most of which must have precipitated. Actually, the diagnosed convergence was smaller than the measured precipitation in this period (Fig. 1a). Note that JRA-55 is a global reanalysis with a limited horizontal resolution (~ 60 km). The 7-day moisture flux convergence peak in early July 2020 was the greatest among the recent 30 years from late June to July. Three of the top four convergence events between 25 June and 10 July occurred in the last three years (2018–2020). The greatest peak in mid-June occurred in 2012.

Figure 1d shows the influx through the western and southern sides of the rectangular domain in Fig. 1g (cyan box), which covers Kyushu. It was computed as the convergence in the area by setting the moisture flux at the eastern and northern sides to zero. Comparison between Figs. 1c and 1d indicates that $\sim 20\%$ of the influx converged in the early-July 2020 event (the peak convergence and influx around 6–7 July are ~ 43 and ~ 260 mm/day, respectively, indicating a 17% convergence). This fraction was much higher than usual, which is $\sim 10\%$ (see the 40-year averages shown as cyan lines in Figs. 1c and 1d). Column zonal moisture flux was enhanced over early summer 2020 (Fig. 1e), consistently with T2020, while the meridional flux was intensified during the event (Fig. 1f).

Column moisture flux and precipitable water averaged over 2–8 July are shown in Fig. 1g. The low-level North Pacific subtropical high extended anomalously westward than its climatology to the south of 25°N , as indicated by the 1485-m contours of 850-hPa geopotential height (blue and cyan contours, respectively). Accordingly, a large portion of the moisture flux to Kyushu was brought from the Yangtze River region, to which water vapor was supplied from the South China Sea. Precipitable water increased around the Yangtze River due to convergence in the Meiyu frontal zone, which thickened humid layers while causing precipitation and re-evaporation. The supplementary movie shows a time sequence helpful to grasp the moisture transport.

The 7-day-mean 250-hPa geopotential height (Figs. 1g and 1h) exhibits a trough over the Yellow Sea and the Korean peninsula (120°E – 130°E). The trough was much stronger than the climatological trough at the same longitude, which is detectable as the slight southward deflection of the climatological jet axis (Fig. 1h; cyan line). The high convergence-against-influx ratio mentioned above ($\sim 20\%$) can be explained by convective induction by the ageostrophic ascent to the southeast of the trough, as suggested in the next paragraph. By contrast, the high moisture influx in mid-June 2020 converged only by $\sim 10\%$ (Figs. 1c and 1d). This difference highlights the importance of the upper-level trough, which was nearly absent by 14 June (Fig. S2a) and developed later but situated to the east of Kyushu (Fig. S2b). This fact signifies, in turn, the importance of the upper-tropospheric trough to the heavy rain event. Furthermore, the meridional moisture flux enhancement (Fig. 1f) is consistent with the induction of low-level southerlies to the east of the trough.

H14 showed from composite analyses covering July and August that midlatitude precipitation between 120°E and 140°E is enhanced 2 to 3 times, if the 350-K 2-PVU contour is situated at 200 to 600 km to the north (see Fig. 4d of H14); here, the contour denotes where the EPV value is 2 potential vorticity unit (PVU) on the 350-K isentropic surface (H14 actually used 1.5-PVU contour in a reanalysis, but it is near 2-PVU contours in JRA-55; see HH17), and this contour tends to be near the subtropical jet core (HH17). This precipitation enhancement occurs due to the dynamical induction of secondary circulation and an upper-level control of low-level trajectory (H14). HH17 showed from further analyses for the June to September period that the precipitation enhancement to the south of the 350-K 2-PVU contour is further enhanced to the east or to the south of the tip of upper-level

troughs (see Fig. 4 of HH17). Figure 1g shows that Kyushu was located between 200 and 500 km to the south of the 350-K 2-PVU contour, and it was situated to the east of the tip of the upper-level trough, which was proven to be favorable for the dynamical precipitation enhancement by these studies. An important difference is that the 350-K 2-PVU contour in Fig. 1g is based on a 7-day mean, while these composite studies are based on daily means; the movement of daily-mean based contour should somewhat smear the effect in the 7-day mean. However, as Horinouchi et al. (2019) demonstrated, this enhancement remains even when monthly means are used.

The jet axis and geopotential height contours meandered along $\sim 40^\circ\text{N}$ (Fig. 1h); QGPV contours (not shown) also meandered there similarly, as expected for stationary Rossby waves. These features are interpreted as a manifestation of the Silk-Road teleconnection as a stationary Rossby wave train along the Asian jet wave guide. The aforementioned trough around 120°E – 130°E is a part of this wave train.

4. Multi-year comparison of large-scale features

In this section, we examine environmental conditions for the last nine years; this particular choice of the number of the years was made to secure variability to compare and visibility as a single figure. Their comparison illustrates what was unique and what was not in the 2020 prolonged heavy rainfall event, which is difficult to achieve only by examining the particular year alone.

Figure 2 visualizes year-to-year variations in the time evolution of the Silk-Road wave train as EPV at 40°N and $\theta = 350$ K, where θ is potential temperature; the 350-K isentropic surface is climatologically near 200 hPa. This figure indicates that upper-level troughs tend to be anchored at around 20°E , 70°E , and 120°E in June in most of the nine years, as in the climatology shown in Fig. S3; all the three troughs persisted in 2015, 2018–2020, and some of them are found in most of the other years. Individual troughs move eastward on these stationary features.

Among the nine years the persistence of the three troughs is most evident in 2020, lasting from early June until around 20 July (Fig. 2i). EPV values greater than 3 PVU ($10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$) signifies stratospheric airmass, and its presence indicates southward jet displacement as in Fig. 1h.

In 2018, by contrast, the three stationary troughs existed until the beginning of July. The large-scale extreme precipitation event over western Japan occurred under the influence of this teleconnection (Shimpo et al. 2019; Yokoyama et al. 2020; Kornhuber et al. 2019; Tsuji et al. 2020). Also, in 2019, a heavy rainfall event occurred in southern Kyushu during 1–3 July, when an upper-level trough existed around 120°E (Fig. 2h) similarly to the case of the 2020 heavy rainfall event.

Year-to-year variations of the jet latitudes are visualized in Fig. 3. Consistently with the persistent trough in 2020, the 200-hPa jet axis over 120°E – 130°E was situated predominantly more southward than its upstream until mid-July (compare black and red lines in Fig. 3i; it can also be seen by the relatively large values of EPV in Fig. 2i). Also, the jet axis there was displaced southward than its climatology throughout July (compare black and cyan lines in Fig. 3i), which is consistent with the delay in the Meiyu-Baiu withdrawal in 2020.

In 2018, by contrast, the jet axis latitude moved northward rapidly after 8 July (black line in Fig. 3g) and the stationary wave abruptly weakened and increased its wavelength (Fig. 2g). This change is associated with the abrupt termination of the Baiu period, followed by the record heat wave in Japan from mid-July (Shimpo et al. 2019; Imada et al. 2019; Nishii et al. 2020).

The subtropical Asian jet tilts northward with height, and the 700-hPa jet axis tends to be situated around 5° south of the 200-hPa jet axis (Figs. 3 and 4), indicating overall vertical coupling across the troposphere. The eastward column moisture flux peaks around this lower part of the jet (Fig. 4). Precipitable water also peaks at around the flux peak located along the Meiyu-Baiu rainband (Figs. 4 and 5). Early July 2020 was no exception. The

Fig. 2. Longitude-time section of EPV at 40°N and $\theta = 350\text{ K}$ from 10 June to 31 July for each of the nine years from (a) 2012 to (i) 2020. Lines are shown at longitudes 20°E , 70°E , and 120°E . Time is UTC.

Fig. 3. Latitude-time section of some quantities smoothed temporarily with the 5-point running mean over 24 hours: zonal wind at 200 hPa averaged over 120°E – 130°E (color shading); same but for 700 hPa (blue contours shown only where 9 m s^{-1} or greater at the interval of 3 m s^{-1}). The black lines show the jet axis defined as the local maximum of 200-hPa zonal wind averaged over 120°E – 130°E (color shading), while its climatology is shown by cyan lines. The red lines are the black lines but for zonal wind averaged over 60°E – 120°E (i.e., mean upstream jet axis).

Fig. 4. Latitude-time section of the eastward component of the column moisture flux at 128.75°E (color shading). Red and black contours show zonal wind at 200 hPa (only where 30 m s^{-1} or greater with the interval of 10 m s^{-1}) and 700 hPa (only where 15 m s^{-1} or greater with the interval of 5 m s^{-1}), respectively (without temporal running mean unlike Fig. 3).

Fig. 5. As in Fig. 4 but for precipitable water (color shading). The 700-hPa zonal wind is not shown, and the 200-hPa zonal wind is shown by black contours (only where 30 m s^{-1} or greater with the interval of 10 m s^{-1}).

Fig. 6. Spherical QGPV averaged vertically over 300–200 hPa (based on integration along pressure) at 00 UTC of (a) 25, (b) 26, (c) 27, and (d) 28, June 2020. The longitudes and latitudes are indicated in (a). The blue and red arrows depict strong QGPV gradients indicating polar-front and subtropical jets, respectively. The circles (pink filled, blue, and white in a–d) and the “C” symbols (a) are overlaid to help explanation in the text.

magnitude of eastward moisture flux peaks was not particularly large (Fig. 4i), and the precipitable water peaks are normal as the ones along the Meiyu-Baiu rainband and fewer than in 2019 (Fig. 5; the peak values are generally smaller than those in the mesoscale analysis shown in Araki et al. 2021, and satellite observations, owing to the limitation of the global JRA-55 reanalysis). What was unique in 2020 was that the peak latitude was anchored persistently around Kyushu (31°N–34°N) without interruption. Synoptic fluctuations of the subtropical jet are generally dominated by dynamical processes in the upper troposphere, as shown by H14 with a quasi-geostrophic potential enstrophy analysis.

5. Silk-Road wave train formation associated with the 2020 rain event

Here, we investigate the evolution of the Silk-Road wave train that led to the trough over the Yellow Sea and the Korean Peninsula in early July 2020. The existence of the three persistent troughs at around 20°E, 70°E, and 120°E shown in Fig. 2 suggests downstream wave propagation, at least in terms of climatology. However, at a close look, the trough around 20°E was weak in late June in 2020 (Fig. 2i). Thus it appears that an additional origin of the wave train may have contributed to the trough formation around 120°E when the prolonged heavy rainfall event occurred.

Figure 6 shows QGPV averaged over 300–200 hPa. This averaging was conducted to capture disturbances both at subpolar

latitudes and along the subtropical jet, which are evident around 300–250 hPa and 250–200 hPa, respectively. A pronounced subpolar trough was present at around 60°N, 60°E on 25 June (the pink filled circle in Fig. 6a), which was accompanied by the polar-front jet (indicated by pronounced PV gradient: blue arrows in Fig. 6a). The trough extended southward on 26 June to reach (blue circle in Fig. 6b) the subtropical Asian jet, as indicated by pronounced QGPV gradient around 40°N (red arrows in Fig. 6a). The trough was cut off later (white circles in Figs. 6c and 6d) to generate a high q region in Fig. 2i. Similar cut-off occurred repeatedly; the two high q regions around 45°N, 80°E and around 45°N, 110°E on 25 June (blue “C” symbols in Fig. 6a) had also been cut off from the subpolar trough around 60°E.

The above argument suggests energy transfer from subpolar disturbances to the waveguide along the subtropical jet. Such transfer at around 30°E–60°E has been reported in many statistical studies (e.g., Ding and Wang 2005; Yasui and Watanabe 2010; Kosaka et al. 2012). A traditional way to investigate it is to use WAF from empirical-orthogonal-function analyses (e.g., Kosaka et al. 2012).

To apply WAF to actual cases requires special care in defining the background (supplementary document). Figure 7 shows thus obtained WAF from 7-day-mean geopotential height. This figure indicates that the Silk-Road wave train from Central to East Asia gradually enhanced from late June to early July. In late June, a wave-train was pronounced at high latitudes (~60°N; Figs. 7a and 7b). In early July, this wave train gradually weakened, and

Fig. 7. Geopotential height averaged vertically over 300–200 hPa and with time over 7-days (± 84 h) centered around 12 UTC on (a) 23 June, (b) 27 June, (c) 1 July, (d) 5 July (contours; interval: 100 m); perturbation stream function divided by the gravity acceleration ψ'/g (geopotential-height anomaly divided by Coriolis parameter; color shading); Takaya-Nakamura WAF computed from ψ' (arrows; $\text{m}^2 \text{s}^{-2}$). Red contours show where 7-day-mean horizontal wind speed is 25 m s^{-1} .

the Silk-Road teleconnection intensified along the subtropical jet around 40°N (Figs. 7c and 7d); the intensification of the Silk-Road wave train at $\sim 50^\circ\text{E}$ – 70°E resulted in the downstream enhancement of the trough around 120°E – 130°E during the period of the heavy rainfall event (Fig. 7d).

The southward wave-train transition argued above with Fig. 6 occurred during the period covered by Fig. 7b. However, WAF around 45°N , 60°E in Fig. 7b is rather northward. Thus, one may think that our interpretation is denied. However, it should be reminded that WAF is guaranteed to be proportional to group velocity only when it is computed for a quasi-monochromatic linear stationary Rossby wave packet. Therefore, its applicability to case studies has limitations, even if conducted carefully. From its definition (TN2001), it is understood that the northward WAF component arose because ψ' is tilted northwest-southeast (Fig. 7b). However, this tilt can be interpreted as a result of the cut-off high q , a highly nonlinear transient process. We speculate that this nonlinear process is a key in the southward wave-train transition to enhance the Silk-Road wave train. However, we have not shown its actual mechanism. Further study is needed to elucidate short-term interaction between wave trains that affects the Silk-Road teleconnection, which could include baroclinic aspects (Kosaka et al. 2009).

6. Conclusions and discussion

We have investigated large-scale circulation features associated with the prolonged heavy rainfall event in Kyushu in

early July 2020. The 7-day-mean precipitation and moisture flux convergence over Kyushu based on the JRA-55 reanalysis was the greatest among the last 40 and 30 years, respectively. This prominent convergence was supported by the greatest influx to the region, as well as a high ratio of convergence against influx. These conditions are attributable to an upper-level trough that persisted over the Yellow Sea and the Korean peninsula to the northwest of the heavy rainfall region.

However, the magnitude of instantaneous moisture flux was not particularly strong as the peak along the subtropical jet or the Meiyu-Baiu frontal zone. What made this event unique was the persistence of its peak latitude, situated at around 30°N , to the south of its climatological position. This was associated with the Silk-Road teleconnection. In June, three upper-level troughs tend to occur at 20°E , 70°E , and 120°E along the subtropical jet, and this wave train was persistent in 2020, lasting until mid-July. It was suggested that this wave train was enhanced by non-linear processes at around 60°E to transfer energy from a large-scale subpolar trough prior to the prolonged heavy rainfall event, but the interaction between the subpolar and Silk-Road wave trains remains to be elucidated.

Further studies of the present event would be desired from broad perspectives. Investigation from climate change projection is also desired. As shown in Section 3, the three of the four greatest 7-day moisture flux convergence occurred in the last three years. Rainfall in Kyushu in early July may be enhanced by the southward shift of the jet projected for June to July (Horinouchi et al. 2019).

Acknowledgements

We thank the members of the JMA Advisory Panel on Extreme Climate Events for discussion and two anonymous reviewers for helpful comments. This study was partially supported by the Environment Research and Technology Development Fund (JPMEERF20192004) of the Ministry of the Environment, Japan, and by JSPS KAKENHI Grants JP18H01278, JP19H05702 and JP19H05703.

Edited by: M. Ishii

Supplements

Supplementary document: method description and Figs. S1–S3.

Supplementary movie: 6-hourly precipitable water (color shading) and column water vapor flux (arrows) from 10 June to 31 July 2020.

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Manuscript received 6 January 2021, accepted 6 April 2021
 SOLA: <https://www.jstage.jst.go.jp/browse/sola/>