Development of Intensive APHRODITE Hourly Precipitation Data for Assessment of the Moisture Transport That Caused Heavy Precipitation Events

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Abstract
This study developed a rain-gauge-based hourly precipitation dataset to analyze the heavy precipitation event of July 2018 in Japan (H2018). We modified the APHRODITE algorithm to treat hourly precipitation data, and we detected orographically induced heavy precipitation patterns in western Japan. We compared the heavy precipitation pattern along with moisture transport with that of another disastrous precipitation event in 2014 over Hiroshima (H2014). It is evident that heavy precipitation occurred over a much wider area in Chugoku district during H2018 than in H2014, and extreme precipitation which exceeded 10mm/hr appeared three times in H2018 while at one time in H2014.

Atmospheric rivers (ARs) were detected during two distinct episodes of heavy precipitation over Hiroshima, i.e., 19 August 2014 and 6 July 2018. Of the two events, the precipitation amount and the depth (height) of the AR were much greater in the latter. In the mid-troposphere, abundant moisture and high equivalent potential temperature along the Meiyo frontal system can produce a large area of continuous heavy precipitation. The intensive hourly rainfall dataset developed in this study will be useful for investigations of AR and meso-scale system that affect heavy precipitation and validation of numerical models.

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1. Introduction
In order to investigate meteorological disasters such as heavy precipitation events that cause flash flooding, debris flows and landslides, analysis of the link between heavy precipitation and atmospheric moisture transport is important because substantial moisture convergence is one of the prerequisite conditions for heavy precipitation events. Recently, it is pointed out that narrow synoptic-scale (or larger) moisture flow, called atmospheric rivers (ARs), could improve medium-range weather forecasts in respect of disastrous heavy precipitation events (e.g., Lavers et al. 2016).

On the other hand, disastrous heavy precipitation that often happens overnight is sometimes linked to orographic precipitation that has a strong diurnal cycle (e.g., Yasuda 1970; Schumacher et al. 2006). Heavy mesoscale precipitation can be attributed to many causes, e.g., mesoscale convective systems. However, self-organizing convective systems might also be influenced by the effects of local geography such as mountains and local warm water bodies (e.g., inland seas). Studies of sub-daily timescale heavy precipitation rely largely on mesoscale numerical weather models.

For the both time-spatial scale of the perspectives, quantitative hourly precipitation data over land areas are invaluable. For large-scale analysis or forecast purposes, a critical rainfall amount that may cause local disasters is often pre-determined. Areas with record-breaking rainfall needs to determine new criteria of the areal precipitation for future warning. While, meso-scale meteorological simulation needs a quantitative hourly precipitation data to validate their models. The APHRO_JP product Kamiguchi et al. (2010) is often used for assessment of the heavy precipitation change in Japan, however, we had not released hourly products. Hence, in order to understand the mechanisms that cause and maintain precipitation systems that cause heavy rainfall events, we try to develop a new hourly data by including additional rain-gauge data during the event that occurred in Japan in July 2018 (JMA defined heavy precipitation events as the 11-d period from 28 June to 8 July 2018.; Tsuguti et al. 2018; Shimpo et al. 2019).

The purpose of this study was to construct a set of rain-gauge-based hourly precipitation data from western parts of Japan for June–July 2018 to understand the linkage of both synoptic-scale moisture flow and mesoscale systems to the heavy precipitation events. As an elucidating example, the moisture flow of two heavy precipitation events that affected Hiroshima, where usually we do not have heavy precipitation. Recent report pointed out that there are many coincidence with the area where historically maximum two-day rainfall renewed and where floods and debris disasters took place (Tanaka 2019). The record is significantly renewed over the large part of Hiroshima prefecture in the year 2018, however, the central part is not renewed at this time, since they had heavier event in the year 2014.

Here we show our method to develop an hourly rain-gauge-based daily gridded precipitation dataset for western Japan with the same grid interval as APHRO_JP. Using the developed hourly precipitation dataset, we examined the moisture transport associated with the 2018 precipitation event (hereafter, H2018) over Hiroshima Prefecture on the synoptic scale, focusing on ARs (e.g., Hirota et al. 2016) and on the mesoscale. Hiroshima Prefecture was affected by an earlier disastrous heavy precipitation event during 18–20 August 2014 (hereafter, H2014). The causes of this event were reported as an AR, cut-off low and orographic effects (Hirota et al. 2016). As H2018 and H2014 occurred in the same area and had similar meteorological causes (i.e., a line-shaped precipitation zone and AR, Tsuguti et al. 2018), we compared the precipitation distribution and synoptic-scale/mesoscale moisture transport associated with the two events.

In future, we should analyze the change of meteorological systems to predict the future change of extreme events. To acquire this, we need to assess each meteorological event with local accurate hourly precipitation. Hence, here we show an example of moisture transport during the two events.

2. Data and method
2.1 Station precipitation data used in this study
We used Automated Meteorological Data Acquisition System (AMeDAS) precipitation data acquired during 1980–2015 from approximately 1300 meteorological stations in Japan. In addition to the 24-h accumulated (Japanese local time) precipitation data used in the conventional AHIRO JP dataset (Kamiguchi et al. 2010), we also used hourly AMeDAS observational data for the target years of 2014 and 2018.

For the target periods (both H2018 and H2014), we also used hourly precipitation data from western Japan acquired by the Water Information System, which is operated by the Ministry of Land, Transport, Infrastructure, Transport and Tourism (MLIT, available at http://www1.river.go.jp/). The locations of the AMeDAS and MLIT rain gauges are plotted in Fig. 1a.
2.2 Development of APHRODITE hourly data

We employed the station value conservation (SVC) option to interpolate daily/hourly precipitation data (Kamiguchi et al. 2010), which was employed with APHRO_V1901 products to represent observed extreme values. Namely, in producing statistics for 2018, i.e., in comparing the 11-d precipitation (28 June to 8 July 2018) with normal years, we used the same scheme with APHRO_JP (Kamiguchi et al. 2010) but for with SVC.

Targeting the two heavy precipitation events that triggered disastrous landslides in Hiroshima Prefecture, we incorporated both AMeDAS and MLIT precipitation and we developed the hourly precipitation products by adopting the steps 1–6 below. However, first, we defined the hourly climatology using hourly AMeDAS precipitation for 1980–2012 by adopting the same method used for the APHRO_JP.

1. We adopted the JMA mesh monthly climatological precipitation as a base, applied a fast Fourier transform and selected the first six harmonics (as used for the daily climatology in APHRO_JP).
2. We used hourly precipitation data for specific hours. First, we compiled 00–01 UTC precipitation data by interpolating the “ratio” to the daily climatology (step 1) for 1980–2012. For this interpolation, we did not incorporate the “correlation distance” option, as elucidated from 20-km MRI model daily precipitation (Kamiguchi et al. 2010), because the correlation distance of hourly precipitation is different from that of daily precipitation.
3. We produced the average 00–01 UTC precipitation for each of the 365 calendar days for 1980–2012 (365-d climatological precipitation for 00–01 UTC precipitation).
4. For other hourly precipitation, we repeated steps 2–3.
5. When we interpolated the 00–01 UTC precipitation, we interpolated the “ratio” to the hourly precipitation climatology (step 3).
6. For other hourly precipitation, we repeated step 5.

2.3 Other data used

For the atmospheric circulation fields and large-scale moisture analysis, we used the ERA-Interim reanalysis dataset (Dee et al. 2011). For AR detection, we used daily mean precipitable water and we employed the same scheme as described in Yatagai et al. (2019).

To depict the local moisture transport, equivalent potential temperature and wind fields, we used the three-hourly mesoscale model (MSM) outputs released by the JMA. To illustrate the horizontal hourly precipitation over western Japan together with the atmospheric circulation fields, we also used the GPM IMERG (late) product to cover ocean areas.

3. Results

3.1 Precipitation during H2018 (28 June to 8 July 2018)

The spatial distribution of H2018 precipitation is shown in Fig. 1b, and its anomaly and ratio to the climatological precipitation for the same period are presented in Figs. 1c and 1d, respectively. Extreme heavy precipitation that exceeded 1000 mm during the 11-d period occurred in southern parts of Shikoku (Kochi Prefecture) and Gifu Prefecture. Moreover, the distribution of precipitation > 700 mm (colored yellow) in Kyushu and Chugoku districts (marked in Fig. 1c) highlights that heavy precipitation occurred along the southern/southwestern slopes of the mountains. In the Setonai-kai area (around the inland sea), including the city of Hiroshima, there was less precipitation than normal because these areas are surrounded by mountains in Shikoku (south), Chugoku (north), Kyushu (west) and the Kii Peninsula (east). However, during the 11-d period, precipitation over inland areas was > 400 mm. As shown in Fig. 1c, the anomaly was approximately 400 mm in inland areas. The ratio field (Fig. 1d) shows that in addition to the two peaks in Kochi and Gifu, the prefectures of
Kagawa, Hyogo and Kyoto received five times the normal precipitation, while Hiroshima and Okayama prefectures had about four times the normal precipitation during the 11-d period. Based on the wide area of the distribution of anomalous precipitation during H2018, it is undoubted that there was considerable moisture transport and a continuous system that maintained the precipitation. The existence of an AR, which is river-shaped corridor of warm moist air transported from the tropics to the mid-/higher latitudes, has been identified in relation to the two disastrous heavy precipitation events (H2014 and H2018) that caused widespread landslides in Hiroshima Prefecture (Hirota et al. 2015; Yatagai et al. 2019b). Both the large-scale and the local transport of moisture are evidenced by the hourly precipitation around Setonai-kai (the inland areas, shown in Fig. 1a).

3.2 Extreme precipitation during H2014 and H2018

Hourly precipitation during H2014 and H2018 is shown in Figs. 2a and 2b, respectively. In H2014, peak precipitation was reasonably localized to Miiri, whereas it was much more widespread across Hiroshima Prefecture in H2018. The distribution of precipitation in both events is clearly related to a line-shaped precipitation system, i.e., a type of mesoscale convective system that is known to cause heavy precipitation in Japan (Tsuguti et al. 2018). It is evident that heavy precipitation occurred over a much wider area in Chugoku district, including Hiroshima, during H2018 than in H2014.

Hourly time series for H2014 and H2018, including the time of maximum hourly precipitation, is shown in Figs. 2c and 2d, respectively. For comparison, also presented are the 0.05° precipitation data at Miiri station (Fig. 1a) in Hiroshima Prefecture, which had record-breaking hourly/daily precipitation in H2014, and the area-averaged (1° × 1°) precipitation data. It is evident that heavy precipitation occurred over a much longer period during H2018 in comparison with H2014. In addition, the time of peak precipitation differed in each event. The time of peak precipitation in H2014 was at 19–20 UTC (04–05 Japan Standard Time, JST), whereas heavy precipitation occurred in the evening (15 and 17 JST) and overnight (02 JST) during 5 July 2018. These peak time characteristics are also observed in the area-averaged (averaged over 34°N–35°N, 132°E–133°E) precipitation data.

3.3 Characteristics of large-scale moisture transport of ARs

The distribution of precipitable water in H2014 and H2018 is shown in Figs. 3a and 3b, respectively. In H2014, the AR was aligned SW–NE, while that in H2018 was aligned WSW–ENE over the Kyushu/Chugoku/Shikoku area (western parts of Japan). The moisture transport/convergence and the AR associated with H2014 and H2018 are shown in Figs. 3c and 3d, respectively.

In H2014, the moisture flux pattern over Japan (Fig. 3c) was similar to that of the precipitable water (Fig. 3a); however, its convergence was weak and discontinuous over Japan, except over Hokkaido. Anticyclonic circulation centered on 30°N, 140.5°E contributed to the moisture transport toward Japan.

In H2018, strong moisture convergence over Japan, except for Hokkaido (Fig. 3d), occurred on the southeastern side of the Meiyu (Baiu) front. To the northwest of the front, moisture was transported from the northeast, leading to moisture divergence over the Japan Sea.

3.4 Characteristics of three-dimensional local moisture transport

Vertical cross sections of the eastward moisture transport and convergence and graphs of the land-falling precipitation averaged...
over 132.0°E−133.5°E (Hiroshima Prefecture) for each event are shown in Fig. 4. It can be seen that the heaviest precipitation occurred in Hiroshima Prefecture during both H2014 and H2018. As also shown in Figs. 2a and 2b, it is evident that the amount of precipitation in H2018 far exceeded that in H2014.

Remarkably, the axis of strong eastward moisture transport corresponding to the AR was located in a different place in each event. In H2014, it was centered north of Chugoku (about 37°N) and there was no strong westward flux, whereas in H2018, it was located over the area of Shikoku to Hiroshima and it inclined northward with height (Figs. 4a and 4b). Over the Chugoku area, a strong and deep convergence zone existed from the surface to 500 hPa, which is identified as the Meiyu front. Consequently, a westerly moisture flux existed to the north of the front.

The height of the AR was higher (deeper) in H2018 than in H2014. The zone of heavy precipitation in H2018 (Fig. 4d) corresponds to the position of the Meiyu frontal system. In H2014, only weak convergence was observed in the upper level (700 hPa) over Hiroshima Prefecture (Miiri), which was not simulated well by the MSM (Hirota et al. 2015).

To establish the differences in moist–static energy transport, we compared the equivalent potential temperature and wind fields at 975, 925, 700 and 400 hPa heights for both peak periods, i.e., 18 UTC on 19 August 2014 and 09 UTC on 6 July 2018 (Fig. 5). Clearly, the upper and middle levels had high equivalent potential temperatures and high humidity associated with the AR in H2018 (Figs. 5b and 5d). In the middle level, a temperature minimum to the west of the target area (34.5°N, 131°E) caused strong vertical instability in comparison with the lower atmosphere.

In the lower level, in H2014, a strong wind blew from the...
Bungo Channel (132°E) and air with high equivalent potential temperature was transported toward Hiroshima, which caused the heavy localized precipitation at Miiri. In H2018, there were two routes of moisture flux: from the south (Bungo Channel) and from the southwest (north Kyushu) at the 925 hPa level (Fig. 5f).

Comparing the two events, location of ARs are different and synoptic events are different. AR in H2018 was appeared as persistent moisture flow along Baiu front, and it ups the moist air in the mid-tropopause. The relative importance of the location of mountains and lower moisture flow which are appeared both in H2014 and H2018 should be investigated by using numerical models and further moisture budget analysis. The hourly grid data developed in this study should be used for such quantitative analyses.
Table 1. Comparison of features of heavy precipitation events that affected Hiroshima in 2014 and 2018. The common characters in both events are shown in italic.

|                        | Heavy Precipitation in August 2014                               | Heavy Precipitation in July 2018                        |
|------------------------|-----------------------------------------------------------------|--------------------------------------------------------|
| Hourly peak precipitation | Occurred at Miiri 19−20 UTC, 19 August (4−5 JST, 20 August 2014) | Occurred wide area of Hiroshima, 8−9 UTC (17−18 JST) 6 July 2018, and 17−18 UTC, 6 July (2−3 JST, 7 July) 2018 |
| (averaged 1 × 1 degree) | No extreme (not over 10 mm/hr)                                   | Exceed 10 mm/hr                                         |
| AR appearance          | North of Japan (over Japan sea), SW−NE oriented over Hiroshima area | Over the western part of Japan centered at Shikoku Islands |
| Synoptic features, trigger | Cut-off low                                                     | Meiyu (Baiu) front                                     |
| Local moisture and precipitation | Eastward moisture flux is converged                             | Largely converged along with the Meiyu front (boundary of Easterly and westerly moisture flow) |
| Location               | South of the mountains in Chugoku district                    | South of the mountains in Chugoku district            |
| Lower moist air intrusion | Bungo Channel                                                  | Bungo Channel and from northern Kyushu                |

4. Conclusions

This study developed a rain-gauge-based hourly precipitation dataset to analyze a heavy precipitation event that occurred in Japan in 2018 (H2018), and compared the findings with another rainfall event that occurred in 2014 (H2014). We modified the APHRODITE algorithm to treat hourly precipitation data. Using the newly developed hourly precipitation climatology and adopting new interpolation method, we detected orographically induced heavy precipitation patterns in western Japan.

In H2014, peak precipitation was localized to Miiri, whereas it was much more widespread across Hiroshima Prefecture in H2018. It is evident that heavy precipitation occurred over a much wider area in Chugoku district during H2018 than in H2014. At Miiri station, more than 70mm/hr rainfall was observed at 4 JST (local time), and areal averaged (1deg × 1deg) precipitation did not show strong peak (less than 10 mm/hr). On the contrary, in H2018, the same station showed three peaks (15 JST of 5°, 17 JST of 6° and 2 JST of 7°) during 4−7 July, and areal average (1deg × 1deg) precipitation at the three time all exceed 10 mm/hr.

The main features of the two studied events (H2018 and H2014) are summarized in Table 1. In each event, the presence of an AR was detected in association with two distinct heavy precipitation episodes in Hiroshima: 19 August 2014 (H2014) and 6 July 2018 (H2018). In the former, the AR appeared aligned SW−NE over northern Hiroshima, while in the latter, the AR was aligned WSW−ENE over southern Shikoku in the latter event. Of the two events, the precipitation amount and depth (height) of the AR was found much greater in the latter. Although line-shaped precipitation systems appeared in both periods, moisture/energy transport in the mid-troposphere and from two directions in the lower levels produced heavy precipitation over a wider area of Hiroshima Prefecture in H2018 in comparison with H2014. In the mid-troposphere, abundant moisture and high equivalent potential temperatures associated with the Meiyu frontal system contributed to the continuous heavy precipitation that spread across northern Kyushu, Chugoku and the Setonai-kai (Seto Inland Sea).

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