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Meteorological overview and mesoscale characteristics of the Heavy Rain Event of July 2018 in Japan

Abstract An extremely heavy rainfall occurred over wide areas of Japan from 28 June to 8 July 2018. Heavily damaged areas were distributed from western Japan to Tokai region. This event was officially named the "Heavy Rain Event of July 2018" by the Japan Meteorological Agency. This paper provides a meteorological overview of the event. A comparison with other heavy rainfall events that have occurred since 1982 showed that the heavy rainfall event of 2018 was characterized by rainfall that was unusually widespread spatially and persistent temporally. Factors primarily responsible for this event included the prolonged concentration of two very moist airstreams over western Japan and persistent upward flow associated with activation of the stationary Baiu front. In some areas, line-shaped precipitation systems led to locally anomalous precipitation totals.

Keywords Heavy rainfall · Baiu front · Line-shaped precipitation system

Introduction

Extremely heavy rain fell over wide areas of Japan from 28 June to 8 July 2018. The heavy rainfall, referred to as the Heavy Rain Event of July 2018 (Japan Meteorological Agency [JMA] 2018; Tokyo Climate Center [TCC], JMA 2018), resulted in unprecedented amounts of precipitation. The greatest damage occurred from western Japan to Tokai region. Figure 1 shows relevant geographical names and locations. The Heavy Rain Event of July 2018 caused tremendous damage. There were 221 fatalities, 6296 buildings were completely destroyed, and 8929 houses were inundated above the floor level (Cabinet Office 2018a). In addition, the event led to widespread and devastating floods, landslides, and mudflows (Hirota et al. 2018). The Heavy Rain Event of July 2018 was the first such event to cause more than 200 fatalities since the heavy rainfall event of July 1982 (e.g., Ogura et al. 1985), which caused severe flooding at Nagasaki city in Kyushu region and resulted in 299 fatalities or missing persons (Cabinet Office 2005).

As discussed in "Characteristics and primary factors responsible for the heavy rainfall" section, the Baiu front and Typhoon Prapiroon (T1807) had a large effect on the Heavy Rain Event of July 2018. Tsuguti and Kato (2014), who investigated 386 heavy rainfall events that occurred from 1995 to 2009 in Japan, showed that 32.4% (21.2%) of these heavy rainfalls occurred in the vicinity of a typhoon or a tropical cyclone (a stationary front) and 17.9% were affected by a typhoon or tropical cyclone more than 1000 km from Japan. They also reported that more than 75% of the heavy rainfall events occurred from July to September. Numerous studies have been conducted of previous heavy rainfall events that occurred in the Baiu season (e.g., Akiyama 1975; Ninomiya 1978; Ninomiya and Yamazaki 1979; Ogura et al. 1985; Watanabe and Ogura 1987; Nagata and Ogura 1991; Kato et al. 2003). Heavy rainfall events are often accompanied by a "line-shaped precipitation system," which is an almost stagnant rainband 50–300 km long and 20–50 km wide (Kato 1998; Kato and Goda 2001; Kato and Aranami 2005; Kato 2006; Seko 2010; Tsuguti and Kato 2014; Unuma and Takemi 2016). A line-shaped precipitation system is regarded as one kind of mesoscale convective system (MCS), and it can be formed from a group of convective clouds organized quasi-stationary in a back-building process (Schumacher and Johnson 2005). Tsuguti and Kato (2014) determined the appearance frequency of line-shaped precipitation systems in Japan from 1995 to 2009 using a precipitation dataset of radar and rain-gauge observations (the Radar/Raingauge-Analyzed Precipitation product) made by the JMA. In recent years, heavy rainfall events occurring not only in the Baiu season but also in other seasons have caused serious hazards, e.g., August 2014 (Hiroshima city), September 2015 (Kanto-Tohoku areas), and July 2017 (Northern Kyushu areas) (Table 1) (Meteorological Research Institute 2014, 2015, 2017; Kitabatake et al. 2017). Line-shaped precipitation systems have played an important role in these events.

This paper provides meteorological overview and mesoscale characteristics of the Heavy Rain Event of July 2018 that caused widespread landslides. "Characteristics and primary factors responsible for the heavy rainfall" section describes the characteristics and primary factors that led to the heavy rainfall event. "Mesoscale characteristics of the heavy rainfall during 5–8 July 2018" section focuses on the period during 5–8 July 2018 and describes the mesoscale features of the precipitation, including the line-shaped precipitation systems during that time. "Discussion" section presents a comparison with previous heavy rainfall events that resulted in flood-related serious devastation and identifies the common characteristics of these events. "Summary and conclusions" section summarizes the study and presents conclusions.

Characteristics and primary factors responsible for the heavy rainfall

A stationary Baiu front and Typhoon Prapiroon were primarily responsible for the Heavy Rain Event of July 2018. A stationary Baiu front came to be located over Japan on 28 June 2018 (Fig. 2a). Typhoon Prapiroon, which was upgraded from a tropical cyclone on 29 June, far south of Japan, gradually moved northward and approached Kyushu Island on 3 July 2018 (Fig. 2b). Although the typhoon passed to the far east of Japan in the late afternoon of 5 July 2018, the active Baiu front remained stationary over Japan from 5 until 8 July 2018 (Fig. 2c). During6–8 July 2018, the heavy rainfall was especially severe and widespread. Successive emergency warnings of

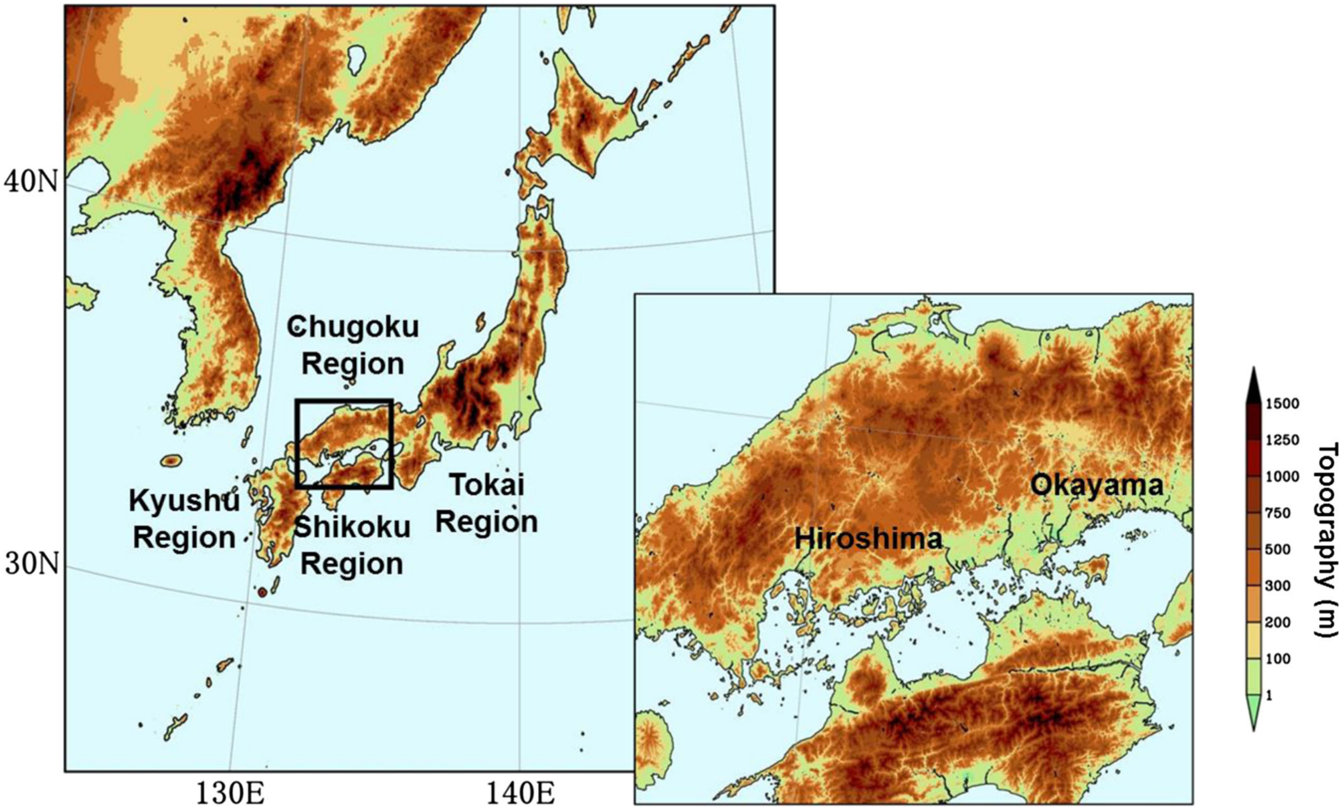

Fig. 1 Geographical names and locations around Japan

torrential rain were therefore issued for 11 of 47 prefectures during this period.

As described in JMA (2018) and TCC, JMA (2018), various parts of Japan experienced significant rainfall during the heavy rainfall event. Unprecedented precipitation was recorded at several JMA Automated Meteorological Data Acquisition System (AMeDAS) stations. Stations in the Shikoku and Tokai regions recorded total rainfall of more than 1800 and 1200 mm, respectively, during the period (Fig. 3). Some areas experienced 2–4 times the monthly climatological precipitation for July.

TCC, JMA (2018) also evaluated the spatial extent of the heavy rainfall by using the AMeDAS data at 966 stations throughout Japan from January 1982. The fact that the10-day total precipitation for early July 2018 at these AMeDAS stations was the highest for any 10-day period since January 1982 (Fig. 4) highlights the nationwide significance of this event.

Based on comparisons with previous heavy rainfall events caused by frontal systems and typhoons, the other prominent characteristic of this event was that areas with record precipitation, particularly within 72 h, were widely distributed over western Japan and the Tokai region, including the coastal

Table 1 Damages caused by the five heavy rain events discussed in this paper: July 1982 (Nagasaki city), August 2014 (Hiroshima city), September 2015 (Kanto-Tohoku area), and July 2017 (the Northern Kyushu area). LS, BF, SF, and RTC represent line-shaped precipitation systems, the stationary Baiu front, a stationary front, and remote influence of tropical cyclones

	Location	Fatalities (persons)	Completely destroyed (buildings)	Inundations above floor level (houses)	References: Cabinet Office, Government of Japan	Meteorological systems
July 1982	Nagasaki city	299	584	17,909	(2005)	LS+SBF
August 2014	Hiroshima city	76	179	1086	(2015)	LS+SF
September 2015	Kanto and Tohoku	8	80	1925	(2016)	LS+RTC
July 2017	Northern Kyushu	42	325	222	(2018a)	LS+SBF
July 2018	Western Japan and Tokai region	221	6296	8929	(2018b)	LS+SBF

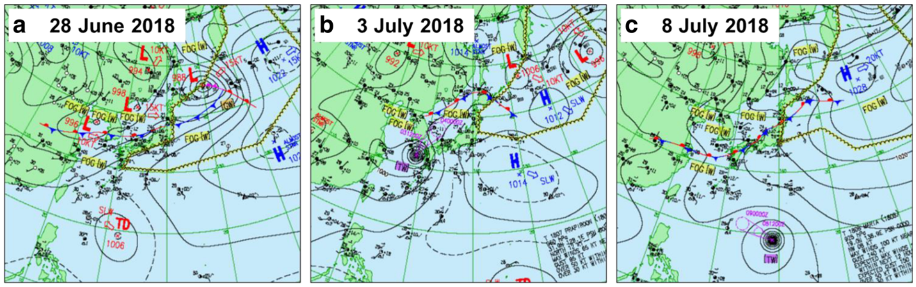

Fig. 2 Surface weather maps on 28 June (**a**), 3 July (**b**), and 8 July 2018 (**c**)

areas of the Chugoku and Shikoku regions, where normal monthly rainfall is lower than in surrounding areas (Fig. 5). Total precipitation at the 966 AMeDAS stations throughout Japan for the period 5–7 July 2018 was 140,567.0 mm (equivalent to 145.5 mm per station), the highest for any 3-day period since 1982.

The primary factors that characterize synoptic and mesoscale[1] atmospheric circulation of the event are considered to be the following (Fig. 6) (TCC, JMA 2018):

(A) Concentration of water vapor in two very moist airstreams maintained over western Japan
(B) Persistence of upward flow associated with activation of a stationary Baiu front
(C) Formation of mesoscale line-shaped precipitation systems

Factors (A) and (B) were the dominant factors associated with the event as a whole, whereas factor (C) played a significant role in certain areas.

Mesoscale characteristics of the heavy rainfall during 5–8 July 2018

Mesoscale features of the precipitation, including line-shaped precipitation systems

In this paper, we focus on the heavy rainfall during 5–8 July that was affected by the enhanced stationary Baiu front. During this period, wide areas from the Kyushu region to the Tokai region of Japan experienced intermittent heavy rainfall. Precipitation totals exceeded 500 mm in some places (Fig. 7).

In some heavy rainfall areas, line-shaped precipitation systems were apparent. The long spell of heavy rainfall experienced by those areas resulted in locally anomalous precipitation totals. Some of the line-shaped precipitation systems exhibited a back-building formation process. Such systems emerged on the night of 6 July in Hiroshima prefecture, just before dawn on 8 July in Gifu prefecture and just before dawn on 8 July in Kochi prefecture. The cumulonimbus cloud tops in the systems were approximately 9 km high in the Chugoku region and as high as 15 km in other regions (TCC, JMA 2018).

[1] Synoptic scale: horizontal dimensions $\geq$ 2000 km; mesoscale: horizontal dimensions < 2000 km (Orlanski 1975).

Locally heavy rainfall events

Landslides and flash floods associated with the Heavy Rain Event of July 2018 caused serious damage in Hiroshima and Okayama prefectures. On the one hand, heavy rainfall associated with line-shaped precipitation systems caused major disasters in Hiroshima prefecture. On the other hand, although line-shaped precipitation systems were not observed in Okayama prefecture, severe flash flooding occurred. In the following subsections, we focus on the two quite different types of precipitation that occurred in Hiroshima and Okayama prefectures.

Heavy rainfall event in Hiroshima prefecture In the vicinity of Hiroshima prefecture, line-shaped precipitation systems were observed during the night of 6 July and the early morning of 7 July (Fig. 8). The line-shaped precipitation system observed during the night of 6 July was associated with a back-building formation process. A time series of precipitation in Kure city revealed intense rainfall on two occasions during passage of line-shaped precipitation systems (Fig. 8). Even in Hiroshima city, a similar pattern of precipitation was observed (not shown). This pattern indicates that line-shaped precipitation systems accounted for much of the heavy rainfall in Hiroshima prefecture.

Heavy rainfall event in Okayama prefecture During the heavy rainfall, there was no clear, line-shaped precipitation system around Okayama prefecture (Fig. 8). However, serious flooding occurred in the vicinity of Okayama prefecture. A time series of precipitation in Takahashi city showed that cumulative precipitation increased continuously during prolonged moderate rainfall (Fig. 8).

Discussion

Comparison with the heavy rainfall event of August 2014 in Hiroshima prefecture

In August 2014, heavy rainfall induced by a line-shaped precipitation system occurred in and around Hiroshima prefecture (Hirota et al. 2016). Here, we compare the heavy rainfall between July 2018 (case2018) and August 2014 (case2014).

Both the location and duration of the case2014 and case2018 line-shaped precipitation systems were similar. However, the amount of short-term precipitation was much larger in case2014 than that in case2018. The observed maximum amounts of 3-h precipitation were > 200 mm in case2014 and ~ 100 mm in case2018. The area of heavy rainfall in case2014 was limited to

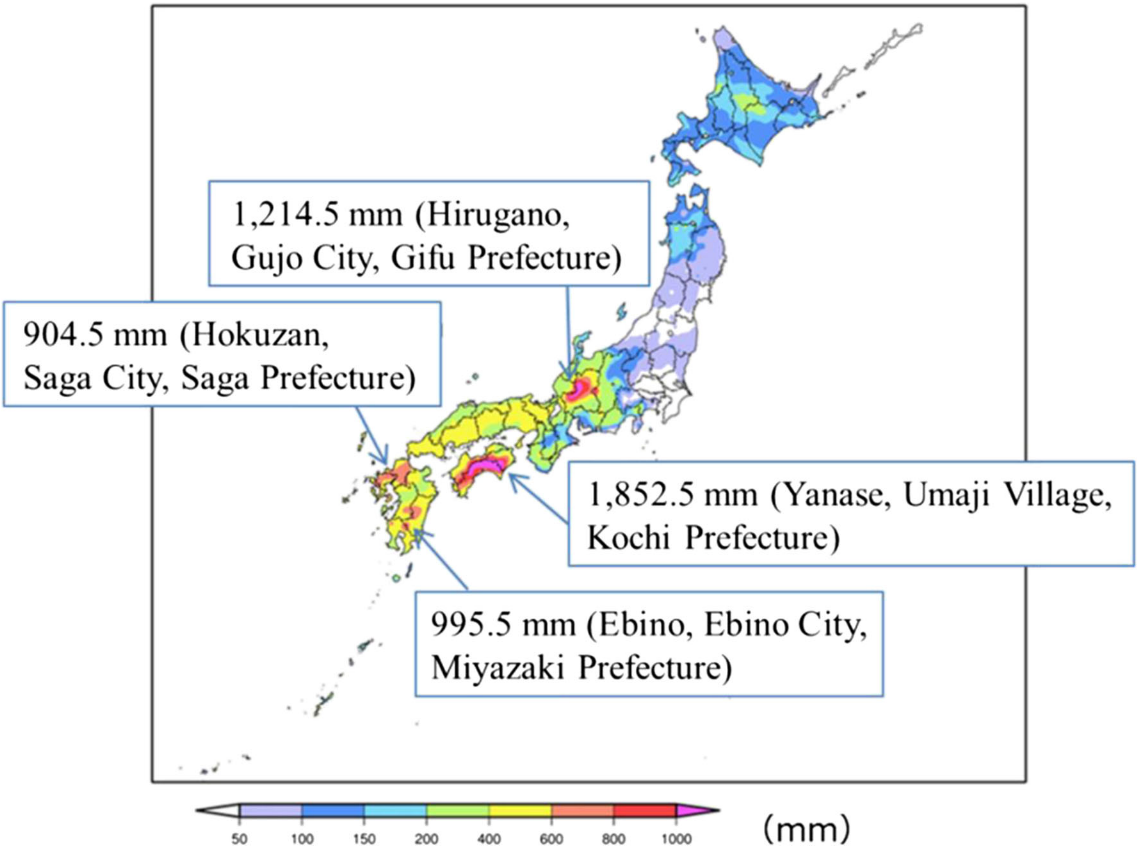

Fig. 3 Total amounts of precipitation during the Heavy Rain Event of July 2018 (28 June to 8 July). From TCC, JMA (2018)

Hiroshima prefecture. Thus, the area of precipitation was more concentrated in case2014 than in case2018 (Fig. 9).

Comparison with the heavy rainfall event of July 1982 in Nagasaki

Table 1 summarizes the damages caused by five selected Heavy Rain Events that have occurred in Japan: four occurred in the recent years as mentioned in "Introduction" section and the other occurred in 1982 with the number of fatalities similar to the Heavy Rain Event of July 2018. The five Heavy Rain Events shared similar characteristics: all but one were associated with line-shaped precipitation systems embedded in mesoscale stationary fronts (except for the Kanto-Tohoku Heavy Rain Event of September 2015; Tsuguti and Kato 2014). However, the five events caused very different amounts of damage. We compared the Nagasaki Heavy Rain Event of July 1982 with the Heavy Rain Event of July 2018 because they caused similar numbers of fatalities.

Depth-area-duration relationships distinguished these two heavy rainfall events. The Heavy Rainfall Event of July 2018 was

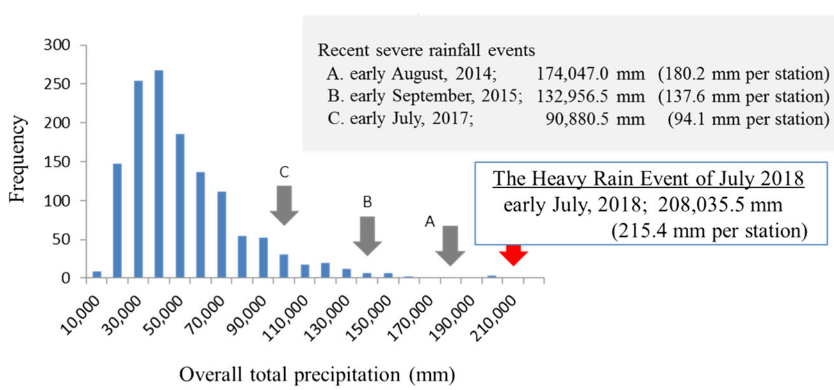

Fig. 4 Overall total precipitation at 966 selected AMeDAS stations throughout Japan for 10-day periods starting on the 1st, 11th, and 21st of the month since 1982. From TCC, JMA (2018)

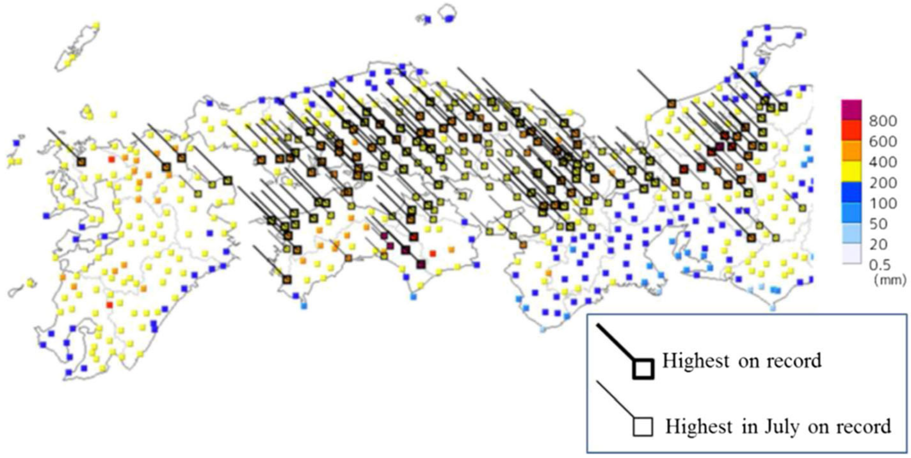

Fig. 5 Maximum amounts of 72-h precipitation during the event (from 28 June to 8 July) from western Japan to the Tokai region. From TCC, JMA (2018)

characterized by record-breaking 72-h rainfall totals, with moderate 24-h rainfall totals at rain gauge stations, and by rainfall over wide areas from western Japan to Tokai region (TCC, JMA2018). In contrast, the Heavy Rainfall Event of July 1982 was characterized by record 1-h and 2-h rainfalls of 187 mm and 286 mm, respectively, in Japan and by rainfall over a small area adjacent to Nagasaki city in Kyushu region. The rainfall occurred along a warm front associated with a 1000–2000-km or sub-synoptic-scale depression that developed along a weather front that extended along the east coast of China to eastern Japan from June to July (i.e., the Baiu front) and stayed in the Nagasaki area for 5 h (Ogura et al. 1985). As mentioned in "Characteristics and primary factors responsible for the heavy rainfall" and "Background large-scale aspects of the Heavy Rain Event of July 2018" sections, the Heavy Rainfall Event of July 2018 was characterized by abundant moisture convergence associated with many local line-shaped precipitation systems embedded in the stationary Baiu front. Although these two heavy rainfalls that occurred in July caused similar numbers of fatalities, the characteristics of the two rainfalls differed.

Extremely heavy rainfalls affecting huge areas of Japan occurred many times before 1982 (Cabinet Office 2018c). An example is the Heavy Rainfall Event of July 1972 described by the Ministry of Education, Science and Culture (1973). Akiyama (1975) has investigated the moisture budget of that event in the vicinity of the Japan Islands. Comparisons of the Heavy Rainfall Event of July 2018 with more previous heavy rainfall events will be needed to better understand the processes associated with the occurrence of these heavy rainfall events.

Background large-scale aspects of the Heavy Rain Event of July 2018

Global-scale and synoptic-scale backgrounds that surrounded the disaster areas in western Japan were also characterized by unusual

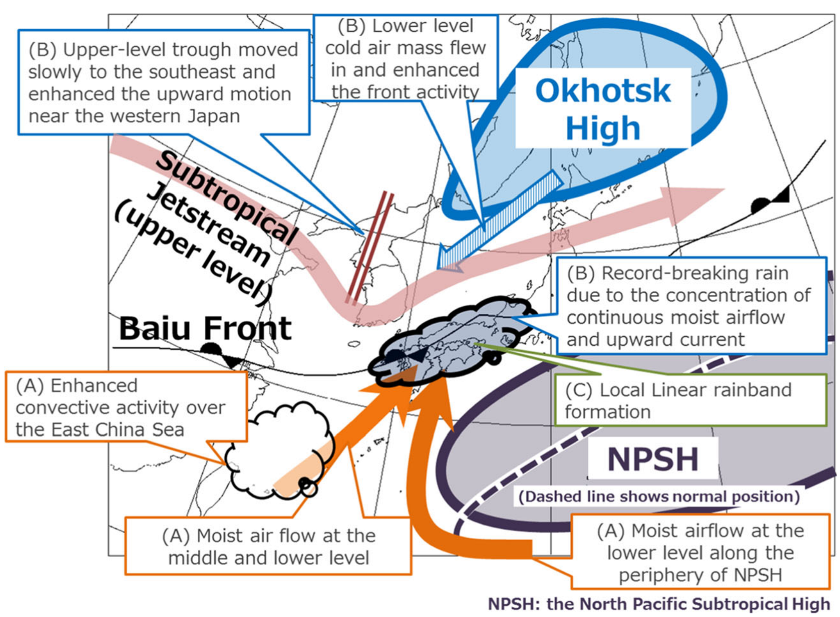

Fig. 6 Primary synoptic-scale motion factors that contributed to the record rainfall from western Japan to the Tokai region. From TCC, JMA (2018)

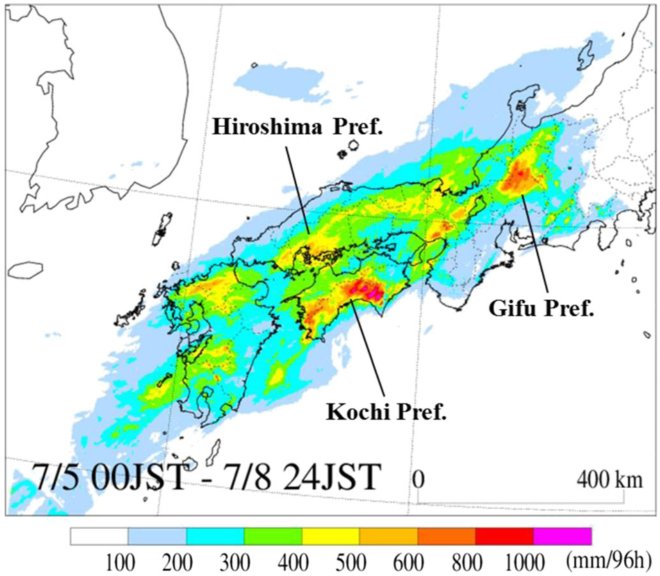

Fig. 7 Horizontal distribution of 96-h (5–8 July) accumulated Radar/Raingauge-Analyzed amounts of rainfall

conditions in early July 2018 that provided preconditions favorable for extreme rainfall in western Japan. On a synoptic scale, the key phenomena were (1) the enhancement of the North Pacific Subtropical High (NPSH) to the southeast of Japan, (2) the intense development of the cold Okhotsk High (OH), and (3) an upper-level trough (~ 500 hPa geopotential height) that lingered around the Korean Peninsula (Fig. 6). The NPSH and the OH routinely influence the weather throughout the Japanese rainy season because the Baiu front stays between the NPSH and the OH. In a normal rainy season, southwesterly monsoon winds blow into the

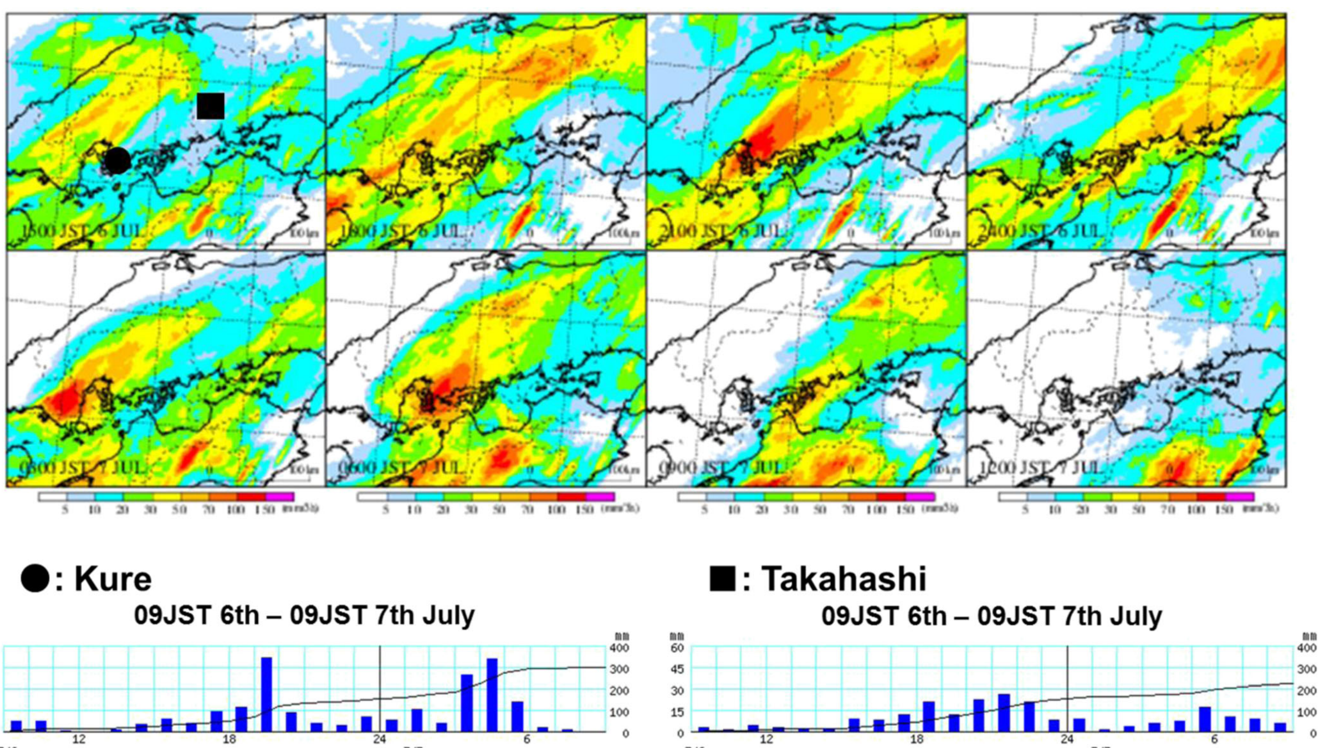

Fig. 8 (Top) Horizontal distributions of 3-h accumulated Radar/Raingauge-Analyzed amounts of rainfall from 15 JST on 6 July to 12 JST on 7 July 2018. (Bottom left) Time-series of amounts of precipitation for Kure AMeDAS station in Hiroshima prefecture (● denotes the location) from 9 JST on 6 July to 9 JST on 7 July 2018. (Bottom right) Same as bottom left, but for Takahashi AMeDAS station in Okayama prefecture (■ denotes the location)

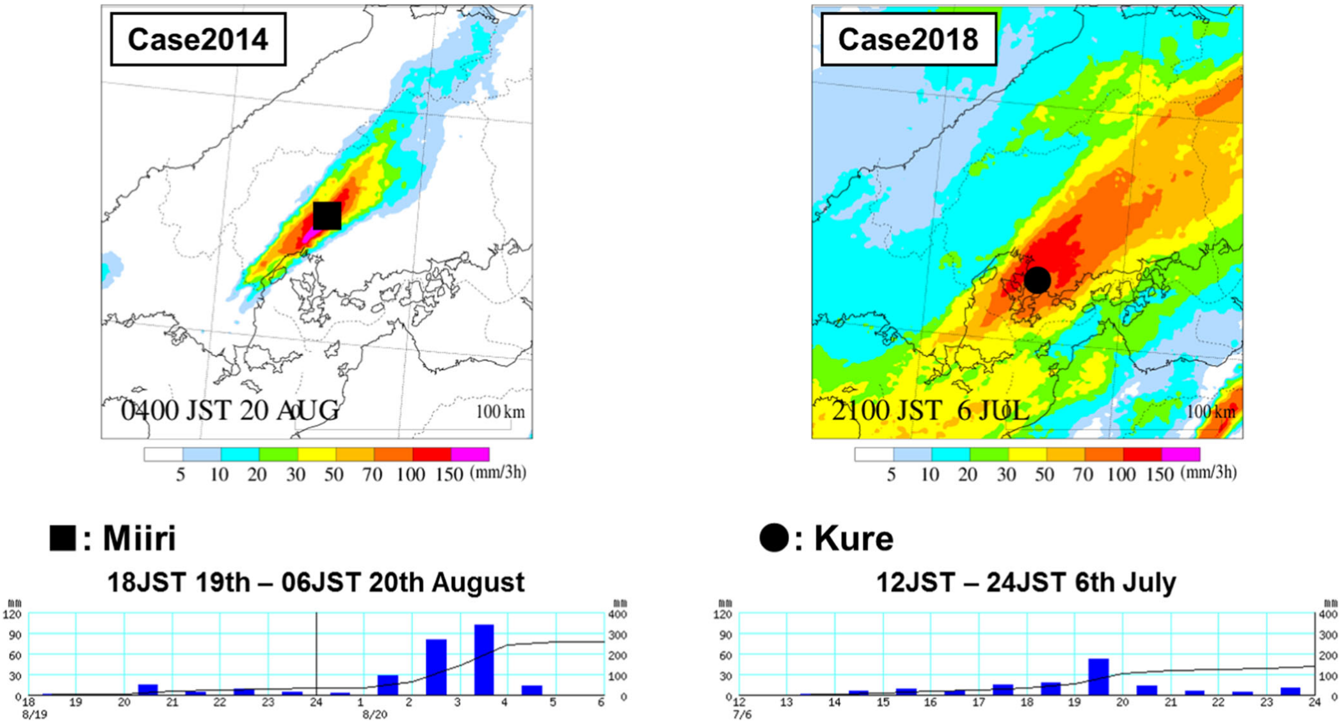

Fig. 9 (Top) Horizontal distributions of 3-h accumulated Radar/Raingauge-Analyzed amounts of rainfall. (Bottom) Time series of amounts of precipitation (left) for the Miiri AMeDAS station in Hiroshima prefecture (■ denotes the location) during the Heavy Rain Event of August 2014, and (right) for Kure AMeDAS station in Hiroshima prefecture (● denotes the location) during the Heavy Rain Event of July 2018

Baiu front and bring moist air along the periphery of the NPSH. However, during 5–8 July 2018, the unusual development of the NPSH to the southeast of Japan caused unusually strong southerly moist airflows over western Japan. The preceding passage of Typhoon Prapiroon also produced a flow of moist air over the East China Sea. As a result, significant amounts of moisture converged over the disaster areas.

In addition, the concurrent development of the OH brought lower-level cold air masses southward over the Sea of Japan. These cold air masses increased the meridional temperature gradient across the Baiu front, and the upward motion was therefore enhanced over western Japan.

Furthermore, an upper-level trough developed over the Korean Peninsula and moved to the western part of the Sea of Japan on 7 July. That trough further enhanced the upward motion of air on the Baiu front. An upper-level trough causes southwesterly moisture transport via what is sometimes called an "atmospheric river." An atmospheric river is often observed during the Japanese rainy season and results in heavy rainfall (Hirota et al. 2016; Kamae et al. 2017a, b). Thus, both the OH and the upper-level trough created preconditions favorable for generating MCSs over western Japan.

On a global scale, a series of meanders of the jet stream also contributed to the anomalous development of the NPSH, the OH, and the upper-level trough around Japan in 2018. Persistent northward and southward meanders of the subtropical jet stream contributed to the development of the NPSH and the lingering of the upper-level trough, respectively. A similar atmospheric wave train was also observed during the heavy rainfall event in western Japan during July 2012 (Imada et al. 2013). The development of an intense OH was caused by the persistent meandering of the polar front jet stream in the upper troposphere. This unusual concurrence of global-scale atmospheric circulation phenomena increased the likelihood of this unprecedented heavy rainfall event. For more detail on the large-scale aspects, refer TCC, JMA (2018).

Global warming due to increases in the concentrations of anthropogenic greenhouse gases can also contribute to the enhancement of heavy precipitation caused by greater water vapor concentrations in the lower atmosphere. It is apparent that the mean surface air temperature is increasing in Japan (JMA 2017). The saturation water vapor pressure depends on the temperature of the air (i.e., Clausius–Clapeyron relationship). According to the relationship, a warming of 1 K theoretically increases the amount of precipitation by about 7%. Nayak et al. (2017) have compared the increase of precipitation relative to the increase of temperature in the present and future climates and have indicated that the ratio is larger in the future climate (4.6% per K) than that in the present climate (3.5% per K). Analysis of high-resolution regional climate model simulations by Lenderink and van Meijgaard (2008) has revealed that hourly precipitation extremes have increased at a rate about 14% per K over much of Europe. This pattern has been called the super Clausius–Clapeyron relationship (e.g., Berg and Haerter 2011; Loriaux et al. 2013; Lenderink et al. 2017). Future studies will be needed to quantitatively evaluate the impact of global warming on the Heavy Rain Event of July 2018.

Summary and conclusions

We investigated the meteorological characteristics of the Heavy Rain Event of July 2018. Compared to the other heavy rainfall events that have occurred since 1982, a prominent characteristic of this heavy rainfall event was the extremely broad and persistent spatial and temporal pattern of the rainfall. The primary factors responsible for the Heavy Rain Event of July 2018 were the prolonged localization of two very moist airstreams over western Japan and the persistence of upward flow associated with activation of the stationary Baiu front. These phenomena were influenced by global teleconnections. In terms of mesoscale characteristics of the heavy rainfall, precipitation totals exceed 500 mm in some limited places, such as Hiroshima, Gifu, and Kochi prefectures, during 5–8, July. Our results suggested that the formation of line-shaped precipitation systems led to locally anomalous precipitation totals in some areas, e.g., Hiroshima prefecture. The role of the line-shaped precipitation systems in the intensification of rainfall during this event should be more quantitatively investigated in future studies.

The Heavy Rain Event of July 2018 involved meteorological phenomena ranging from mesoscale rainfall systems to global-scale processes. Deeper understanding of this extreme rainfall event will require analyses that span meteorological phenomena over a wide range of scales.

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