

# Primary Factors behind the Heavy Rain Event of July 2018 and the Subsequent Heatwave in Japan from Mid-July Onward

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<https://ds.data.jma.go.jp/tcc/tcc/index.html>

## Abstract

Japan experienced significant rainfall particularly from western Japan to the Tokai region mainly in early July (The Heavy Rain Event of July 2018), which caused widespread havoc nationwide. Extremely high temperatures subsequently persisted throughout most of Japan from mid-July onward.

In this context, the Japan Meteorological Agency (with the help of the Tokyo Climate Center Advisory Panel on Extreme Climatic Events) investigates atmospheric and oceanic conditions considered to have contributed to such climate extremes and summarizes related primary factors. Based on this work, the Heavy Rain Event of July 2018 is attributed to an ongoing concentration of two massively moist air streams over western Japan and persistent upward flow associated with the activation of a stationary Baiu front. The related heatwave is attributed to the expansion of a persistent North Pacific Subtropical High and Tibetan High to the Japanese mainland. The serial occurrence of these two extreme climate events was caused by significant and persistent meandering of the subtropical jet stream in the upper troposphere. The long-term trend of increased intensity in observed extreme precipitation events in Japan and the clear upward trend in amounts of airborne water vapor also suggest that the Heavy Rain Event may be linked to global warming. Global warming and ongoing higher-than-normal zonally averaged tropospheric air temperatures associated with the northward shift of the subtropical jet stream are also considered responsible for the extreme heatwave.

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## **Introduction**

The Heavy Rain Event of July 2018 is the official name given by the Japan Meteorological Agency (JMA) to an extreme climate event that brought unprecedented amounts of precipitation throughout Japan. It caused significant disaster conditions, particularly from western Japan to the country's Tokai region, in early July in association with the presence of a stationary Baiu front and Typhoon Prapiroon (T1807), which caused widespread havoc nationwide. Extremely high temperatures subsequently persisted throughout Japan (except in the Okinawa/Amami region) in association with a stronger-than-normal North Pacific Subtropical High in the vicinity of the nation from mid-July onward.

To clarify the conditions of the event, identify possible causative factors and enable the timely provision of related climate information to the public, JMA has analyzed the general characteristics of and primary factors behind the Heavy Rain Event of July 2018 (28th June – 8th July) and the notable heatwave conditions observed from mid-July onward. In parallel with these efforts, the Tokyo Climate Center (TCC) Advisory Panel on Extreme Climatic Events (a JMA body staffed by prominent experts on climate science from universities and research institutes) has investigated atmospheric and oceanic conditions considered to have contributed to such extreme climatic conditions.

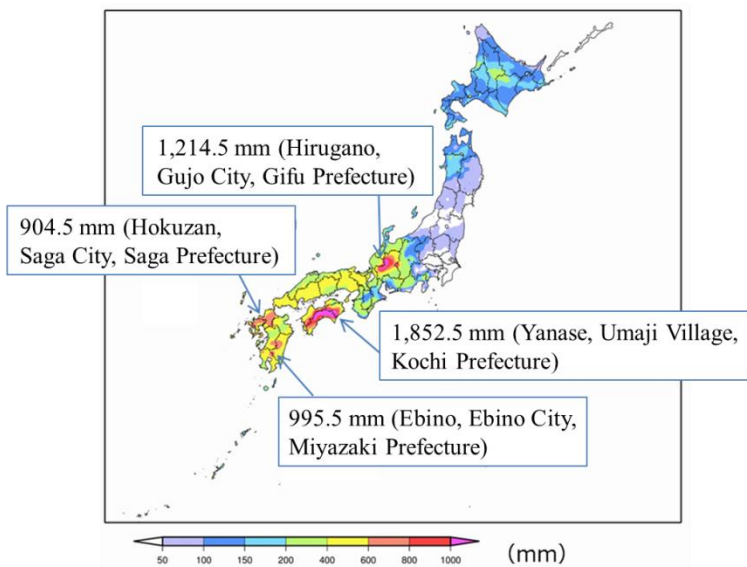
This report summarizes the above climate extremes and possible related factors based on analysis conducted by JMA with the help of the panel. It consists of two chapters – one for each event – and related annexes.

# 1. The Heavy Rain Event of July 2018

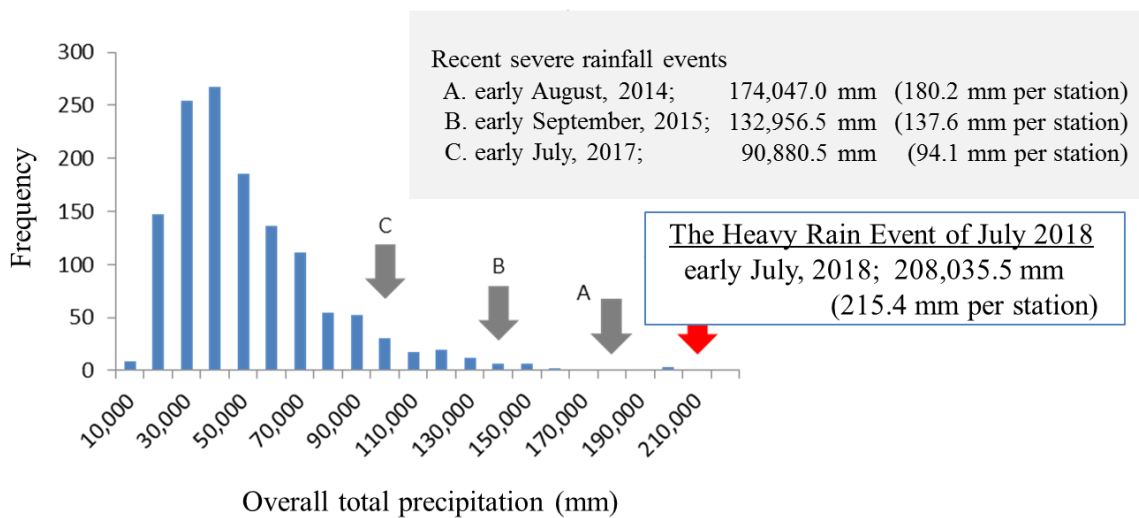
## 1.1 Climate conditions

Various parts of Japan experienced significant rainfall during the Heavy Rain Event of July 2018 (28th June – 8th July), with unprecedented precipitation being recorded at some JMA Automated Meteorological Data Acquisition System (AMeDAS) stations. Stations in the Shikoku and Tokai regions recorded more than 1,800 and 1,200 mm, respectively, during the period (Figure 1.1.1). Some areas experienced two to four times the precipitation of the monthly climatological normal for July (Figure A1.1, annex).

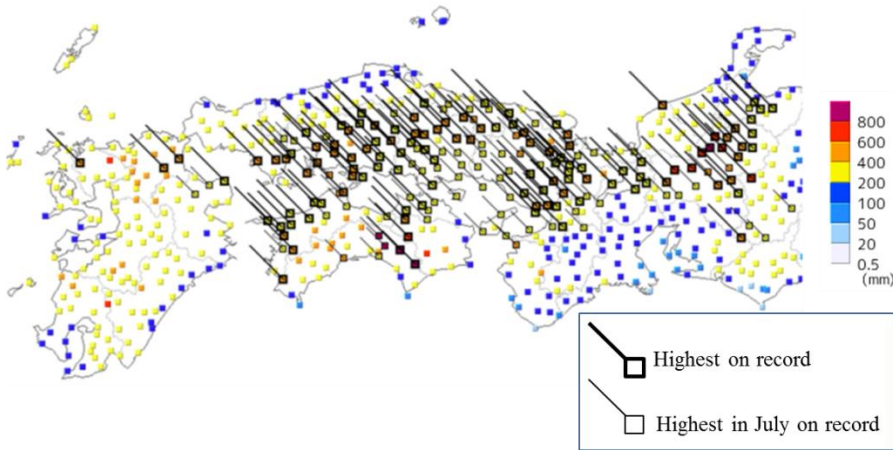
Overall precipitation at 966 selected AMeDAS stations throughout Japan for early July 2018 was the highest for any 10-day period since 1982 (Figure 1.1.2), highlighting the nationwide significance of this event.



**Figure 1.1.1 Total precipitation amounts for the Heavy Rain Event of July 2018 (28th June – 8th July)**



**Figure 1.1.2 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**



**Figure 1.1.3 Maximum 72-hour precipitation amounts during the event (from 28th June to 8th July) from western Japan to the Tokai region**

**Table 1.1.1 Record three-day precipitation totals at selected AMeDAS stations throughout Japan from 1st January 1982 to 10th July 2018**

rank	Nationwide (966 stations)	the Northern part of the Kyushu region (80 stations)	the Shikoku region (55 stations)	the Chugoku region (78 stations)	the Kinki region (68 stations)	the Tokai region (73 stations)
1	140,567.0 *1 (145.5) *2 [7th July 2018] *3	24,379.0 (304.7) [4th July 1995]	22,509.0 (409.3) [19th Sept. 1990]	22,788.5 (292.2) [7th July 2018]	21,093.5 (310.2) [4th Sept. 2011]	21,102.5 (289.1) [3rd Aug. 1982]
2	128,099.5 (132.6) [21st Sept. 2011]	21,792.0 (272.4) [7th July 2018]	20,229.5 (367.8) [6th Sept. 2005]	18,798.5 (241.0) [6th July 2018]	19,130.0 (281.3) [7th July 2018]	19,138.5 (262.2) [12th Sept. 2000]
3	124,167.0 (128.5) [23rd Oct. 2017]	21,014.0 (262.7) [10th July 1997]	19,982.5 (363.3) [7th July 2018]	17,570.0 (225.3) [25th June 1985]	17,918.0 (263.5) [23rd Oct. 2017]	18,838.5 (258.1) [13th Sept. 2000]
30	-	-	-	-	-	13,370.0 (183.2) [7th July 2018]

\*1 Sum of total precipitation amounts in the region (unit: mm)

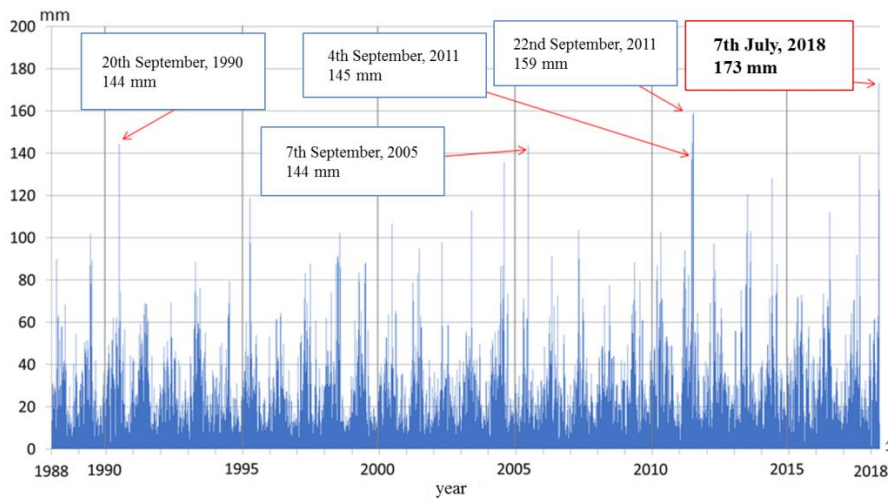
\*2 Precipitation amounts per station (unit: mm/station)

\*3 Three days up to this day

Red indicates events occurred during the period in the heavy rain of July 2018

In comparison with past heavy rainfall events caused by frontal systems and typhoons, a prominent characteristic here is that areas with record precipitation, particularly within 48 to 72 hours, were widely observed over western Japan and the Tokai region, including the Seto Inland Sea side of the Chugoku and Shikoku regions, where monthly normals are lower than those of surrounding areas (Figure 1.1.3, Table A1.2). Total precipitation at the selected AMeDAS stations throughout Japan for the period from 5th to 7th July 2018 was 140,567.0 mm (equivalent to 145.5 mm per station), which was the highest for any three-day period since 1982. The three-day total during the event was the highest ever for the Chugoku region (Table 1.1.1).

Analysis of 72-hour precipitation amounts averaged over Japan's land areas using a precipitation dataset of radar and rain-gauge observation (namely, the Radar/Raingauge-Analyzed precipitation product) for the event shows a total maximum of 173 mm up to 10:00 JST on 7th July 2018, which was the highest since the product was launched in April 1988 (Figure 1.1.4).



**Figure 1.1.4 Cumulative 72-hour precipitation averaged over grid points nationwide from JMA gridded analysis precipitation products**  
The period is April 1988 – July 2018.

## 1.2 Primary factors behind rainfall with relatively large temporal/spatial scales

Primary synoptic/meso-scale atmospheric circulation-related factors contributing to the heavy rainfall event detailed in Section 1.1 are considered to be as follows (Figure 1.2.1):

- (A) Ongoing concentration of two massively moist air streams over western Japan
- (B) Persistence of upward flow associated with activation of the stationary Baiu front
- (C) Characteristics of line-shaped precipitation systems

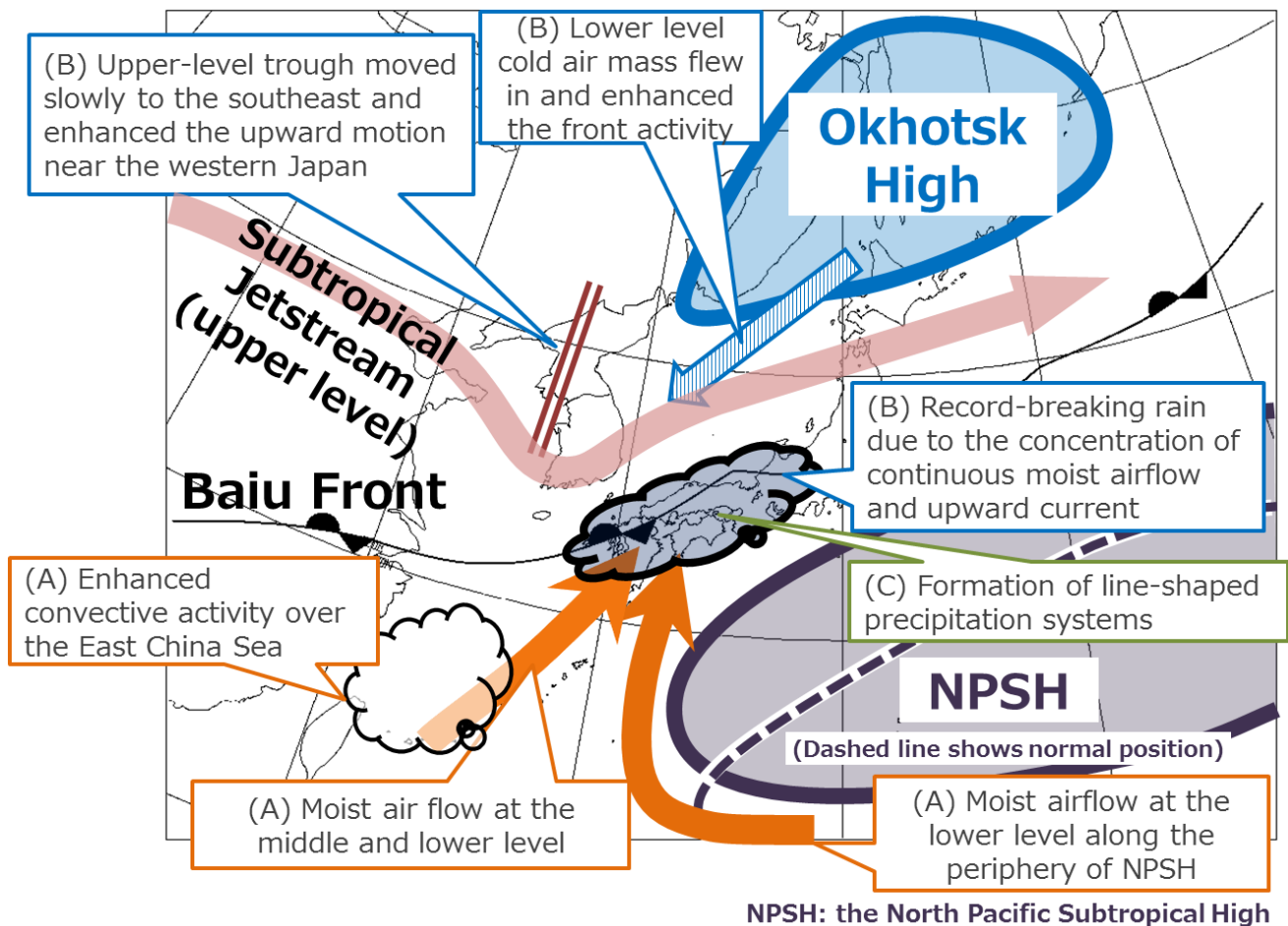
(A) and (B) were the dominant factors behind the event as a whole, while (C) played a significant role in certain areas.

### 1.2.1 Ongoing concentration of two massively moist air streams over western Japan (A)

Two massively moist air streams continued to flow over the area to the south of Japan from 5th to 8th July in association with the following:

- Convective activity over the East China Sea was enhanced and lower- to mid-tropospheric air containing huge amounts of water vapor due to local convection flowed over western Japan on southwesterly winds.
- The North Pacific Subtropical High (NPSH) was enhanced to the southeast of Japan, causing stronger southerly winds over seas south of Japan and a consequent flow of massively moist air in the lower troposphere over western Japan along the periphery of the NPSH.

The ongoing confluence of these two moist airflows over western Japan brought significant amounts of water vapor to the region. With reference to Japanese 55-year Reanalysis data (JRA-55, Kobayashi et al. 2015) from January 1958, it was found that unprecedented amounts of water vapor were concentrated in western Japan and elsewhere from 5th to 7th July (Figure 1.2.2). This continuous confluence is attributed to a relatively stagnant atmospheric pressure pattern around the Japanese archipelago during the period.



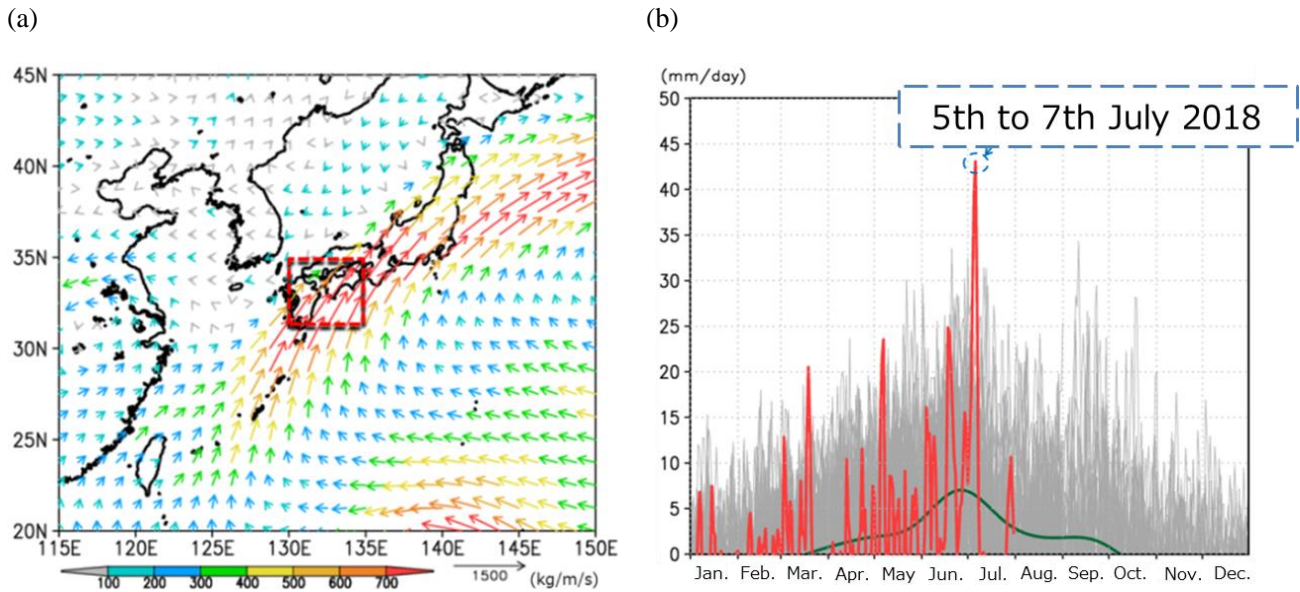
**Figure 1.2.1 Primary synoptic-scale motion factors behind record rainfall from western Japan to the Tokai region from 5th to 8th July 2018**

Enhanced convective activity in and around the East China Sea was probably attributable to ongoing local atmospheric instability associated with moist air inflow from the South China Sea until 6th July after Typhoon Prapiroon (T1807) moved northward over the East China Sea on 2nd July.

### 1.2.2 Persistence of upward flow associated with activation of the stationary Baiu front (B)<sup>1</sup>

The Okhotsk High turned dominant around 3rd July, and the Baiu front stayed between the NPSH and the Okhotsk High from the northern part of the Sea of Japan to Hokkaido. On 4th July, the frontal system moved further northward in association with Typhoon Parapiroon's movement northward over the Sea of Japan. The typhoon subsequently transformed into an extratropical cyclone and reached the vicinity of Hokkaido on 5th July. At the same time, the Baiu front turned more distinct in the vicinity of western Japan in association with the development of the Okhotsk High. The lower-level cold air mass moved southward to the Sea of Japan on the northern side of the

<sup>1</sup> See Annex 2 for more on the three stages of persistence of the upward flow associated with the activation of the stationary Baiu front.



**Figure 1.2.2 (a) Vertically integrated horizontal water vapor flux averaged over the period from 5th to 7th July, 2018, and (b) time-series representation of vertically integrated horizontal water vapor convergence (the three-day running mean) in the red rectangle of panel (a)**

(a) The unit is kg/m/second. (b) The unit is mm/day and the target area is 31.25 – 35°N and 130 – 135°E as shown by the red rectangle in (a). Data for the period from 1958 to 2018 are overlaid into one calendar year. The red, gray and green lines indicate values for 2018 (up to 31st July), each year from 1958 to 2017, and the average from 1981 to 2010, respectively. (a) and (b) are generated from JRA-55 data, and vertical integration here represents integration from the surface to 300 hPa.

zonally oriented front. The Okhotsk High was thereafter exceptionally developed, leading to increased meridional temperature differences across the Baiu front, and upward motion was enhanced from 5th to 6th July. Against this background, the Baiu front turned active over western Japan and elsewhere, leading to heavy precipitation on both the Pacific side and the Sea of Japan side of western Japan.

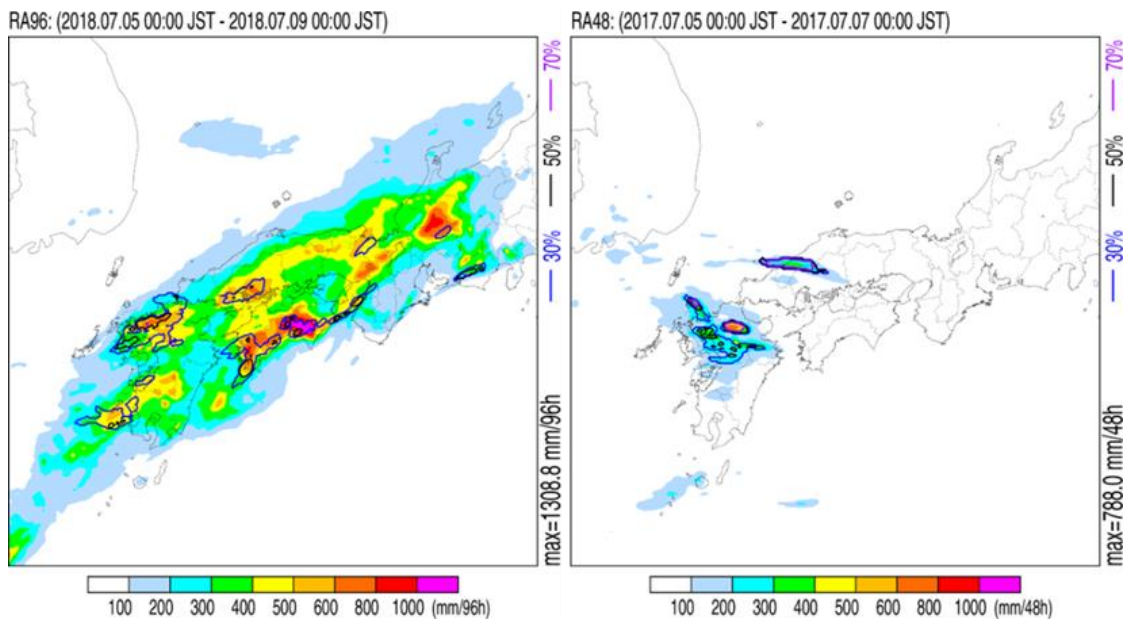
While the NPSH over the sea southeast of Japan was dominant again from 6th July onward, the Baiu front remained in the vicinity of western Japan. The upper-level trough moved from its location over the Korean Peninsula to the western part of the Sea of Japan and intensified on 7th July, generating a meso-scale low-pressure system on the Baiu front to the east of the upper trough. This system brought increased water vapor inflow to western Japan and the area of heavy precipitation moved eastward, bringing significant rainfall to the Seto Inland Sea side of the Chugoku and Shikoku regions. Although the large-scale cloud area associated with the upper trough and the low-pressure system moved eastward and away from western Japan during the night on 7th July, lower-level warm moist air persisted and generated several meso-scale localized convective cloud systems over the Pacific side of western Japan, causing further heavy rainfall on 8th July.

### 1.2.3 Characteristics of line-shaped precipitation systems (C)

From 4th to 8th July during the Heavy Rain Event of July 2018, wide areas from the Tokai region to the Kyushu region of Japan intermittently experienced heavy rainfall, with precipitation totals exceeding 200 mm in many places. During this period, a total of 15 line-shaped precipitation systems affected various areas (see Annex 3). Nine of these systems were prominent, with maximum three-hour precipitation amounts exceeding 150 mm.

Some areas affected by the line-shaped precipitation systems experienced extended periods of torrential rainfall, resulting in locally anomalous precipitation totals. In some places, precipitation caused by these systems alone accounted for more than 50% of all precipitation in the event for certain parts of the Tokai, Chugoku, Shikoku and Kyushu regions of Japan. The ratios of precipitation caused by line-shaped precipitation systems to the total in this event were lower than those in the Heavy Rain Event of July 2017 in the northern part of the Kyushu region, but heavy rainfall covered a wider area in the 2018 event (Figure 1.2.3).

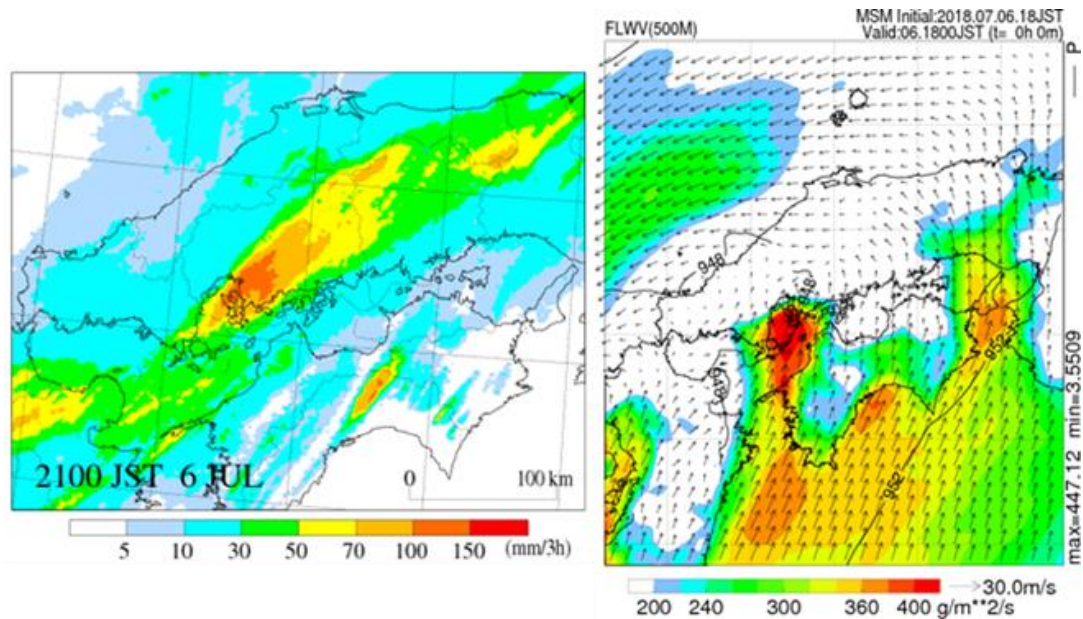
Some of the line-shaped precipitation systems observed in this event exhibited a back-building formation process, such as those emerging on the night of 6th July in Hiroshima Prefecture (see Annex 4), just before dawn on 8th July in Gifu Prefecture and just before dawn on 8th July in Kochi Prefecture. The cumulonimbus cloud top in the systems was approximately 9 km high in Hiroshima and as high as 15 km elsewhere. The systems developed at a time of air inflow with huge amounts of lower-level water vapor (Figure 1.2.4).



**Figure 1.2.3 Total precipitation amounts and ratios of contribution from line-shaped precipitation systems**

(Left) The Heavy Rain Event of July 2018 (5th – 8th July 2018) and (right) the Heavy Rain Event of July 2017 in northern Kyushu (5th – 6th July 2017). Shading indicates total precipitation amounts calculated from JMA’s gridded analysis precipitation products, and contours represent ratios of contribution from precipitation amounts caused by line-shaped precipitation systems to the total. Blue, red and purple lines correspond to 30, 50 and 70%, respectively.





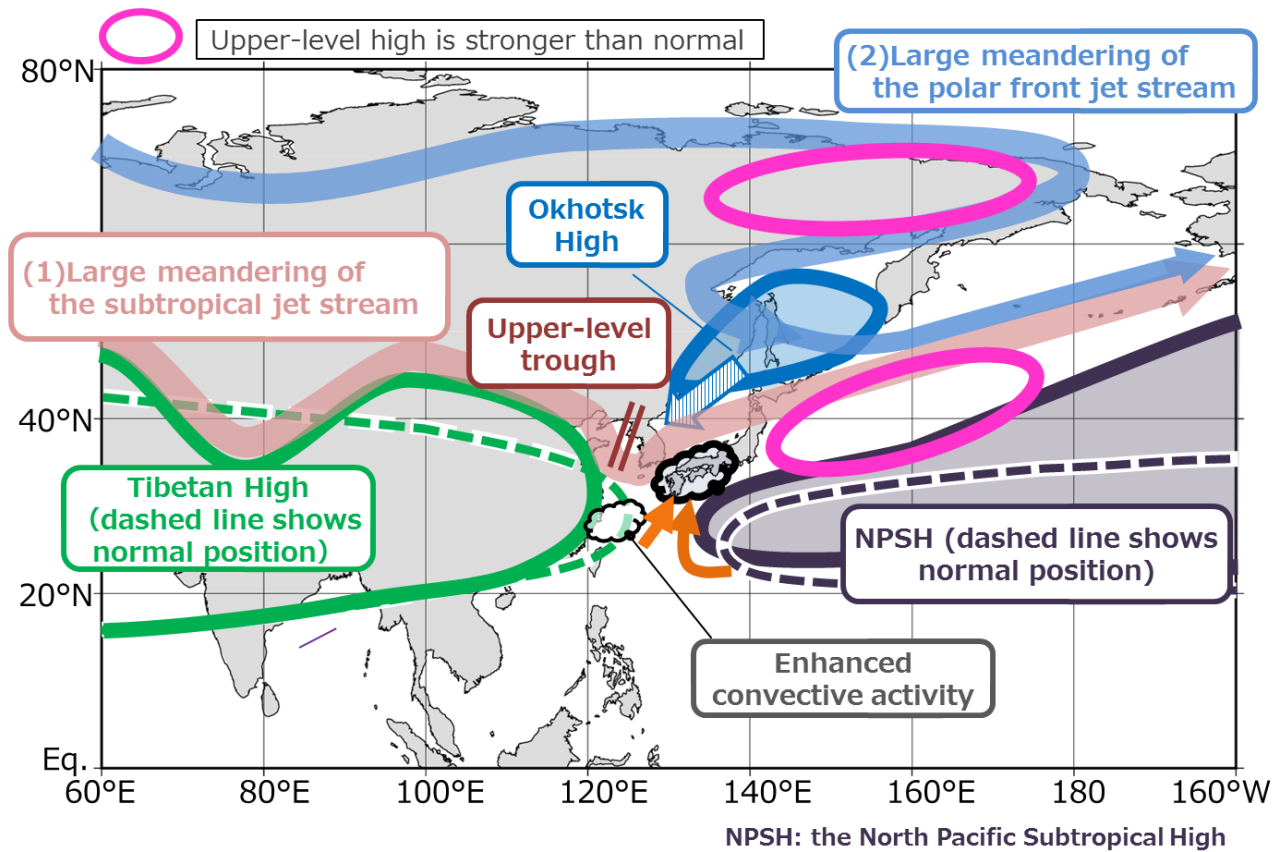
**Figure 1.2.4 Line-shaped precipitation system emergence in Hiroshima**

(Left) Distribution of three-hour cumulative precipitation amounts up to 9 p.m. on 6th July 2018. A line-shaped precipitation system formed in the vicinity of Hiroshima. (Right) Distribution of water vapor flux (shading), wind (arrows) and pressure (contours) at an altitude of 500 m at 6 p.m. on 6th July. The system developed at a time of air inflow with huge amounts of lower-level water vapor.

### 1.3 Primary factors behind large-scale atmospheric circulation

The primary factors behind the large-scale atmospheric circulation contributing to the heavy rain event detailed in Section 1.1 are illustrated in Figure 1.3.1. Numbers in parentheses below correspond to those in the figure.

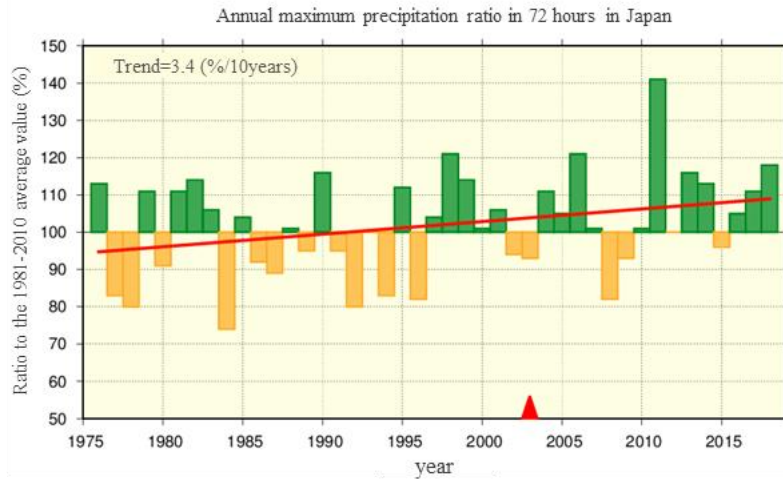
- The expansion of the NPSH to the southeast of Japan was caused by the significant and persistent northward meandering of the subtropical jet stream (STJ) to seas east of Japan in the upper troposphere (1) and the consequent development of a stationary high-pressure system there.
- The development of the Okhotsk High was caused by the significant and persistent meandering of the polar front jet stream (SPJ) in the upper troposphere (2) and the consequent development of a stationary high-pressure system over eastern Siberia.
- The persistent meandering of these two jet streams affected the positions and strength of the NPSH and the Okhotsk High, and the Baiu front remained stagnant over western Japan during the event.
- The upper-level trough lingering around the Korean Peninsula was associated with the southward meandering of the STJ in the area.
  - Meandering of the STJ over the Eurasian continent in boreal summer is sometimes observed in association with quasi-stationary Rossby wave propagation (teleconnection) along the jet stream. Its primary pattern is known as the Silk Road pattern (Enomoto et al. 2003).



**Figure 1.3.1 Primary factors behind the unprecedentedly heavy rain affecting areas from western Japan to the country's Tokai region from 5th to 8th July 2018**

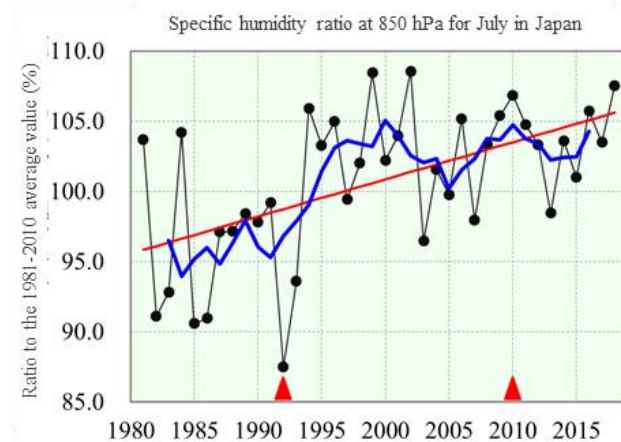
- Significant meandering of the STJ also occurred in late June, bringing the earliest-ever end to the Baiu (at the beginning of boreal summer) in the Kanto-Koshin region of Japan (preliminary evaluation).

On a longer time scale, a trend of increased intensity in extreme precipitation events in Japan is observed. Based on analysis using rainfall data from AMeDAS stations all over Japan, nationwide averages of the ratio of annual 72-hour maximum precipitation have increased by about 10% over the past 30 years (Figure 1.3.2). This is associated with a long-term trend of surface air temperature increase due to global warming and a similar increasing trend in the amount of water vapor in the air (Figure 1.3.3). It is widely known that when the atmospheric temperature increases by 1°C, the amount of water vapor in the atmosphere increases by approximately 7%. These observations suggest that the Heavy Rain Event of July 2018 may be linked to global warming.



**Figure 1.3.2 Annual maximum precipitation ratio in 72 hours from 1976 to 2018 in Japan**

This graph is based on precipitation data from 685 AMeDAS stations which have been continuously operated from 1976 to 2018. Bars indicate the ratio to the baseline (the 1981 – 2010 average), and the red line indicates the long-term linear trend (statistically significant at a confidence level of 90%). The value for 2018 is preliminary as of 1st of August. The red triangle marks the timing of a change in the observation method for precipitation (observed every hour before 2003 and every 10 minutes thereafter).



**Figure 1.3.3 Specific humidity ratio at 850 hPa for July from 1981 to 2018 in Japan**

The data are presented as ratios against the baseline (the 1981 – 2010 average).

Note: The term specific humidity refers to the mass of water vapor in a unit mass of moist air (g/kg). The data used in this analysis were based on radiosonde observations (balloon-borne instrument platforms with a radio-transmitting device) at 13 upper-air observation stations in Japan. The dots show the averages of the data for the 13 stations. The thick blue line indicates the five-year running mean, and the straight red line indicates the long-term linear trend (statistically significant at a confidence level of 99%). Data from the period marked by the red triangles may include biases due to instrument changes.

## 2. Heatwave in Japan from mid-July onward

### 2.1 Climate conditions

The Heavy Rain Event of July 2018 ended in association with the northward shift of the stationary Baiu front due to re-enhancement of the NPSH. This shift precipitated the withdrawal of the Baiu, and preliminary analysis indicates that the dates of withdrawal from Japan's Hokuriku region to the northern part of the Kyushu region were significantly earlier than those of the climatological normal. From mid-July onward, in association with an NPSH that was notably stronger than normal in the vicinity of Japan, area-averaged temperatures in northern, eastern and western Japan were significantly above normal (Figure 2.1.1). The monthly mean temperature anomaly for July 2018 in eastern Japan was  $+2.8^{\circ}\text{C}$ , which was the highest on record for July since 1946 when collection of the area-averaged statistical data referenced here began.

The daily maximum temperature was  $30^{\circ}\text{C}$  or more at many weather stations, with values exceeding  $35^{\circ}\text{C}$  also being recorded. Several stations reported maximum temperatures exceeding  $40^{\circ}\text{C}$  at the peak of the heatwave, and on 23rd July a new national record maximum temperature of  $41.1^{\circ}\text{C}$  was recorded in the Saitama Prefecture city of Kumagaya. A total of 130 AMeDAS stations reported record maximum temperatures after mid-July (as of 9th of August).

Figure 2.1.2 shows cumulative numbers of AMeDAS stations in Japan with daily temperatures of  $35^{\circ}\text{C}$  or more from 1st June to the end of September. The thick and thin red lines indicate cumulative numbers of stations from June 1st 2018 (as of 9th of August) and the period from 2013 to 2017, respectively. The dashed red line indicates cumulative numbers for 2010, when the annual total was the highest since 1976. Cumulative numbers for stations from June 2018 onward show unprecedented increases, and already exceeded 90% of the annual total for 2010 on 9th August.

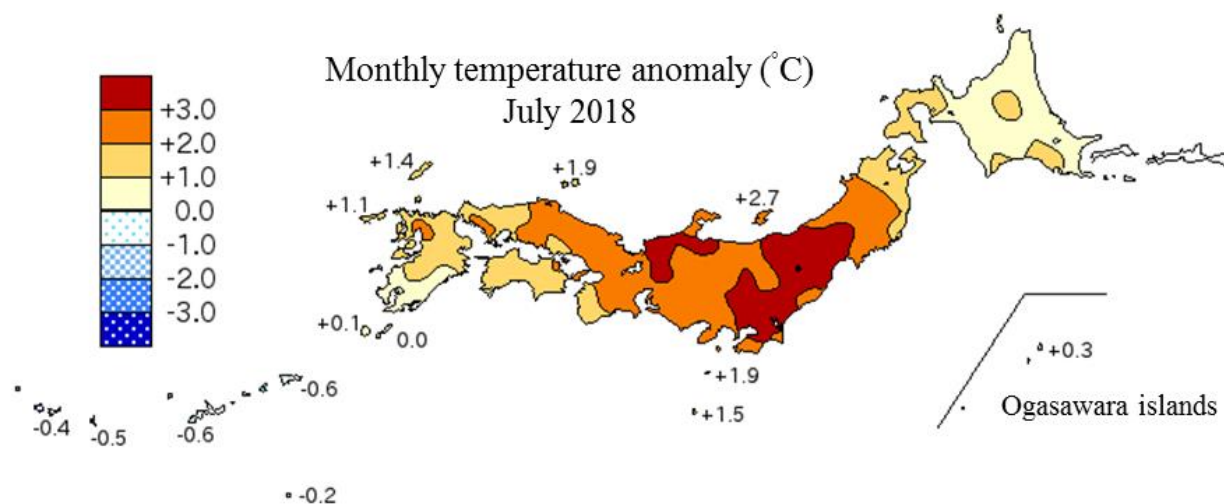
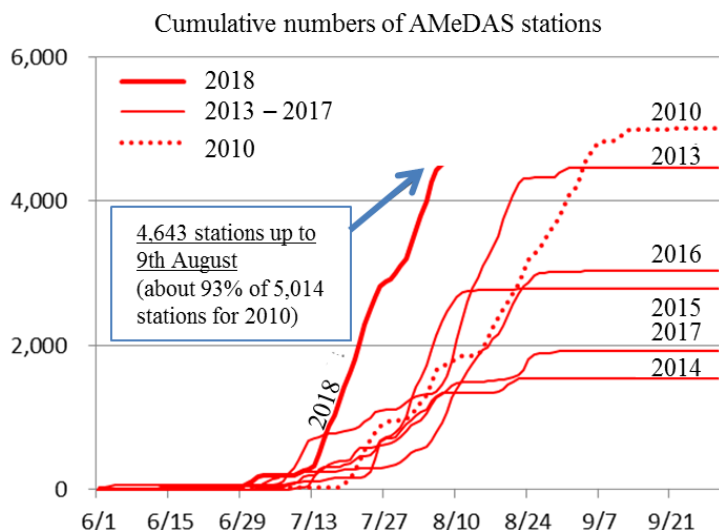


Figure 2.1.1 Monthly temperature anomaly (July 2018)



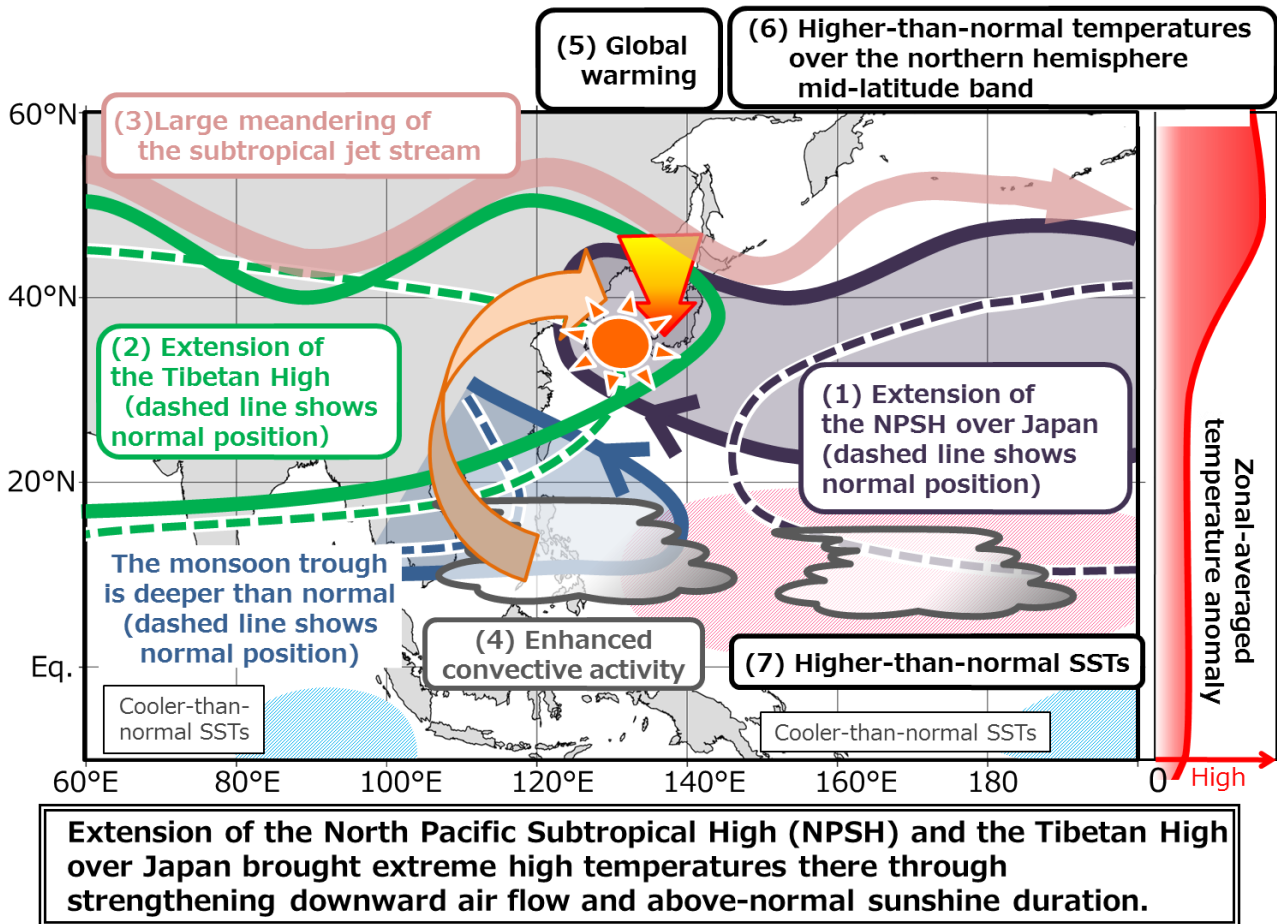
**Figure 2.1.2 Cumulative numbers of AMeDAS stations with daily maximum temperatures of 35°C or more**

Numbers of AMeDAS stations vary by year (2010: 918; 2013/2015/2018: 927; 2014: 923; 2016/2017: 929 (as of 1st June)).

## 2.2 Primary factors behind the heatwave

The primary factors behind the climatic conditions detailed in Section 2.1 are illustrated in Figure 2.2.1. Numbers in parentheses below correspond to those in the figure.

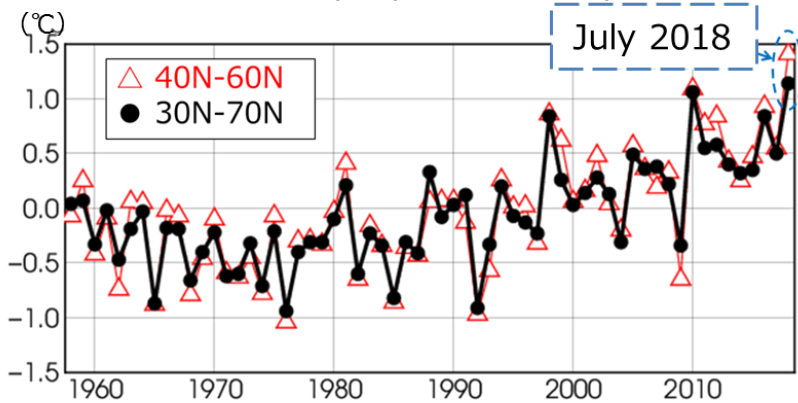
- Both the NPSH (1) and the Tibetan High (2), which govern Japan’s summer climate, expanded to the main islands of the country and persisted. Surface temperatures in Japan increased due mainly to high-pressure systems with warmer-than-normal air covering these islands, predominant sunny conditions and downward flow associated with these pressure systems.
- The expansion of the Tibetan High to Japan was attributable to the northward meandering of the STJ in the vicinity of Japan with varying but persistent extents (3).
  - The STJ meandered significantly and repeatedly over the area from the Eurasian continent to the sea east of Japan.
  - Northward meandering of the jet stream in the vicinity of Japan is considered to have also influenced the track of Typhoon Jondari (T1812), which moved westward after making landfall on mainland Japan in late July.
- The expansion of the NPSH in the vicinity of Japan appears attributable to enhanced convective activity over and around the Philippines (4) as well as the significant meandering of the subtropical jet stream cited above (3).
  - It is widely known that, while convective activity over and around the Philippines was enhanced in boreal summer, large-scale lower-level cyclonic circulation over the area from Southeast Asia to the Philippines (the monsoon trough) was strengthened and the NPSH in the vicinity of mainland Japan was accordingly enhanced and expanded in association with downward airflow in and around the country following upward airflow around the Philippines (the Pacific-Japan (PJ) pattern (Nitta 1987; Kosaka and Nakamura 2010)).



**Figure 2.2.1 Primary factors behind the unprecedentedly hot conditions observed from mid-July 2018 onward**

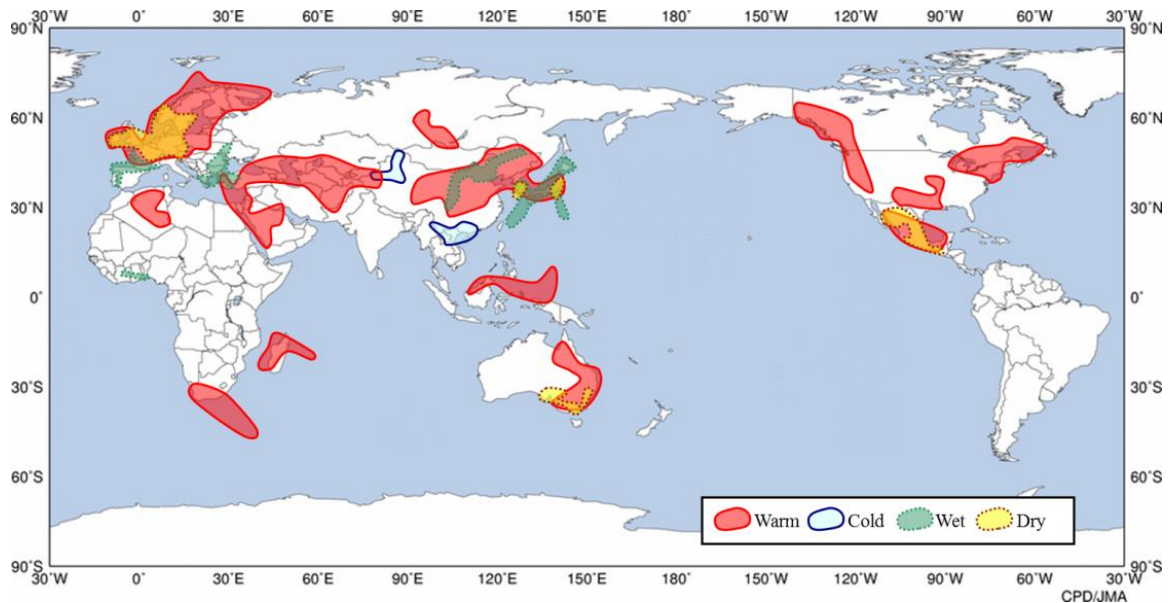
- In addition to the effects caused by the expansion of the NPSH (1) and the Tibetan High (2), the following factors are also considered responsible for a number of degrees in the increase of surface air temperatures during the heatwave:
  - The global surface air temperature has risen, due largely to global warming (5).
  - Zonally averaged tropospheric air temperatures in the mid-latitudes of the Northern Hemisphere were significantly higher than normal (6).
- Zonally averaged tropospheric air temperatures in the mid-latitudes of the Northern Hemisphere (e.g., 40 – 60°N) had been high since boreal spring, and the value for July 2018 was the highest for the month since 1958 (Figure 2.2.2). This was attributable to enhanced convective activity over a wide area of the Northern Hemisphere in association with higher-than-normal sea surface temperatures (SSTs) over the tropics in the Northern Hemisphere (7) and lower-than-normal SSTs in the Southern Hemisphere (Figure A6.2).

### Thickness temperature anomaly in the troposphere for July



**Figure 2.2.2 Interannual variations in zonally averaged thickness temperature anomalies in the troposphere for July**

Black dots and red triangles correspond to values averaged over the latitude bands 30 – 70°N and 40 – 60°N, respectively. Anomalies are deviations from the baseline (the 1981 – 2010 average).



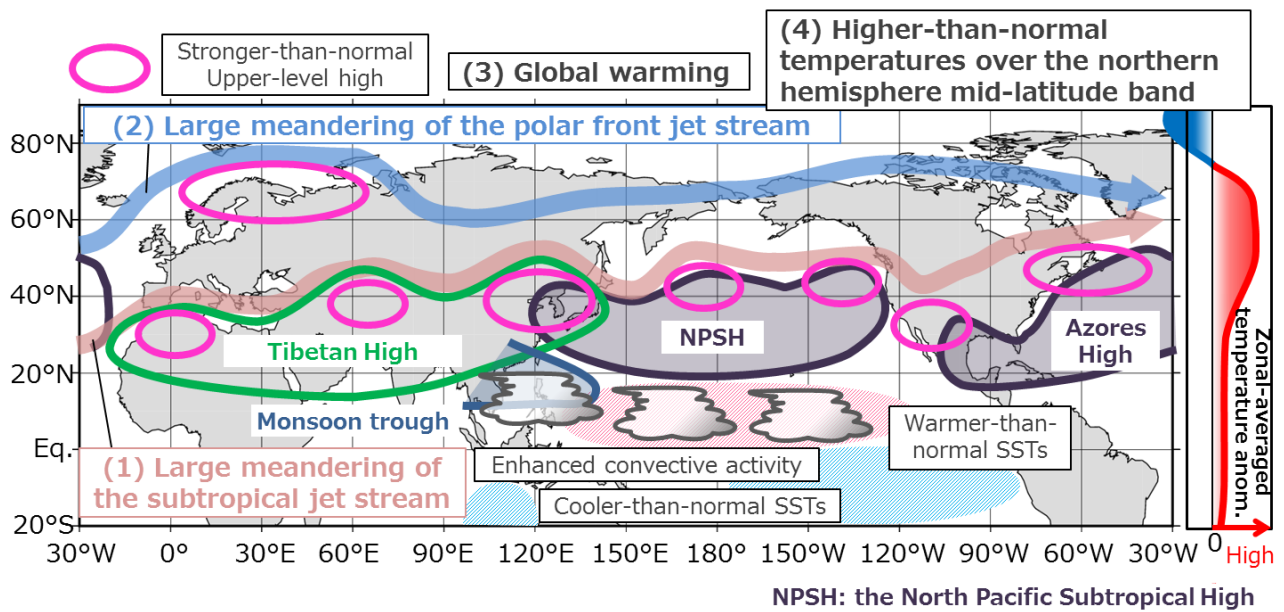
**Figure 2.2.3 Global extreme climate events in July 2018**

This figure shows overlaid climate extremes (warm, cold, wet and dry) from weekly reports for July on the Global Extreme Climate Events section of the TCC website

(<https://ds.data.jma.go.jp/tcc/tcc/products/climate/weekly/index.html>).

Figure 2.2.3 shows major extreme climate events, including the heatwave of July 2018. The World Meteorological Organization also reported extreme weather during the first half of summer in the Northern Hemisphere<sup>2</sup>. Extremely high temperatures in many regions of the world were attributable to significantly warmer-than-normal tropospheric atmospheric air (zonally averaged) in the mid-latitudes as well as global warming, in addition to increased surface temperatures caused by the northward shift and significant meandering of the STJ and the SPJ (Figure 2.2.4).

<sup>2</sup> <https://public.wmo.int/en/media/news/july-sees-extreme-weather-high-impacts>



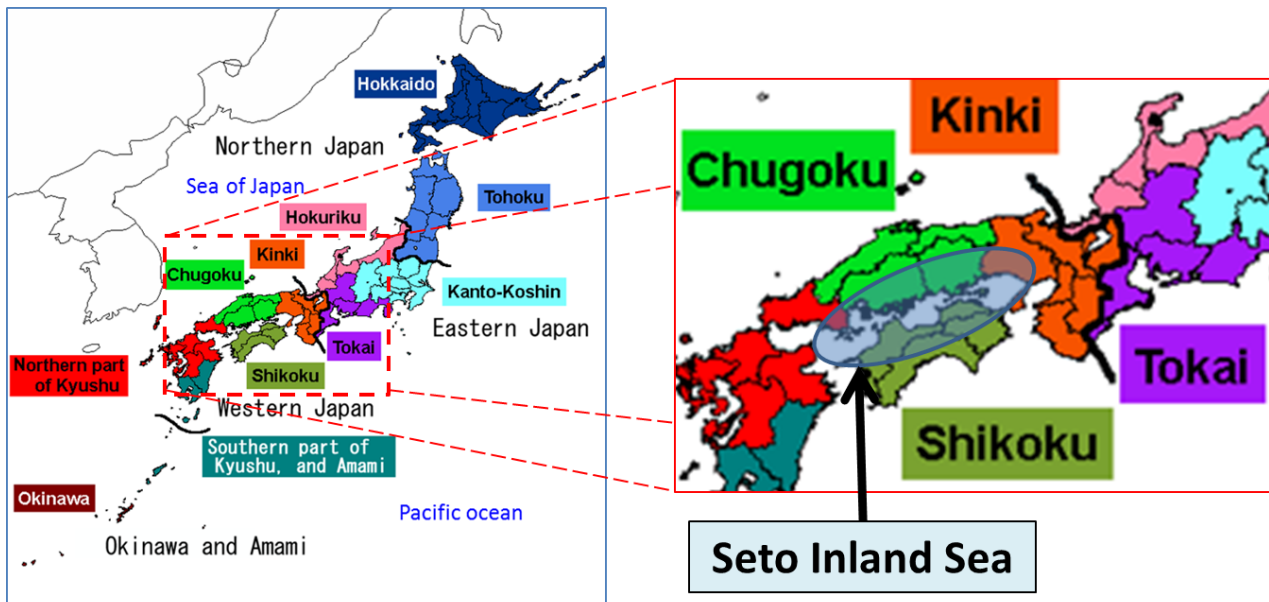
**Figure 2.2.4 Factors behind higher-than-normal temperatures across the Northern Hemisphere**

Areas where extreme high-temperature events occurred (see Figure 2.2.3) correspond closely to those where the subtropical and polar jet streams continued to significantly meander northward from the normal (e.g., over northern Europe).



## References

- Enomoto, T., B. J. Hoskins and Y. Matsuda, 2003: The formation mechanism of the Bonin high in August. *Quart. J. Roy. Meteor. Soc.*, 129, 157 – 178.
- Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan*, 93, 5 – 48.
- Kosaka, Y., and H. Nakamura, 2010: Mechanisms of meridional teleconnection observed between a summer monsoon system and a subtropical anticyclone. Part I: The Pacific-Japan pattern. *J. Climate*, 23, 5085 – 5108.
- Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation. *J. Meteor. Soc. Japan*, 65, 373 – 390.

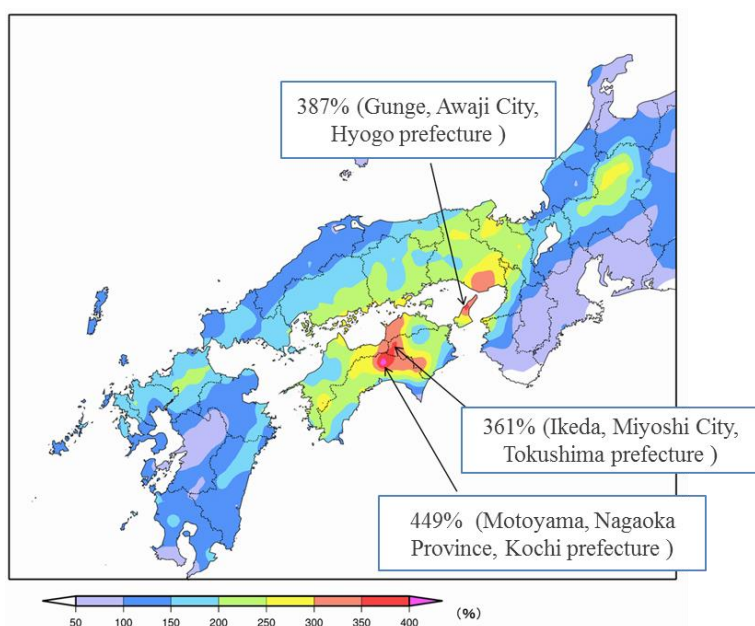


### **Climatological regions of Japan**

The country has four divisions (Northern, Eastern, Western Japan and Okinawa/Amami) and eleven subdivisions (Hokkaido, Tohoku, Kanto-Koshin, Hokuriku, Tokai, Kinki, Chugoku, Shikoku, northern Kyushu, southern Kyushu and Okinawa).

## 1. The Heavy Rain Event of July 2018

### (1) Characteristics of the Heavy Rainfall Event



**Figure A1.1 Ratios of total precipitation amounts in the heavy rain event (28th June to 8th July) against monthly precipitation normal for July**

**Table A1.1 Record precipitation totals at selected 966 AMeDAS stations all over Japan for any 10 days starting from 1st, 11th and 21st of the months since 1982**

Rank	All stations (mm)	1 station average (mm)	Period	Remarks
1	208,035.5	215.4	Early Jul. 2018	Heavy Rain Event of July 2018
2	199,967.0	207.0	Late Jun. 1985	Typhoon IRMA (T8506) and fronts
3	192,097.0	198.9	Late Oct. 2017	Typhoon LAN (T1721) and fronts
4	191,946.0	198.7	Middle Sep. 1990	Typhoon FLO (T9019) and fronts
5	174,047.0	180.2	Early Aug. 2014	Heavy Rain Event of August 2014
Ave.	46,580.6	48.2	–	–

**Table A1.2 Numbers of AMeDAS station where record-breaking maximum rainfall for respective hours reported**

Period	Duration (day)	Number of stations						Remark
		3 hrs	6 hrs	12 hrs	24 hrs	48 hrs	72 hrs	
28 <sup>th</sup> Jun. 2018 ~ 8 <sup>th</sup> Jul. 2018	11	16	31	48	76	124	122	Heavy Rain Event of July 2018
5 <sup>th</sup> Jul. 2017 ~ 6 <sup>th</sup> Jul. 2017	2	2	–	–	3	0	0	Heavy Rain Event of July 2017
9 <sup>th</sup> Sep. 2015 ~ 11 <sup>th</sup> Sep. 2015	3	9	–	–	16	17	18	Heavy Rain Event of September 2015
30 <sup>th</sup> Jul. 2014 ~ 26 <sup>th</sup> Aug. 2014	28	25	–	–	26	33	22	Heavy Rain Event of August 2014

## 1. The Heavy Rain Event of July 2018

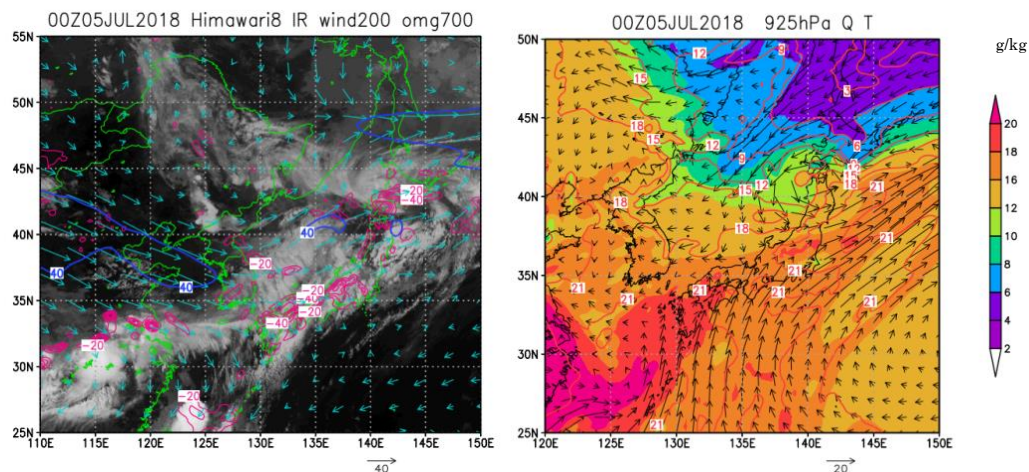
(2) Primary factors behind rainfall with relatively large temporal/spatial scales

(B) Persistence of upward flow associated with activation of the stationary Baiu front

This extreme precipitation event is characterized by a continuance of the heavy rainfall for several days. Factors that contributed to the heavy rainfall were investigated in detail and were found to vary with time.

### Stage 1: Intensification of the Baiu front due to cool airmass

At 09 am on 5th July, a broad band of clouds associated with the Baiu front covered the Honshu (i.e. the Japan Main Island), although the upper-tropospheric subtropical jet stream was still relatively weak. An extratropical low that transformed from Typhoon Prapiroon (T1807) was located to the west of the Tsugaru Strait. From the north of the ex-typhoon, a cool airmass associated with an anticyclone that has its center in the Sea of Okhotsk spread southward toward the northern part of the Sea of Japan, while in the southern part of the Sea of Japan was covered by a relatively warm and moist airmass. Therefore the lower-tropospheric moist air flowed into the Baiu front not only from the south but also from the north (see Figure A2.1). Afterward, the ex-typhoon moved to the east of Hokkaido, and a lower tropospheric cool moist airmass flowed southward above the Sea of Japan. Consequently, meridional temperature gradients were increased, and the heavy rainfall occurred on both the Pacific Ocean side and the Sea of Japan side of western Japan.



**Figure A2.1 (Left) Infrared satellite images with atmospherical data by JMA's global objective analysis at 9 am on 5th July. 200 hPa winds (blue arrows, unit: m/s) and isotachs (blue solid line, intervals of 20 m/s. Lines with more than 40 m/s are depicted) and 700 hPa vertical pressure velocity (red solid line, intervals of 20 hPa/h. Upward areas are depicted). (Right) 925 hPa winds (black arrows, unit: m/s), specific humidity (shade, unit: g/Kg) and isotherms (red solid lines).**

### Stage 2: Activation of the Baiu front due to approach of an significant upper tropospheric trough

On 6th and 7th July, an upper-tropospheric trough above the Korean Peninsula rapidly deepened. On the eastern side of the trough, the subtropical jet stream was accelerated, and a meso-scale low in the lower

troposphere was formed (Figure A2.2). These enhanced upward motion in the troposphere and the related moist airflow from the south. Thus the heavy rainfall occurred not only on the Pacific side of western Japan but also over the Seto Inland Sea side of the Chugoku and Shikoku regions. While heavy rainfall continued over the broad area, the heaviest rainfall area moved eastward associated with the eastward-moving upper trough.

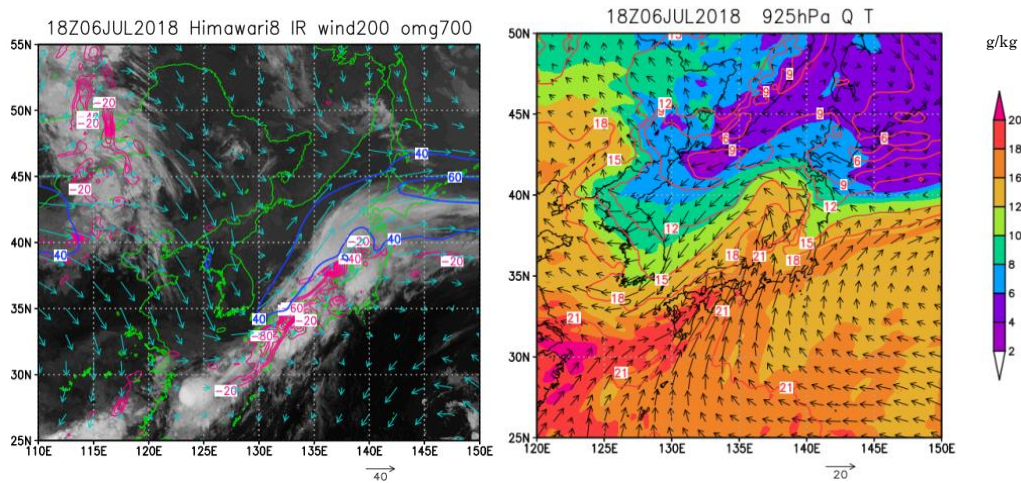


Figure A2.2 Same as Figure A2.1 but at 3 am on 7th July

Stage 3: Rainfall in the less stable troposphere in the western Japan after the passage of the upper trough

At 3 am on 8th July, the above-mentioned upper-tropospheric trough and the associated jet-acceleration area moved eastward and reached over the Kinki region, and the area of the upward motion and the cloud reached the Tokai region. The large-scale clouds were dissipated over western Japan, affected by the downward airflow below and west of the upper trough. However, the lower-tropospheric moist air was still flowed into over western Japan, where the atmospheric vertical stability decreased. Finally several meso-scale heavy rain events (so-called line-shaped precipitation systems) occurred along the Pacific coast of the Kyushu and Shikoku regions.

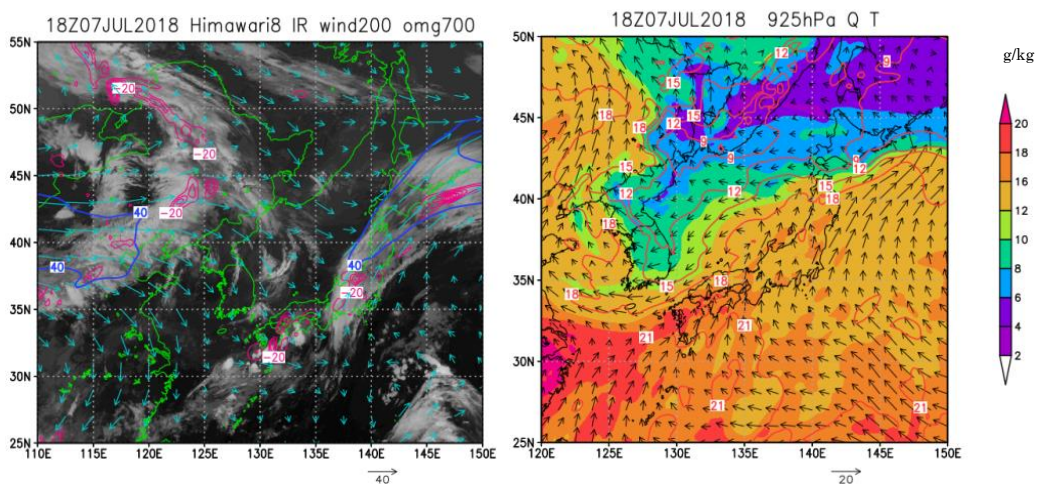


Figure A2.3 Same as Figure A2.1 but at 3 am on 8th July

## 1. The Heavy Rain Event of July 2018

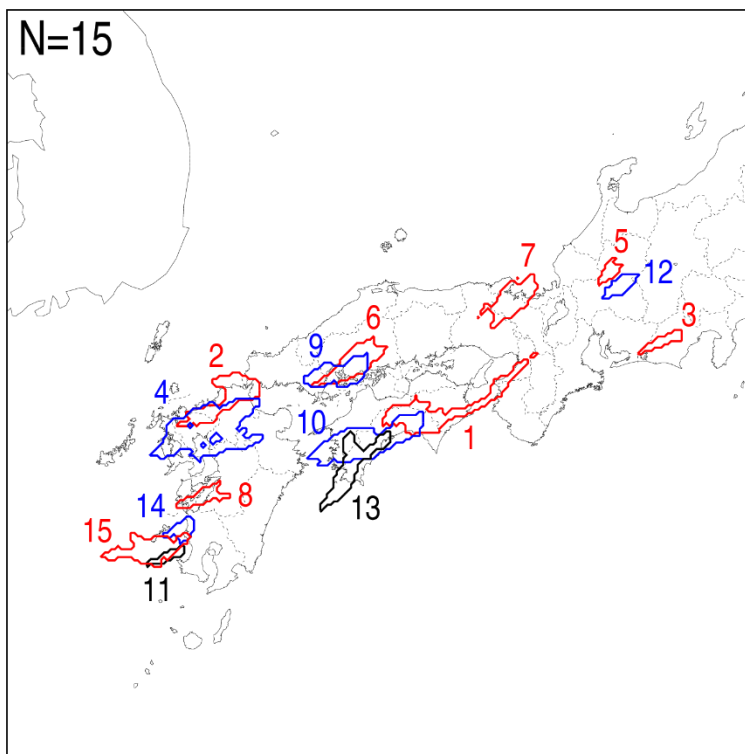
- (2) Primary factors behind rainfall with relatively large temporal/spatial scales
- (C) Characteristics of line-shaped precipitation systems

### Detection method for line-shaped precipitation systems and its contribution to the heavy rain event

In this summary report, line-shaped precipitation systems are defined as follows

- [1] Area whose shape is likely to be linear (ratio of the long axis to the short is more than 2) and area where three-hour cumulative precipitation amounts exceed 80 mm.
- [2] The size of the area exceeds 500 km<sup>2</sup>.
- [3] Maximum three-hour precipitation amounts exceeding 100 mm exists in the area cited in [1].

Several line-shaped precipitation systems, which are emerged in different times but the degrees of their continuity are judged to be high, are regarded as one identical. Based on this detection technique, 15 precipitation systems were confirmed over the wide area from the Tokai to Kyushu regions of Japan.



**Figure A3.1 Detected line-shaped precipitation systems from 5th to 9th July**

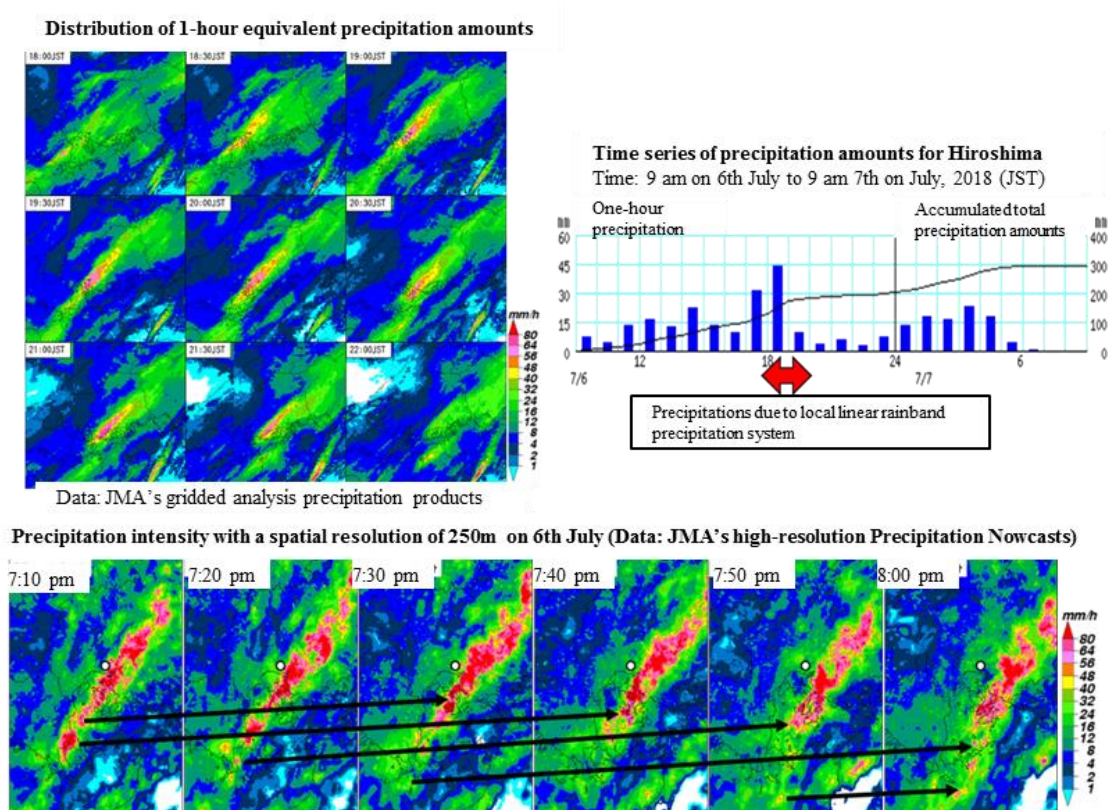
Different colors are used in the case when detected line-shaped precipitation systems overlap each other.

## 1. The Heavy Rain Event of July 2018

- (2) Primary factors behind rainfall with relatively large temporal/spatial scales
- (C) Characteristics of line-shaped precipitation systems

### Characteristics of line-shaped precipitation system observed in Hiroshima Prefecture

Some of the line-shaped precipitation systems observed in the night of 6th July in Hiroshima Prefecture had a back-building formation process. Time series graph on precipitation amounts in Hiroshima for the period when line-shaped precipitation system passes indicates a period with intense rainfall (period during red arrow on the upper-right panel) though percentage accounting for the rainfall amounts due to line-shaped precipitation systems against total precipitation were 30%.



**Figure A4.1 A line-shaped precipitation system observed in Hiroshima Prefecture**

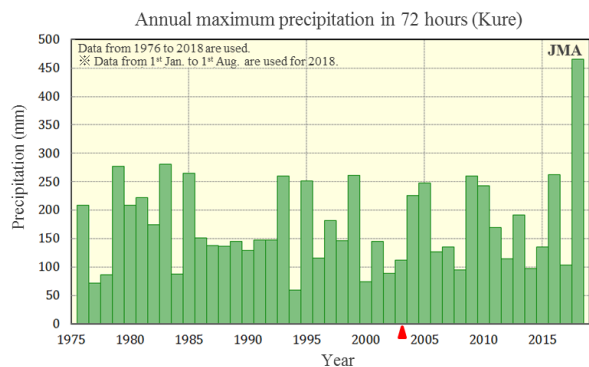
(Upper left) One-hour equivalent precipitation amounts by JMA's gridded analysis precipitation products at the interval of 30 minutes from 6 pm to 10 pm on 6th July. (Upper right) Time-series of precipitation amounts for Hiroshima observed at an AMeDAS station from 9 am on 6th July to 9 am on 7th July, 2018. (Bottom) Precipitation intensity shown by the JMA's high-resolution precipitation nowcasts products<sup>3</sup> from 7:10 pm to 8:00 pm on 6th July (JST) at the interval of 10 minutes. Black arrows indicate movements of cumulonimbus cloud during the process of forming a line-shaped precipitation system. Back-building process was seen during the formation. White dots indicate the location of Hiroshima City.

<sup>3</sup> [https://www.jma.go.jp/jma/en/Activities/highres\\_nowcast.html](https://www.jma.go.jp/jma/en/Activities/highres_nowcast.html)

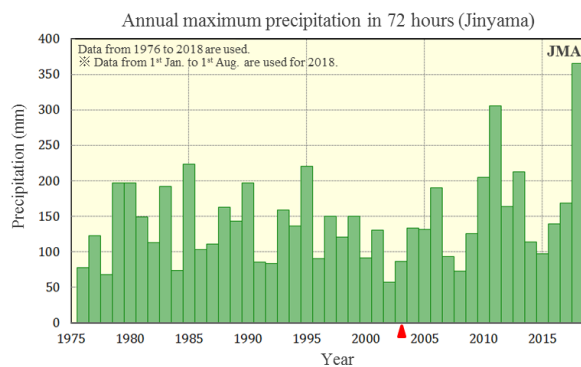
## 1. The Heavy Rain Event of July 2018

### (3) Primary factors behind large-scale atmospheric circulations

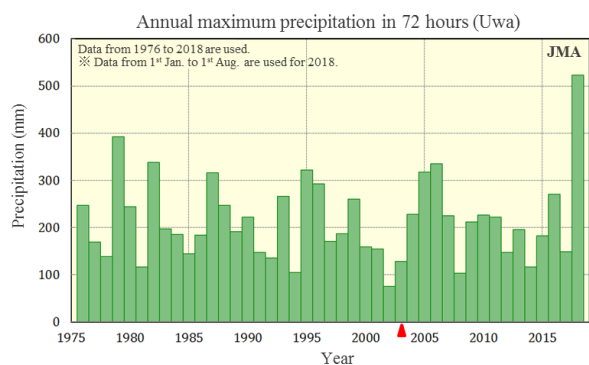
#### (a) Kure, Hiroshima Prefecture



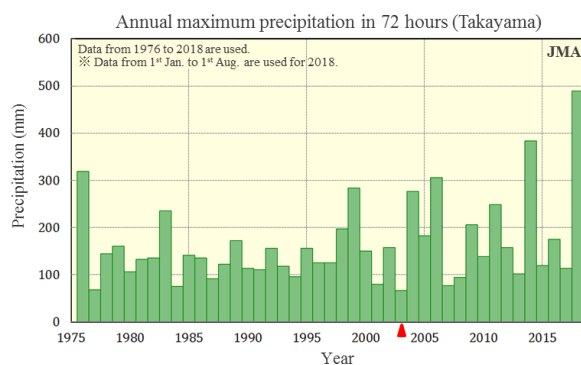
#### (b) Jinyama, Okayama Prefecture



#### (c) Uwa, Ehime Prefecture



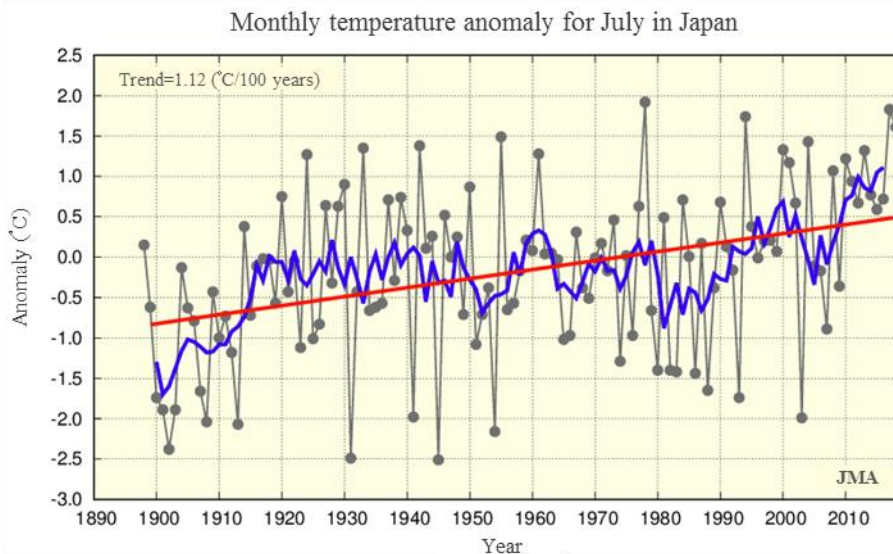
#### (d) Takayama, Gifu Prefecture



**Figure A5.1 Annual maximum precipitation in 72 hours observed at AMeDAS stations from 1976 to 2018**  
The data for 2018 is based on observation up to 1st of August 2018. The red triangle marks the timing of a change in the observation method for precipitation (observed every hour before 2003 and every 10 minutes thereafter).

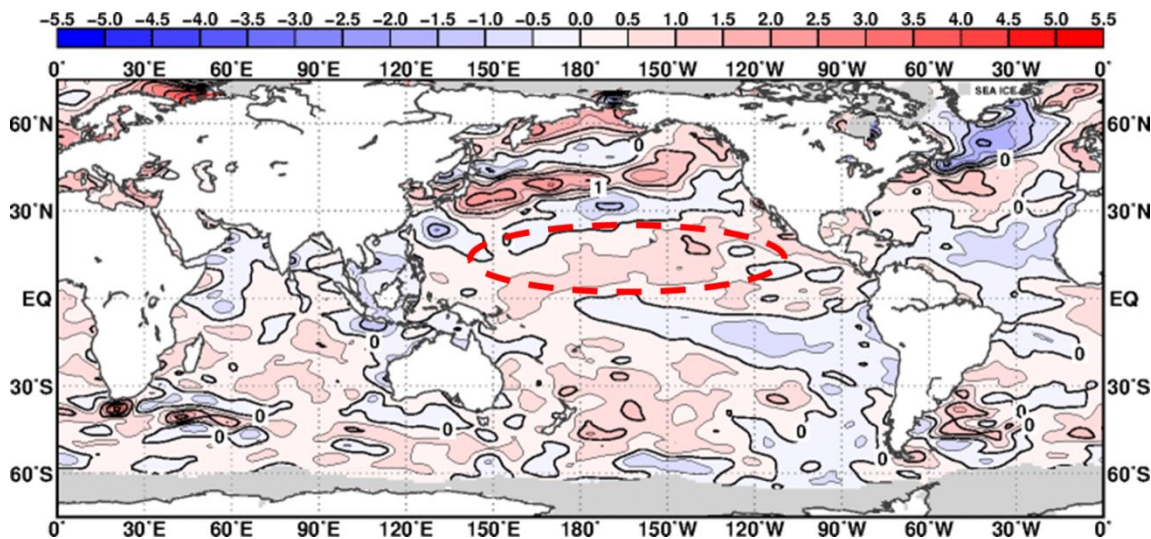
2. Heatwave in Japan from the mid-July onward

(2) 2.2 Primary factors behind the heatwave



**Figure A6.1 Monthly surface temperature anomalies for July from 1898 to 2018 in Japan**

The thin black line with dots indicates monthly surface temperature anomaly averaged over 15 observation stations for each year. The blue line indicates the five-year running mean, and the red line indicates the long-term linear trend (statistically significant at a confidence level of 99%). Anomalies are deviations from the baseline (the 1981 – 2010 average).



**Figure A6.2 Monthly mean sea surface temperature anomaly ( July 2018)**

The contour interval is 0.5 °C. The base period for the normal is 1981 – 2010. Maximum coverage with sea ice is shaded in gray. The red oval locating tropical Northern Hemisphere indicates higher SST than normal referred by the body text.