Climate characteristics and factors behind extremely high temperatures from July onward and heavy rainfall in late July 2024

18 October 2024
Tokyo Climate Center (TCC), Japan Meteorological Agency (JMA)
https://www.data.jma.go.jp/tcc/tcc

Summary

Record-high temperatures were observed nationwide in Japan in July 2024, with the national average even exceeding the previous July 2023 record. This persisted into August, with unprecedented temperatures in western Japan (Figure A1). Heavy rainfall was observed in northern Japan in late July, with the second-highest-ever levels on the Sea of Japan side.

The factors behind these phenomena can be summarized as follows:

- Extremely high temperatures from July onward
  - The subtropical jet stream (STJ) persistently meandered northward near Japan. Areas of western Japan and elsewhere were covered by a warm high extending into the upper troposphere.
  - In July the North Pacific Subtropical High (NPSH) was persistently enhanced south of Japan and extended to western parts of the country. This may be attributable to active cumulus convection over the northern Indian Ocean.
  - In addition to enhanced solar radiation in the high-pressure area, temperatures rose with downward motion.
  - Sea surface temperatures (SSTs) around Japan were extremely higher than normal.
  - In addition to long-term global warming, temperatures in the mid-latitudes of the Northern Hemisphere were record high due to an El Niño event that continued until spring and other factors.

- Heavy rainfall over northern Japan in late July
  - The northward flow of water vapor was strengthened between the NPSH extending to western Japan and Typhoon Gaemi, which moved northwestward over southern China, and the enhanced water vapor flow into the Baiu front[1], which had stagnated in northern Japan, thereby enhancing frontal activity.
  - Abundant water vapor may have come from seas around Okinawa/Amami due to high SSTs.
  - In combination with middle-level cold air, stationary mesoscale convective systems (SMCSs) developed, resulting in unprecedented rainfall.

- Effects of global warming

The joint research team in Advanced Studies of Climate Change Projection at Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) conducted a preliminary assessment using event attribution to evaluate the effects of global warming on these extreme events. The findings indicated that the high temperatures observed would not have occurred in the absence of global warming, which may also have contributed to the heavy rainfall events.

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[1] The Baiu is a period of cloudy and rainy weather in early summer in Japan. The phenomenon is climatologically characterized by the stagnation of a Baiu front extending from west to east.

Introduction

This report summarizes discussions among the JMA Advisory Panel on Extreme Climatic Events (comprised of prominent climate science academics and researchers) held on 2 September 2024 to identify possible causative factors behind the extreme meteorological conditions observed in summer 2024. It should be noted that the details here are as of the time of the meeting.

Analysis of large-scale atmospheric circulation is based on the Japanese Reanalysis for Three Quarters of a Century (JRA-3Q)[2].

1. Climatic factors behind extremely high temperatures from July onward

1-1 High temperatures[3]

○ **July**

- Extremely high monthly mean temperatures nationwide (Figure 1-1)
  - Eastern/western Japan and Okinawa/Amami were affected by downward motion and enhanced solar radiation associated with the NPSH. Warm-air inflow from the south over northern Japan brought considerably higher monthly average temperatures than normal nationwide.
  - The monthly mean temperature anomaly in July was +2.3°C in eastern Japan and an unprecedented +1.3°C in Okinawa/Amami – the highest for the month since records began in 1946.
  - A total of 62 among 153 observation stations in Japan observed the highest monthly average temperatures on record for July (including joint records at 12 stations).

○ **August**

- Noticeably high temperatures persisting in western Japan and elsewhere
  - Over the sea to the southeast of Japan, the NPSH weakened and a cyclonic system formed in the lower troposphere through the middle of the month.
  - However, the area around Japan remained covered by a tall, warm high with a center in the upper level, and continued to be affected by downward motion and enhanced solar radiation over western parts and elsewhere.

○ **July and August**

- July and August are the hottest months even in normal years. Sano (Tochigi Prefecture) recorded 41.0°C on July 29, close to the national daily maximum record (41.1°C).
- A total of 144 among 914 observation stations nationwide set high daily maximum temperature records for the entire year from July 1 to August 31 (including joint records).
- The number of stations observing extremely hot days (daily maximums of 35°C or higher) continued to increase from late July onward. By mid-August the number had

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2 https://jra.kishou.go.jp/JRA-3Q/index_en.html

3 For details of summer 2024 weather in Japan, see “Climate report over Japan” on the TCC website (https://www.data.jma.go.jp/tcc/tcc/products/japan/index.html).

exceeded that at the end of August 2023, when the national average summer temperature was the highest to date (Figure 1-2) at the time.

- Figure 1-2 shows the total number of extremely hot days observed at Automated Meteorological Data Acquisition System (AMeDAS) stations nationwide from June 1 to August 31, with years featuring particularly high average summer temperatures (2010, 2013, 2018, 2022 and 2023) listed for comparison.

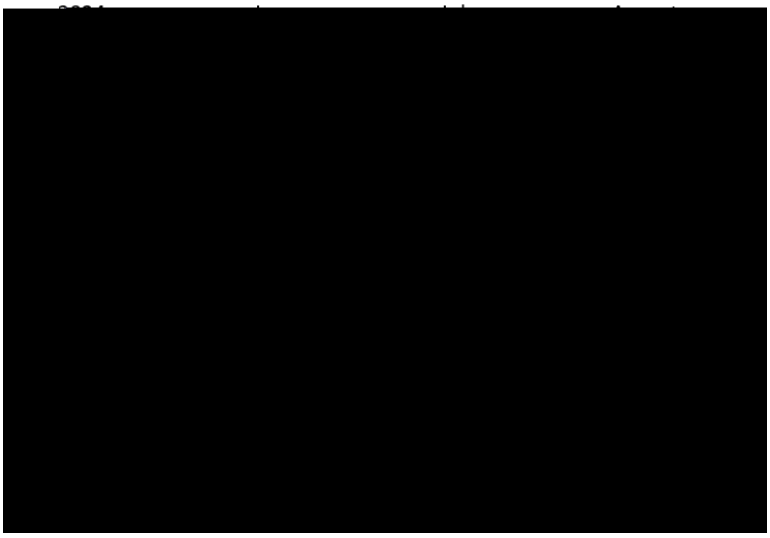

Figure 1-1 Five-day moving-average regional mean temperature anomalies from June to August 2024
The circled numbers and values in red indicate the rank of mean temperatures since 1946 for each month and season (up to the top three).

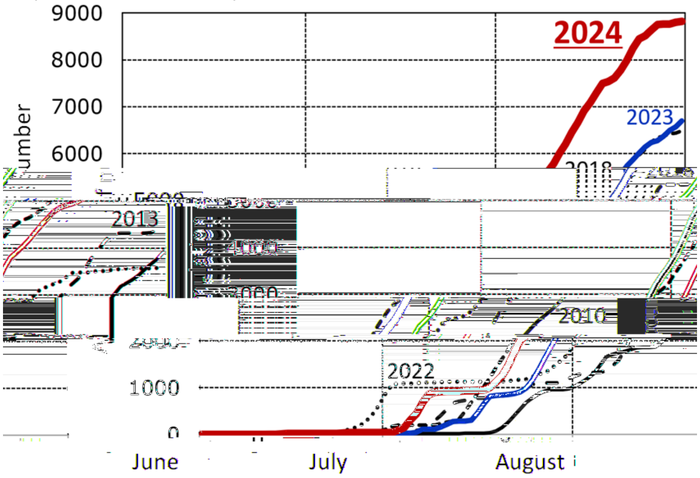

Figure 1-2 Cumulative number of extremely hot days observed at AMeDAS stations nationwide
The figure shows cumulative number of extremely hot days from June 1 to August 31, 2024 (red) and for major hot years since 2010. The numbers of AMeDAS stations as of April 1 were 919 for 2010, 927 for 2013 and 2018, 914 for 2022, 915 for 2023 and 914 for 2024.

○ Japan-wide characteristics

- The deviation of the national average July temperature[4] from the base value, which is used to monitor long-term climate change elements such as global warming, was +2.16°C, exceeding the previous year's record and the highest for July since records began in 1898 (Figure 1-3).
- June and August were both the second hottest on record, and summer as a whole (June – August) was the hottest on record, matching the previous summer's high-temperature record (+1.76°C above normal).
- The June – August average SST anomaly in seas around Japan was also +1.5°C, making it the warmest since records began in 1982.

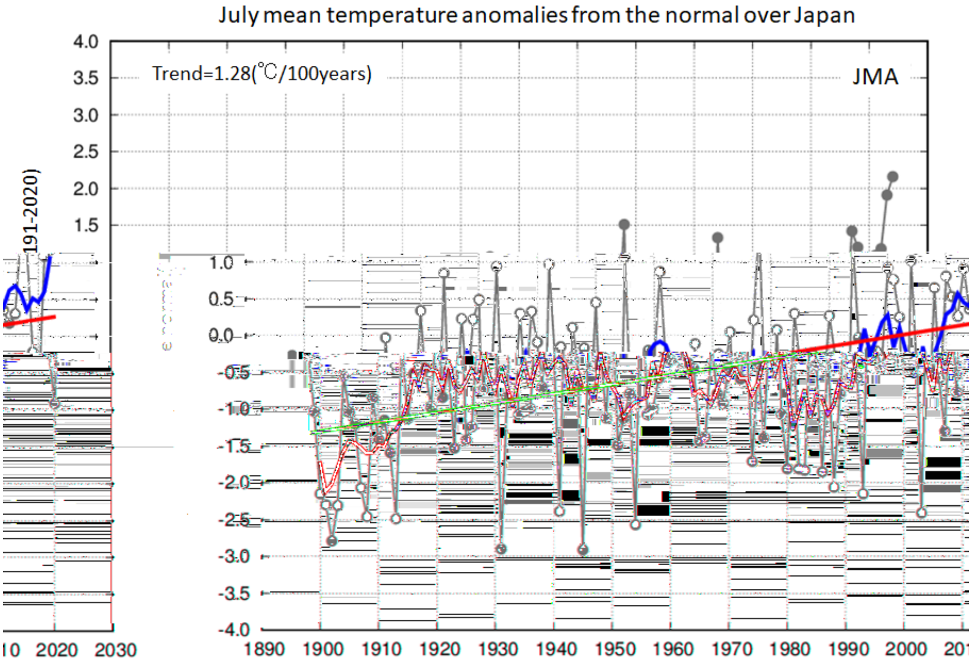

Figure 1-3 July mean temperature anomalies over Japan for 1898 – 2024
The base value for the anomaly is the 30-year average from 1991 to 2020. The grey line shows average deviations from the base value for each year at 15 stations in Japan, the blue line shows the five-year running mean of the anomaly, and the red line shows the long-term average trend.

1-2 Large-scale atmospheric flow resulting in high temperatures

In July the NPSH was enhanced over the sea to the south of Japan (Figure 1-4), but weakened in the first half of August over the sea to the southeast of the country in association with a large low-level cyclonic system in the region. Given these changes in atmospheric flow, the factors contributing to the high temperatures in July and August are described separately here. The effects of high SSTs around Japan and persistent high temperatures in the troposphere are common to both months.

[4] Average temperature anomalies for Japan are based on 15 observation stations (Abashiri, Nemuro, Suttsu, Yamagata, Ishinomaki, Fushiki, Iida, Choshi, Sakai, Hamada, Hikone, Miyazaki, Tadotsu, Naze and Ishigakijima) to ensure long-term homogeneity of data and distribution without regional bias among sites with limited environmental change caused by urbanization.

(1) Atmospheric flow

○ July

Items 1- 5 below correspond to (1) to (5) in Figure 1-5.

1. To the south of Japan, the NPSH strongly extended to the country throughout July, with noticeably enhanced monthly averages. The STJ meandered northward near Japan in early and late July, and a tall, warm high extended to western Japan and elsewhere.
   - This resulted in a persistent inflow of warm, moist air over northern Japan from the periphery of the NPSH, while the Pacific side areas west of eastern Japan were susceptible to the effects of persistent downward motion in a tall high and enhanced solar radiation due to clear skies. The Foehn phenomenon, where wind blows down over mountains on the Pacific side of northern and eastern Japan, also contributed to a marked increase in surface air temperatures.
2. The persistence of the enhanced NPSH to the south of Japan is associated with a weakening of convergence among lower-level winds over the sea east of the Philippines. This is considered due to weakening of low-level Asian Monsoon westerly winds from around the South China Sea to the sea east of the Philippines, associated with enhanced cumulus convective activity over the northern Indian Ocean.
3. The enhanced cumulus convective activity over the Indian Ocean is associated with persistent above-normal SSTs in the Indian Ocean due to the El Niño event that ended in spring 2024 and the positive Indian Ocean Dipole mode event[5] that occurred from summer to autumn 2023, in addition to periodic fluctuations in summer cumulus convective activity.
4. In late July, an area of active cumulus convection associated with Typhoon Gaemi moved northwestward over the sea to the east of the Philippines. In conjunction, the NPSH strongly extended toward western Japan (Pacific-Japan (PJ) pattern).
5. The northern shift of the STJ near Japan in early and late July is associated with the meandering of the STJ due to Silk Road teleconnection from Europe.

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[5] In the tropical Indian Ocean, SSTs and atmospheric convective activity were anomalous against the normal, with opposite signs in the east and west from summer to autumn, lower temperatures, inactivity to the southeast, and high temperatures/activity in the western part of the tropical Indian Ocean (known as a positive Indian Ocean Dipole, or IOD). Warm water created by the IOD in the ocean may have moved slowly westward across the equatorial Indian Ocean during the following spring, keeping SSTs high.

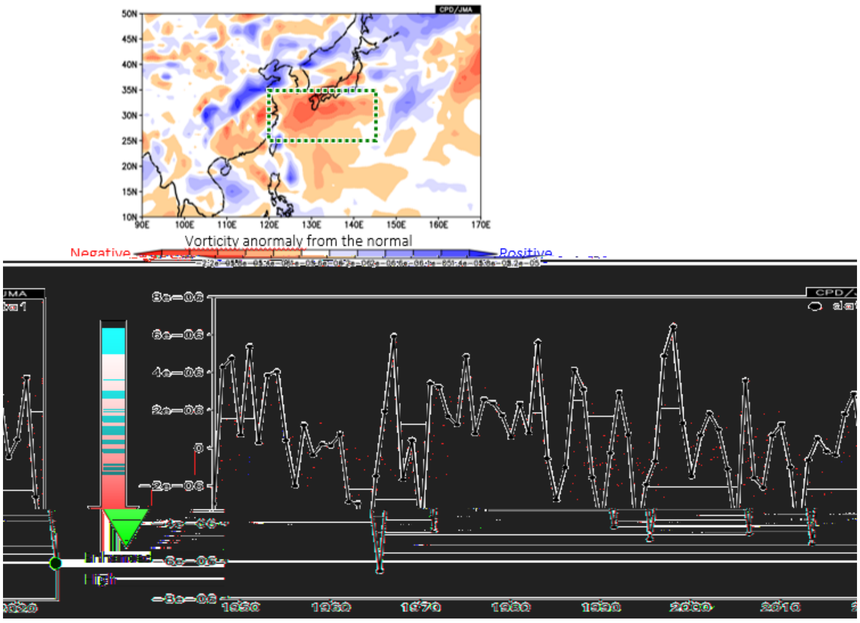

Figure 1-4 July 2024 anomalous enhancement of the NPSH from the normal (top) and interannual variation of July NPSH intensity to the south of Japan (bottom) Top: distribution of relative vorticity anomalies, with larger negative and positive values indicating stronger and weaker highs, respectively. Bottom: interannual variation in intensity of the high (relative vorticity anomaly) in July averaged over the lower troposphere (approx. 1,500 m altitude) in the top green box (25 – 35°N, 120 – 145°E). Higher negative values indicate stronger highs (unit: s^{-1}).

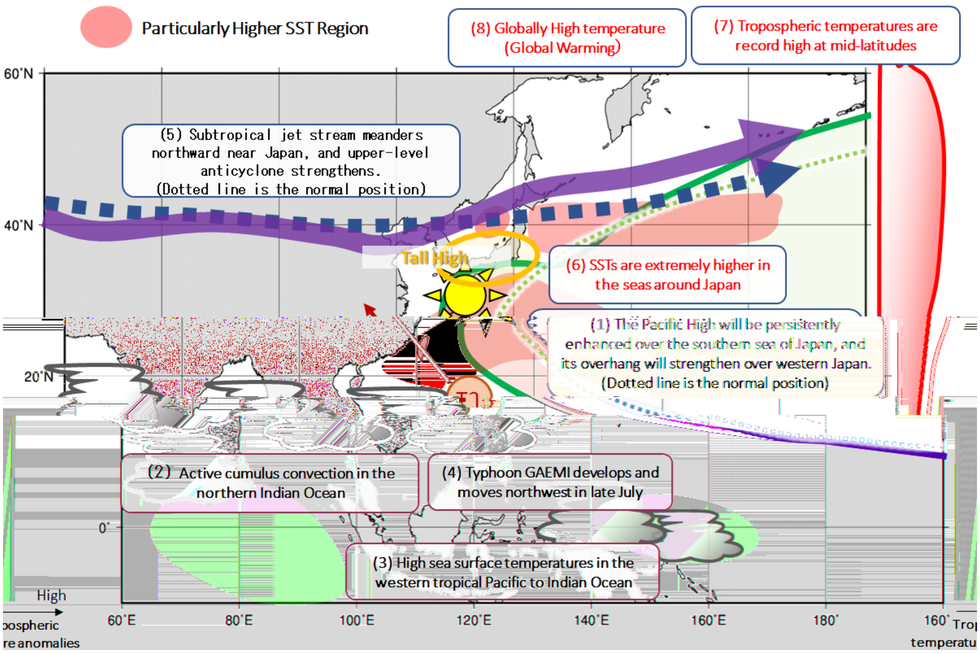

Figure 1-5 Large-scale atmospheric flow producing extremely high temperatures in July

○ **Early-to-mid August**

Items (a) – (g) below correspond to (a) to (g) in Figure 1-6.

(a) The STJ markedly meandered northward over Japan and to the east, and a tall, warm anticyclone covered the country, resulting in high temperatures nationwide. Western parts were particularly susceptible to the effects of persistent downward motion in anticyclonic areas and enhanced solar radiation due to clear skies, producing record-high temperatures.

These factors had a major influence on the northward meandering of the STJ near and east of Japan:

(b) Meandering of the STJ (due to Silk Road teleconnection from Europe)

(c) Enhanced cumulus convective activity to the southeast of Japan

The following processes are considered to be associated with the enhancement of cumulus convective activity over seas southeast of Japan:

- In association with the STJ meandering northward over Japan from late July to early August, cyclonic vortices detached from the upper-level trough and moved southward and westward east of Japan.
- These vortices, with cold air in upper levels, brought conditions favorable for ascent development.
- High SSTs in the area may have also contributed to enhanced cumulus convective activity.

(d) With the increased cumulus convective activity in the area, a large-scale lower-level cyclone formed to the southeast of Japan in the first half of August, along with tropical cyclones Maria, Son-Tinh, Ampil and Wukong.

(e) The maintenance of this low may be related to the formation of a lower-level anticyclone around the South China Sea due to inactive cumulus convective activity in the area.

(f) This low-level anticyclone formation may have been also influenced by active cumulus convection in the Indian Ocean.

(g) As the NPSH extended northward over the sea east of Japan in conjunction with the northward meandering of the STJ, a series of tropical cyclones developing by mid-August moved northward over seas to the east of Japan along the periphery of the NPSH.

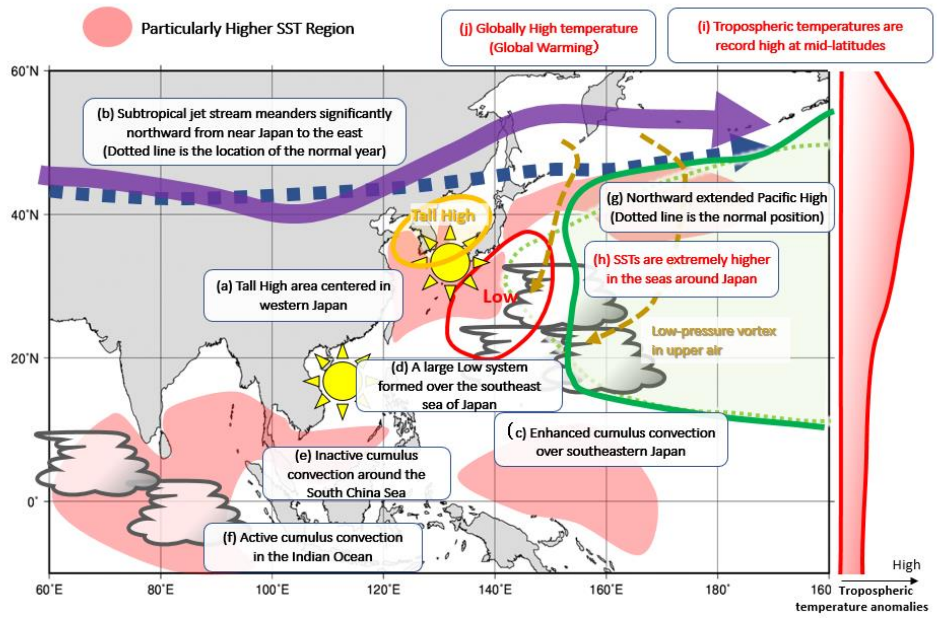

Figure 1-6 Large-scale atmospheric conditions relating to extremely high temperatures in August (based on data up to mid-August)

(2) Effects of extremely high SSTs around Japan

- SSTs were much higher than normal around northern Japan (Figure 1-7), especially off the Sanriku region, and subsurface ocean temperatures were higher (Figure 1-8), although not as high as 2023 due to the northward migration of the Kuroshio Extension (KE) and a warm-water eddy detached from the KEs.
- The record-high surface air temperatures in northern Japan in summer 2023 were likely influenced by a marine heat wave (extremely high SSTs)in the surrounding seas[6]. The effect of a marine heatwave on the high surface air temperatures of northern Japan in July 2024 was evaluated using the same method.
- The ocean directly heated the atmosphere in the area from just off Sanriku to just off the Pacific coast of Hokkaido in July, and the area around northern Japan remained hotter and more humid than normal near the ground surface, which enhanced the greenhouse effect (Figures 1-5 (6) and 1-6 (h)). However, unlike the previous July, northern Japan was more susceptible to the influence of the Baiu front, resulting in a limitation of enhanced solar radiation due to reduced lower-level cloud cover.
- Around Okinawa/Amami, SSTs were much higher from July onward due to heating with enhanced solar radiation associated with the intensified NPSH from late June to mid-July and extremely high subsurface ocean temperatures (Figure 1-7).
  - Since the ocean exerted enhanced directly heating to the atmosphere and the strongest

[6] Hirotaka Sato, Kazuto Takemura, Akira Ito, Takafumi Umeda, Shuhei Maeda, Youichi Tanimoto, Masami Nonaka, Hisashi Nakamura (2024): (Press release: https://www.data.jma.go.jp/tcc/data/news/press_20240815.pdf)

temperature anomalies were found in the lowest layer of the atmosphere (Figure 1-9), high SSTs around Okinawa/Amami may have contributed to the record-high surface air temperatures there in July.

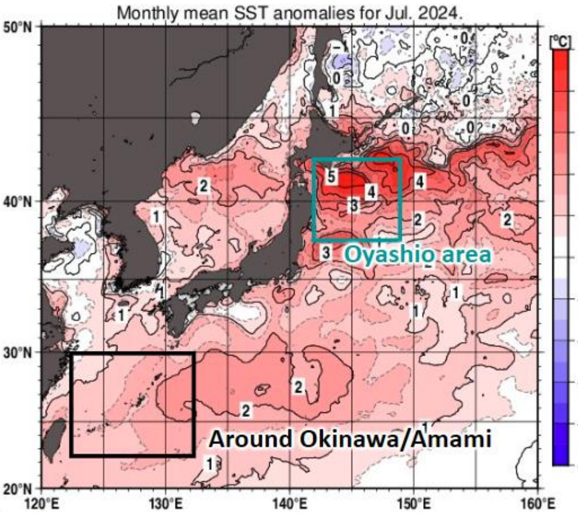

Figure 1-7 July SST anomalies around Japan

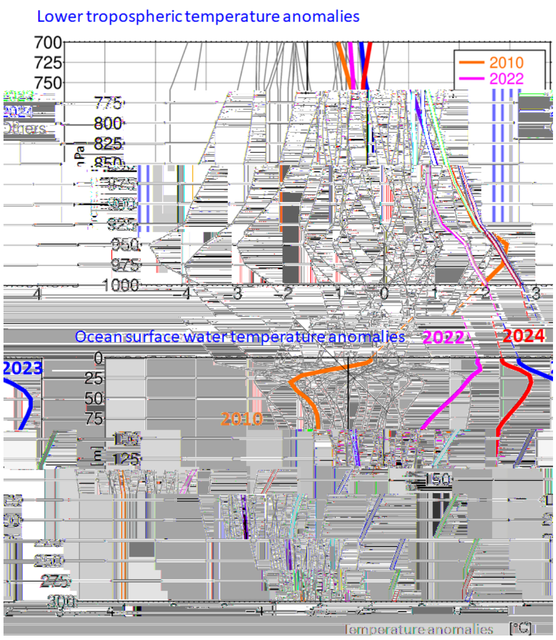

Figure 1-8 Vertical profiles of air and water temperature anomalies averaged over the Oyashio region (Figure 1-7)

July averages for each year from 1993 to 2024. Years with air-temperature anomalies increasing in the lowermost layers and high surface water temperatures in the lowest layers (2024, 2023 and 2022) and the year with temperatures that were higher than normal but lower than normal surface water (2010) are colored accordingly, with grey for other years.

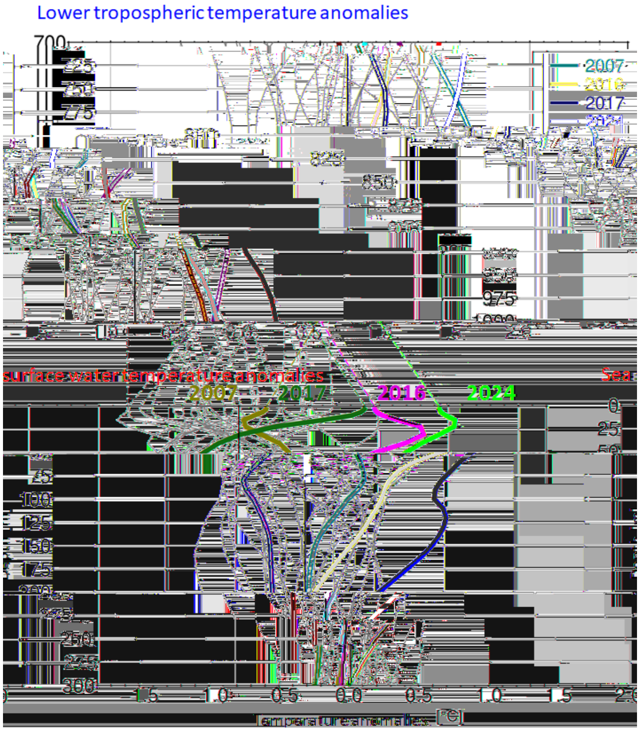

Figure 1-9 Vertical profiles of temperature anomalies averaged over waters around Okinawa/Amami (Figure 1-7)
As per Figure 1-8, but for target regions

(3) Effects of persistent high tropospheric temperatures

- The El Niño event that persisted until spring 2024 brought about record-high tropospheric temperatures in the tropics and mid-latitudes of the Northern Hemisphere. This contributed to the record-high temperatures in Japan in summer, as well as a long-term upward trend of global-scale temperatures associated with global warming (Figures 1-5 (7) (8) and 1-6 (i) (j)).
  - ➢ The persistence of above-normal SSTs in the mid-latitude North Pacific and North Atlantic may have influenced mid-latitude tropospheric temperatures.

1-3 Influence of global warming on record-high temperatures in July

A joint research team from MEXT's Advanced Studies of Climate Change Projection initiative conducted a preliminary climate model reproduction experiment using predictive event attribution method[7] to assess the effects of global warming, and estimated the probability of such a high-temperature event (Figure 1-10) as approximately 1 in 10 years with the effects of SST distribution and global warming (under actual climate conditions) in July. With the assumption of no effects from global warming, no influence at all is estimated.

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[7] Event attribution is used to estimate the effects of global warming on the probability of extreme events using a climate model, with numerous calculated examples of warming and non-warming. This involves reference to sea surface temperature and sea ice boundary conditions from actual numerical forecast data used for seasonal forecasts, enabling efficient simulation with a large volume of advance simulations. Here, numerical forecast data from June onward were used.

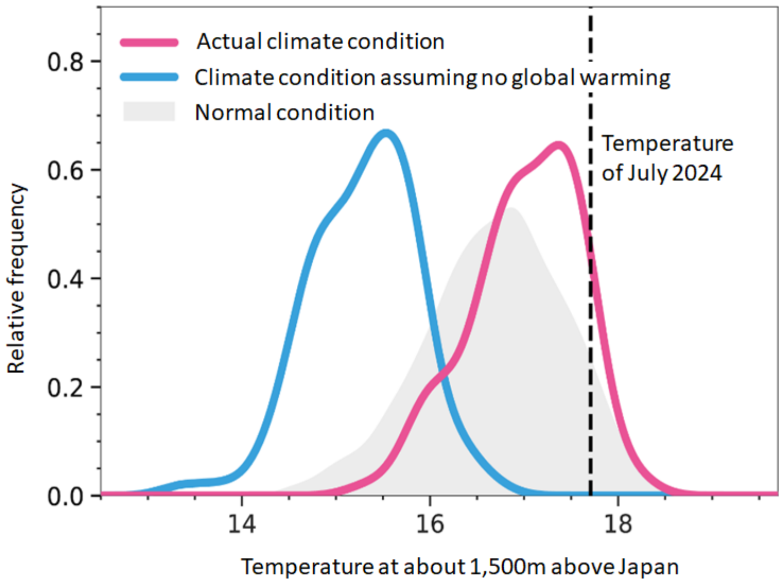

Figure 1-10 Probability of high-temperature events in July 2024 depending on global warming
The horizontal axis is the mean air temperature at around 1500 meters above Japan (130 – 146°E, 31 – 45°N), and the vertical axis is the frequency (mean period is from July 1 to 31). The red line shows frequency under actual global warming conditions in July 2024, and the blue line shows frequency under July 2024 climatic conditions assuming no global warming. The light-grey peak shows July frequency for the 30-year period from 1991 to 2020. The area exceeding the black dashed line representing recorded values for July 2024 indicates the probability of such high-temperature events. The example here had a probability of only around 8.3% in the previous 30-year period. This increases up to 11.2% under actual July 2024 conditions, but the periodicity is still generally decadal. Under conditions assuming no anthropogenic global warming, the event would have had an almost 0% probability of occurrence. As predictive event attribution here was conducted using provisional boundary conditions, the results may incorporate effects from related errors.

1-4 High temperatures worldwide

The World Meteorological Organization (WMO) reported that July 2024 was one of the hottest summer months on record worldwide. JMA analysis also shows that extremely high temperatures were widely recorded during July in the tropics, the mid-latitudes of the Northern Hemisphere and elsewhere (Figure 1-11), and the preliminary global average of land surface temperature and SST for July shows a difference of +0.55°C from the base value (the 30-year average from 1991 to 2020). This is the second-highest value since records began, only after 2023. The global average temperature also saw new monthly highs from May 2023 to June 2024.

Extremely high temperatures in many parts of the world are thought to have been contributed from record-high tropospheric temperatures in the tropics and the mid-latitudes of the Northern Hemisphere due to global warming and the El Niño phenomenon that continued until spring as well as warm anticyclones in areas where upper-level westerly winds meandered northward in the mid-latitudes of the Northern Hemisphere (southern Europe, central Siberia, Japan and western North America).

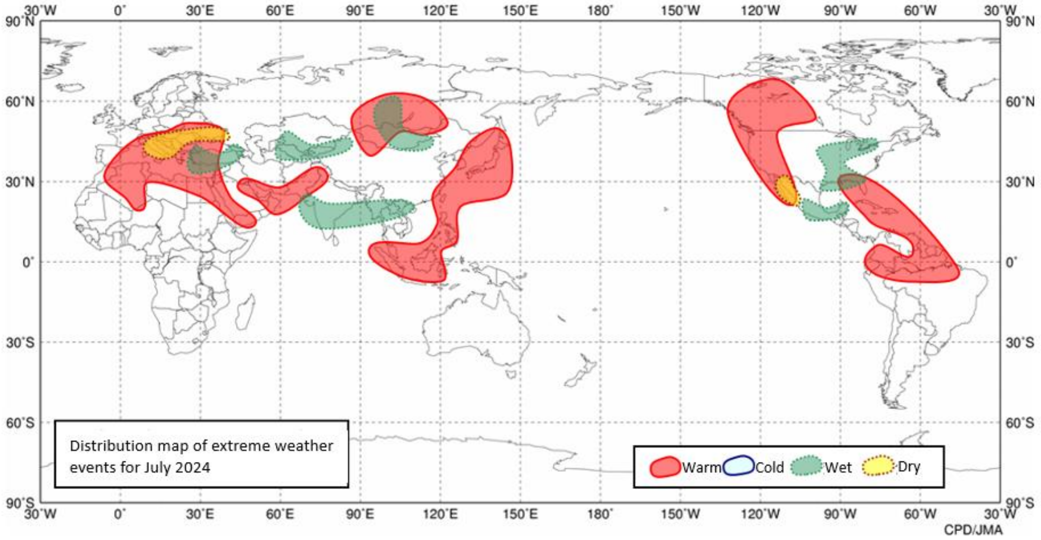

Figure 1-11 Global distribution of extreme weather events in July 2024
Red: extreme high temperatures; green: extreme high rainfall; yellow: extreme low rainfall. Extreme events are defined as those occurring with a periodicity of around 30 years.

2. Heavy rainfall in northern Japan in late July

2-1 Characteristics

- In late July the Baiu front became more active, bringing unprecedented rainfall to northern Japan. The number of stations setting new records for 6- and 12-hour precipitation amounts from July 24 to 30 was 16 in all cases, and 12 in all cases for 24-, 48- and 72-hour precipitation amounts (Figure 2-1).
- Precipitation amounts during this period reached 547.5 mm (approx. 1.6 times the July normal) at Sasunabe and 452.0 mm (approx. 1.9 times) at Semi (both in Yamagata Prefecture).
- In particular, July 24 – 26 saw unprecedented rainfall in places including the prefectures of Yamagata and Akita, with 48-hour precipitation amounts by July 26 reaching 434.5 mm and 402.5 mm in Sasunabe and Shinjo (both in Yamagata Prefecture), respectively, far exceeding previous records.
- The precipitation ratio in the Sea of Japan side of northern Japan in late July was 307% of the normal, close to the 1958 record (313%) and the second heaviest for late July since records began in 1946.

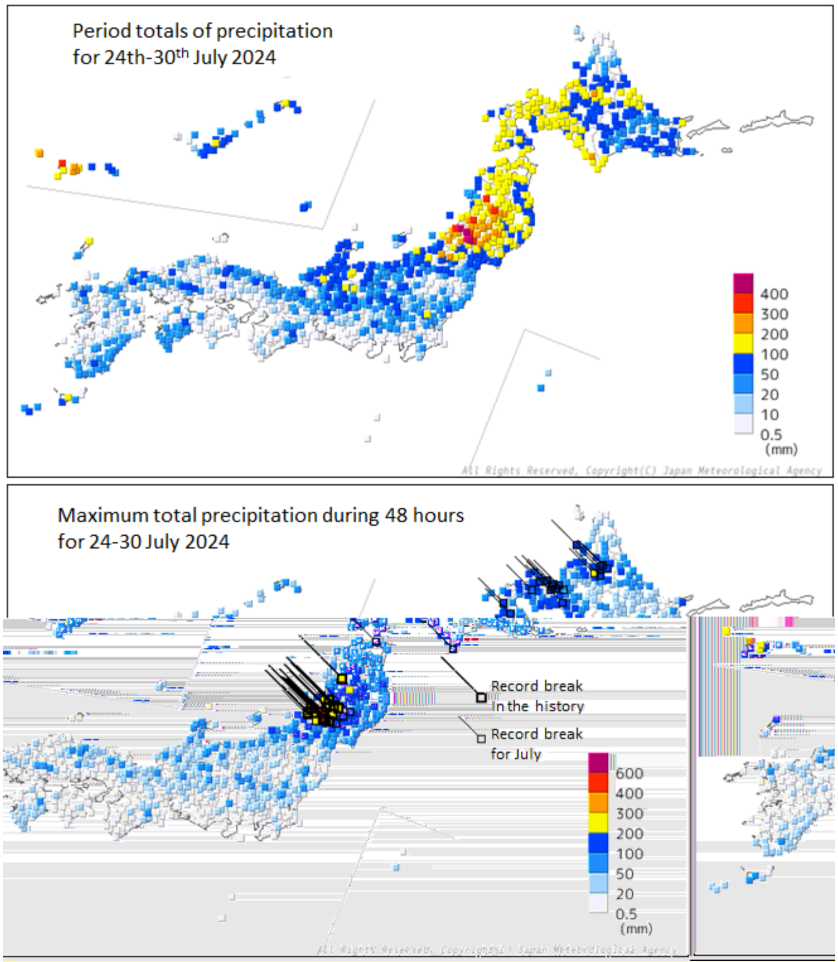

Figure 2-1 Total precipitation for 24 – 30 July (top) and maximum 48-hour precipitation for the period (bottom)
Markers show record-level observation points.

2-2 Large-scale atmospheric flow bringing heavy rainfall

Figure 2-2 details the large-scale atmospheric flow bringing this heavy rain.

- Massive moist-air inflow activated the Baiu front, which had been stagnant over northern Japan. During this period, eastward water vapor transport flowing into the vicinity of northern Japan peaked unprecedentedly around July 28 and remained high throughout late July (Figure 2-3).
- The large amounts of water vapor were likely due to the strong northward transport between the NPSH (which strongly extended to western Japan in association with a meandering STJ northward near the country) and Typhoon Gaemi, which moved northwestward. The water vapor flowed into the Baiu front near northern Japan.
- Abundant water vapor may have been transferred to the lower atmosphere by evaporation from around Okinawa and Amami, where SSTs were high.

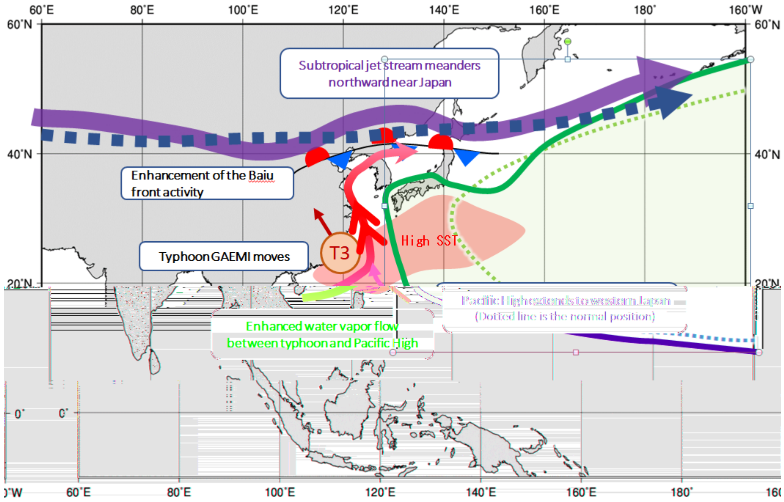

Figure 2-2 Large-scale atmospheric flow bringing heavy rainfall to northern Japan in late July

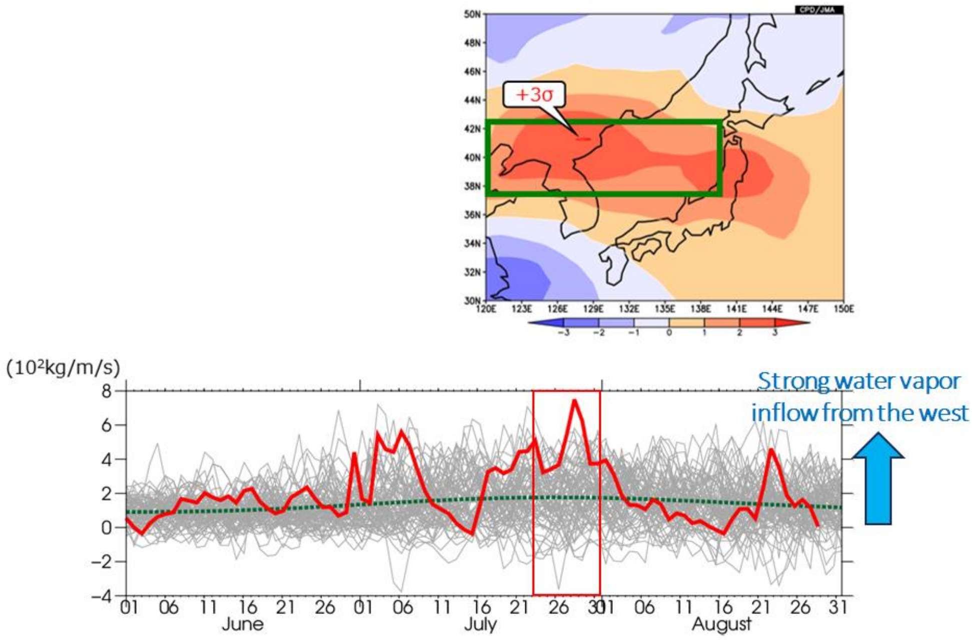

Figure 2-3 Normalized anomalies of eastward moist airflow intensity (vertical integrated water vapor flux) in the troposphere, averaged for 37.5 – 42.5°N, 120 – 140°E, for 24 – 30 July 2024 (top) and daily time-series for June to August (bottom)
The red, green and grey lines indicate 2024, normal years and other years since 1948, respectively.

2-3 Atmospheric conditions during heavy rainfall over Yamagata and Akita around July 25

Around July 25, unprecedented rainfall occurred in places including Yamagata and southern Akita, and Meteorological Information on Significant Heavy Rainfall for Yamagata Prefecture (around 13 JST and 22 JST on July 25) warned of SMCSs. Heavy Rain

Emergency Warnings were issued twice for municipalities in the Shonai and Mogami areas of the prefecture. This section details the atmospheric conditions observed around the peak of this rainfall.

○ **Environmental field for heavy rainfall on July 25**

- The main characteristics behind this event were an inflow of warm moist air in the lower atmosphere and cold air in the middle atmosphere. From the morning of the 25th onward, this air flowed into northern Japan from the East China Sea via the Tsushima Strait and the Sea of Japan (Figure 2-4).
- In the upper atmosphere, a horizontally large upper-level trough approached and passed over northern Japan from the 24th to the 25th, and air at -6°C or lower spread in the middle atmosphere (approx. 5,800 m above the surface) (Figure 2-5).
- The inflow of warm moist air in the lower atmosphere and the influence of cold air in the middle atmosphere produced highly unstable conditions in northern Japan, creating an environmental field where SMCSs are likely to occur.
- The cold air passed in the evening of the 25th, and the subsequent trough approached the Tohoku region and deepened. This made the middle atmosphere cooler and wetter and caused precipitation systems, resulting in another SMCS over northern Yamagata Prefecture (Figure 2-5).

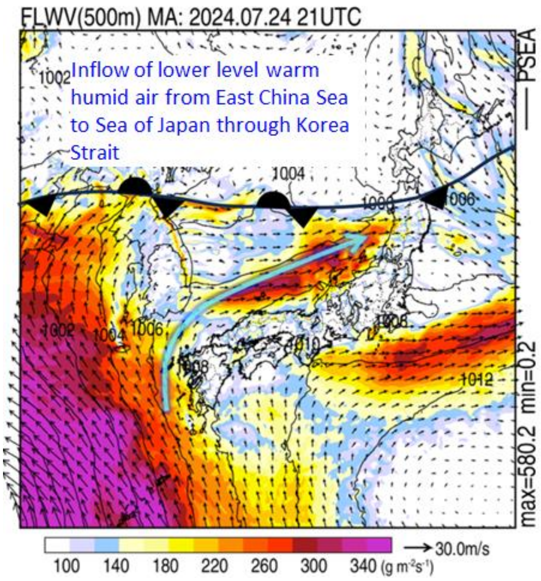

Figure 2-4 Water vapor inflow (colors), horizontal wind (arrows) at around 500 m altitude and sea level pressure (black line) from JMA meso-objective analysis at 06:00 JST on July 25 2024

Arrows: path of warm moist air; thick line: Baiu front

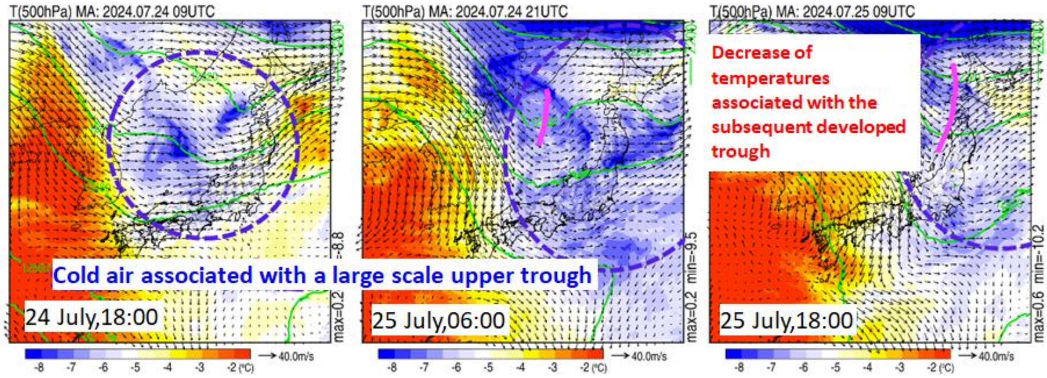

Figure 2-5 Temperature (colors) and horizontal wind (black arrows)at 500 hPa surface (altitude approx. 5,800 m), altitude (green lines) at 200 hPa surface (altitude approx. 12,000 m) from JMA meso-objective analysis at 18:00 JST on July 24, and at 06:00 and 18:00 on July 25 2024

Blue circles: large areas of horizontal-scale cold air; pink lines: backward trough

2-4 Influence of global warming in heavy rainfall around July 25 in Yamagata and Akita

Over the long term, extreme heavy rainfall events in Japan have increased. The number of annual days of heavy rainfall at 300 mm or more at AMeDAS stations in the last 10 years has increased by a factor of 2.1 since around 1980 (Figure 2-6). This may be partially attributable to a long-term increase in atmospheric water content associated with ongoing global warming (Figure 2-7).

A joint research team from MEXT's Advanced Studies of Climate Change Projection initiative conducted a preliminary reproduction experiment using a high-resolution model for Yamagata, Akita and elsewhere for July 24 to 26 using quantitative evaluation method[8] of EA to assess the effects of global warming. The results showed that 48-hour cumulative precipitation was more than 20% higher with current climate conditions than with theoretical experimental conditions assuming no global warming (Figure 2-8, black box, lower right). The outcomes tie the heavy rainfall in Yamagata and Akita to global warming.

[8] A method to estimate the difference in precipitation by performing a reproduction simulation that faithfully reproducing actual extreme phenomena and a quasi-non-warming simulation (warming from industrialization is removed) using high-resolution model. Here, the JMA non-hydrostatic model (JMA-NHM) was used to determine ensemble average precipitation for an eight-member ensemble with initial values from three-hourly meso-objective analysis on July 23.

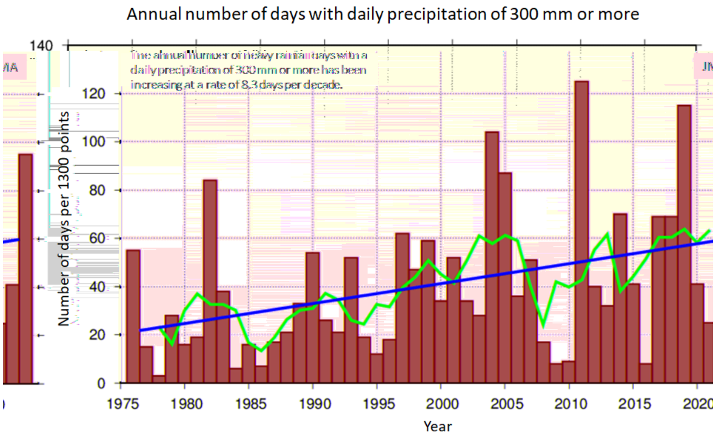

Figure 2-6 Days with precipitation of 300 mm or more (1976 – 2023)
Bars: annual numbers (converted from nationwide AMeDAS observations for 1,300 stations); blue line: five-year moving average; red line: long-term average trend

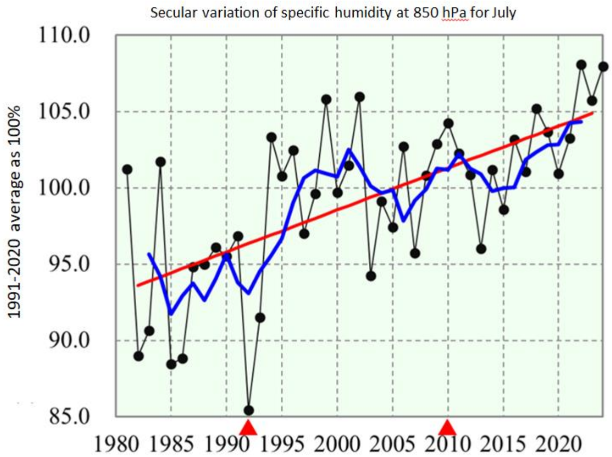

Figure 2-7 Monthly mean specific humidity (water vapor per kg of air) vs. reference at 1,500 m above sea level (850h Pa) in July over Japan for 1981 – 2024
Black: ratio to the standard at 13 high-altitude meteorological observation stations in Japan (Wakkanai, Sapporo, Akita, Wajima, Tateno, Hachijojima, Shimonoseki, Fukuoka, Kagoshima, Nase, Ishigakijima, Minamidaitojima, and Chichijima); blue: five-year moving average; red: long-term change (statistically significant with 99% confidence). Base: average for 1991 – 2020. An instrumentation change between the two red pointers may have produced slightly higher values.

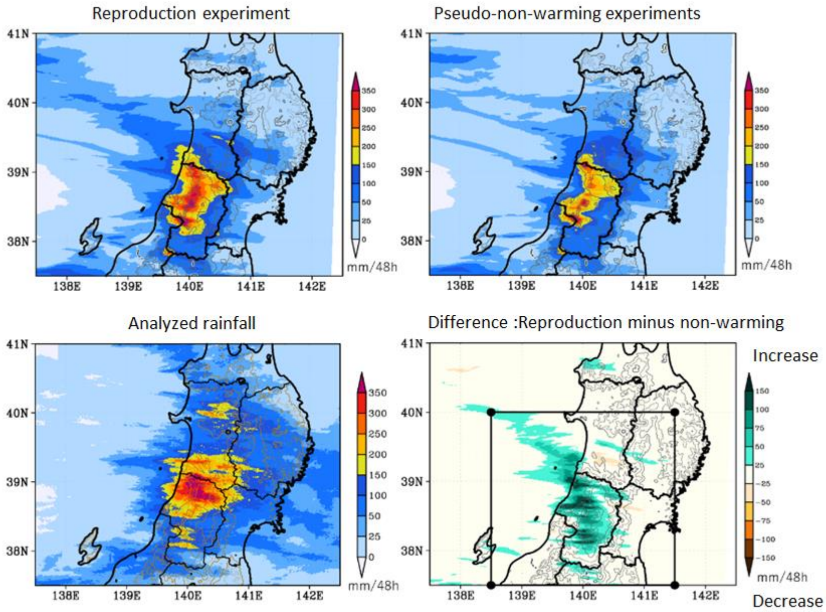

Figure 2-8 Heavy-rainfall simulation for July 24 – 26
Top left: Actual (with warming) 48-hour total precipitation (mm) from 9:00 JST on July 24 to 9:00 JST on July 26
Top right: Total precipitation (mm) during the same period assuming no warming
Bottom right: Difference (mm)
Bottom left: Total analysis rainfall (mm) for the same period

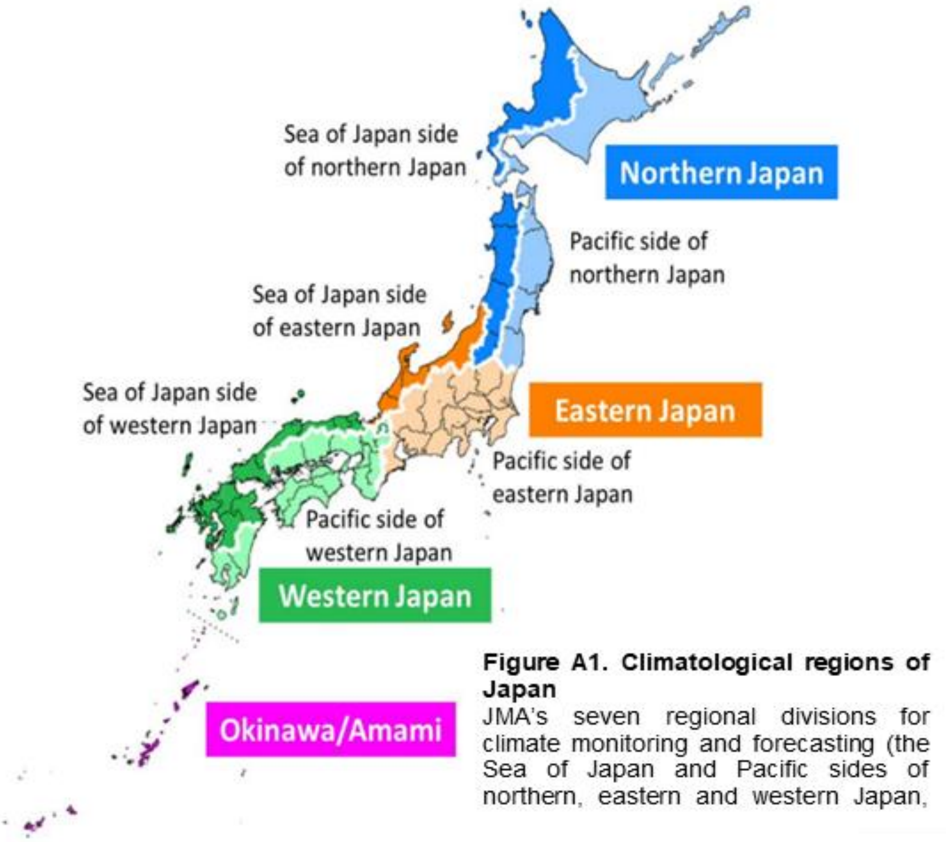

Figure A1. Climatological regions of Japan
JMA's seven regional divisions for climate monitoring and forecasting (the Sea of Japan and Pacific sides of northern, eastern and western Japan,