

THE HEAVY RAIN EVENT OF JULY 2018 IN JAPAN ENHANCED BY HISTORICAL WARMING

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The unprecedented precipitation total in Japan during the heavy rain event of July 2018 was increased by approximately 7% due to recent rapid warming around Japan.

Extrremely heavy precipitation occurred from central to western Japan in July 2018, which was named the “heavy rain event of July 2018” by the Japan Meteorological Agency (JMA). The JMA has approximately 1,300 in situ stations. The 48- and 72-h total precipitation records were broken at 125 and 123 in situ stations, respectively, from 28 June to 8 July (the dates are different in the individual in situ stations). The 10-day total precipitation accumulated at all Japanese in situ stations was the highest for any 10-day periods starting on the 1st, 11th, and 21st of the month since 1982 (Fig. 1a) (Shimpo et al. 2019; TCC JMA 2018). During the heavy rainfall event, there were 221 fatalities, and more than 6,000 buildings were destroyed by floods and landslides (Cabinet Office, Government of Japan 2018). The continuous lower-level moisture transport maintained the active stationary weather front for a couple of days and the passage of the upper-level trough enhanced the heavy precipitation at the end of this heavy rainfall event (Shimpo et al. 2019; TCC JMA 2018). Mesoscale line-shaped precipitation systems appeared locally and strengthened the heavy precipitation in some areas of western Japan (Tsuguti et al. 2019).

In recent years, the surface air temperature during the summer has been increasing rapidly in Japan. The moisture that the atmosphere may hold has increased by approximately 7% K⁻¹ as dictated by the Clausius–Clapeyron relationship. The observed specific humidity at 850 hPa in July shows a rapid increase around Japan from 1981 to 2018 (Shimpo et al. 2019; TCC JMA 2018). It is possible that recent warming and moistening due to global warming contributed to the heavy rain event of July 2018.

Event attribution (EA) is useful for the attribution of specific extreme events, such as heat waves and drought, to global warming due to anthropogenic forcing (e.g., Stott et al. 2004; Shioyama et al. 2013, 2014; Imada et al. 2014). EA uses large ensemble historical and non-warming simulations performed by general circulation models (GCMs) and probabilistically attributed the extreme event to global warming. For the latest extreme event in Japan, Imada et al. (2019) revealed that the July 2018 heat wave event in Japan would have been virtually impossible without anthropogenic global warming. Kim et al. (2019) revealed that the combination of extreme events in Japan, such as the serious flood and heatwave events that occurred in 2018, could be heavily influenced by global warming, even though the intermodel variability is large. However, it is difficult to adapt the EA to heavy precipitation events. Imada et al. (2013) attributed the heavy precipitation event occurring in southwestern Japan in 2012 to global warming using the atmospheric GCM (AGCM) with approximately 150-km horizontal resolution, while they could not simulate the local-scale heavy precipitation. Higher-resolution simulations, such as 5-km grid spacings, are needed to directly reproduce such heavy precipitation influenced by the complex orography in Japan.

The storyline approach (Shepherd et al. 2018) is the other approach to evaluating the impact of global warming on extreme events. In the storyline

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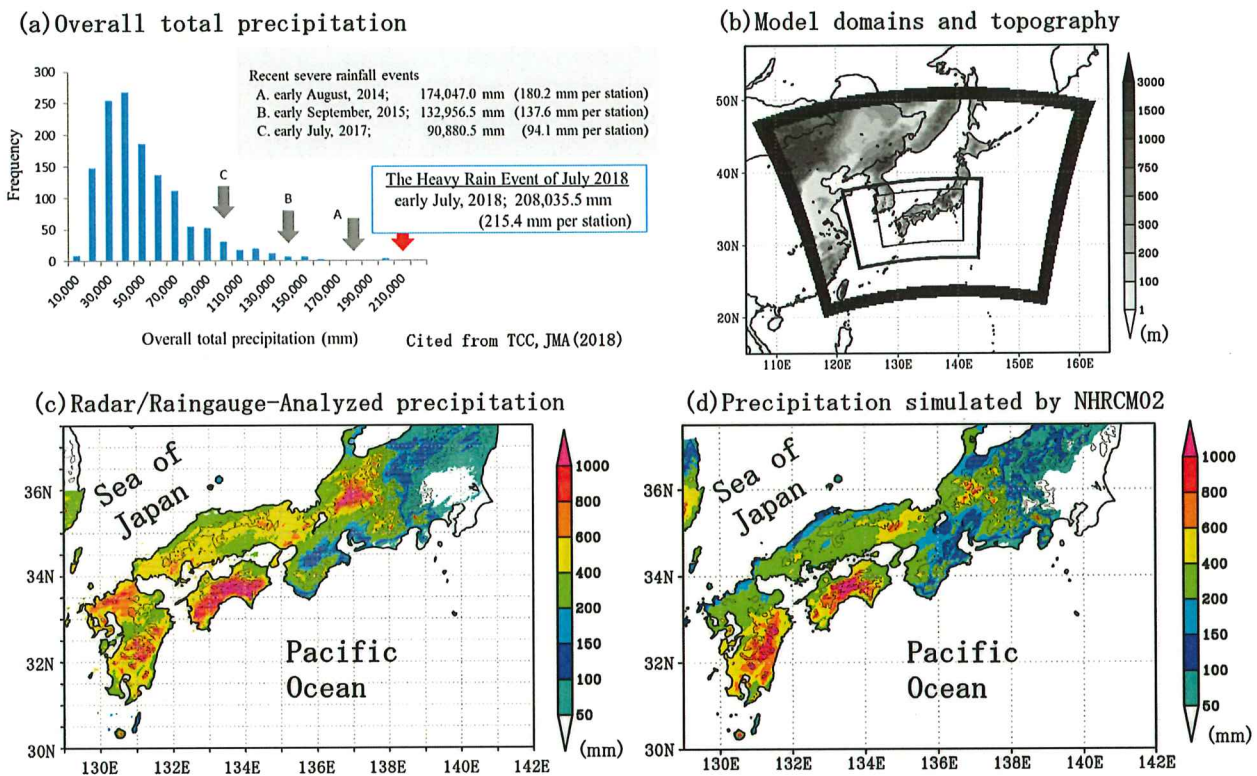


FIG. 1. (a) Frequency distribution of overall total precipitation at 966 selected in situ stations throughout Japan for 10-day periods (TCC JMA 2018). (b) Model domains and topography. Outer, middle, and inner areas represent domains of NHRCM20, NHRCM05, and NHRCM02, respectively. (c) Radar/rain gauge-analyzed precipitation from 0000 JST 28 Jul to 2300 JST 8 Aug 2019. (d) As in (c), but showing total precipitation simulated by NHRCM02.

approach, specific extreme events are simulated by the high-resolution regional climate model with realistic boundary conditions based on the reanalysis data. Then, the impact of global warming is quantitatively evaluated by the counterfactual simulations without the historical warming component estimated by the reanalysis data or global climate simulations. The storyline approach is useful for extreme events caused by mesoscale systems such as stationary weather fronts and tropical cyclones (e.g., Takayabu et al. 2015). For the heavy rain event of July 2018 in Japan, we applied the storyline approach using a regional climate model and evaluated the impact of recent warming and moistening on precipitation amounts.

METHODS. We reproduced the heavy rain event of July 2018 using the Non-Hydrostatic Regional Climate Model (NHRCM) (Sasaki et al. 2008). The boundary conditions were obtained from the Japanese 55-Year Reanalysis (JRA-55) (Kobayashi et al. 2015) whose horizontal resolution is 1.25°. The horizontal grid spacings of NHRCM were 20, 5, and 2 km in the outer, middle, and inner domains (hereafter referred to as NHRCM20, NHRCM05, and NHRCM02),

respectively (Fig. 1b). Both the cumulus convective parameterization scheme (Kain and Fritsch 1993) and a cloud microphysics scheme (Ikawa et al. 1991) were used in NHRCM20 and NHRCM05. Only the cloud microphysics scheme was used in NHRCM02, which is a so-called convection-permitting model. The convection-permitting model can simulate local-scale heavy precipitation influenced by the complex orography and mesoscale convective systems (Prein et al. 2015). The initial date of NHRCM20 was 20 June 2019. NHRCM05 runs started on five different initial dates, from 22 to 26 June, for conducting simplified ensemble experiments. The initial date of NHRCM02 was 27 June in all ensemble experiments. These hind-cast experiments are hereafter called CTL2018 runs. The radar/rain gauge-analyzed precipitation amount produced by JMA was used to validate the precipitation simulated by NHRCM02.

We calculated four kinds of linear trends of regional-mean air temperature at each pressure level and sea surface temperature (SST) during the summer [an average of June–August (JJA)] and each month (June, July, and August separately) from 1980 to 2018, when the temperature rise was accelerated

around Japan. The regional-mean JJA temperature at 1,000 hPa showed a rapid increase with a large interannual variability (Fig. 2a). The warming trend was largest in July (1.11 K per 39 years at 1,000 hPa) and smallest in June (0.75 K), whereas the trend in August (1.04 K) was similar to that in JJA (0.96 K). Note that the temperature trend in reanalysis data includes a natural decadal variability in addition to human-induced global warming. We performed a similar hindcast simulation using the JRA-55 without these four recent warming trends, which are hereafter called the DeTRND2018_JJA, DeTRND2018_JUN, DeTRND2018_JUL, and DeTRND2018_AUG runs, respectively. Each experiment had five ensemble runs using the different initial dates of NHRCM05.

RESULTS. The ensemble mean of five CTL2018 runs well reproduces the horizontal distribution of total precipitation during the heavy rain event of July 2018 (Figs. 1c,d). Time sequences of regional mean precipitation show that NHRCM02 simulates the timing of heavy precipitation periods on 29–30 June, 3–4 July, and 5–7 July (Fig. 2c). The total precipitation amount is, however, underestimated over land. The observed and simulated regional mean total precipitation over land are 357.0 and 269.2 mm, respectively, in 129°–142°E and 30°–37.5°N. The underestimation of precipitation over the coastal areas along the Sea of Japan corresponds to the bias in the location of the stationary weather front simulated by NHRCM02.

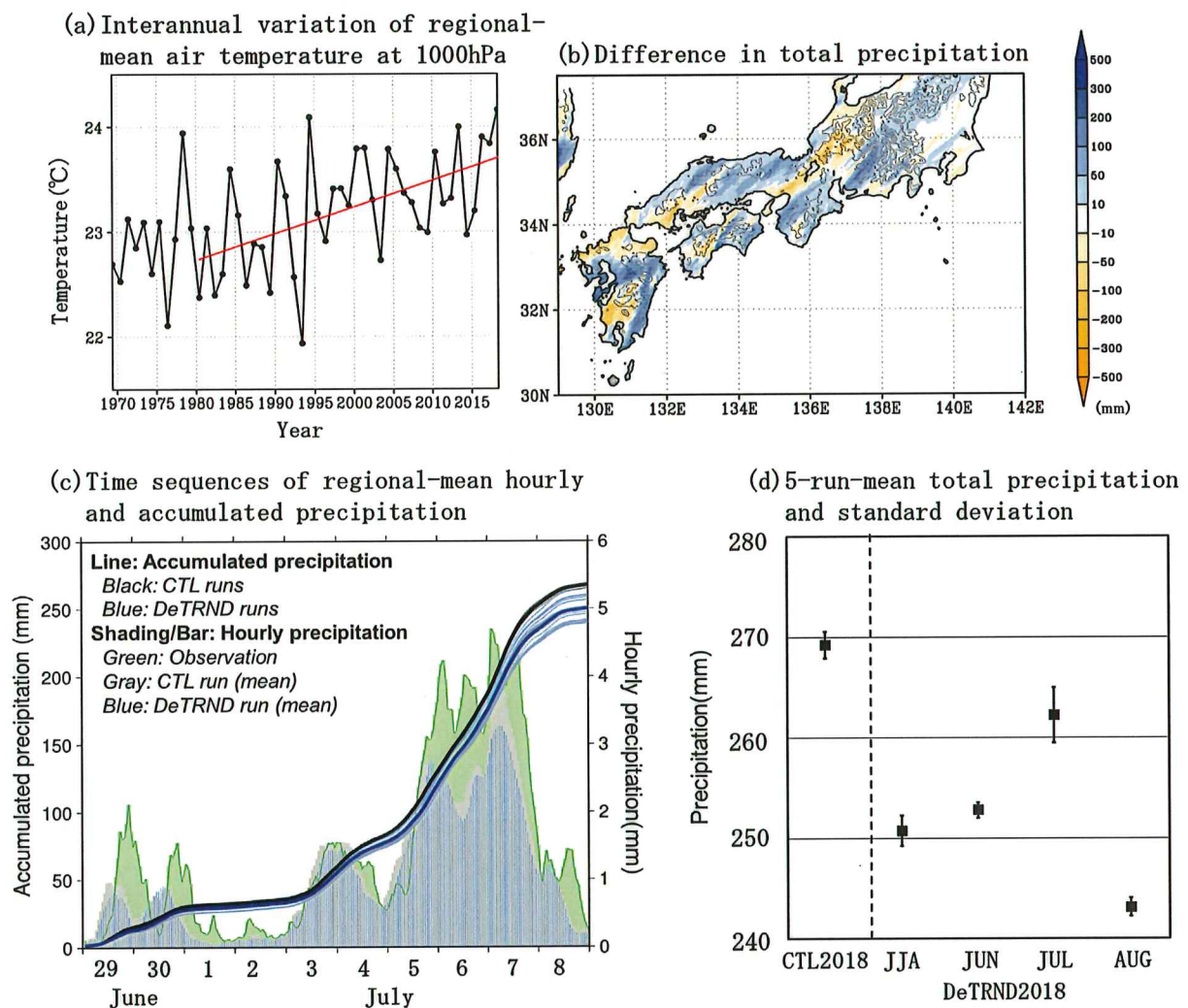
Figure 2b shows the difference in the total precipitation over land between the ensemble mean of the CTL2018 runs and the ensemble mean of the DeTRND2018 runs. The majority of areas show that the precipitation amount is larger in CTL2018 than that in DeTRND2018, suggesting that the recent warming might strengthen the heavy precipitation. We compared the time sequences of the accumulated precipitation amounts between CTL2018 and DeTRND2018 during the heavy precipitation period (Fig. 2c). The difference in the ensemble mean precipitation amounts became larger after 5 July. At the end of the heavy precipitation event, the difference in accumulated precipitation between CTL2018 and ensemble-mean DeTRND2018 runs was 17.0 mm, which is equivalent to 6.7% relative to DeTRND2018. To consider the uncertainty in the detrending method, the discrepancies among the DeTRND2018 ensemble runs (thin blue lines), which result from the four temperature trends eliminated from JRA-55, are also estimated. The percentages of differences in precipitation amounts are +7.4%, +6.5%, +2.7%, and +10.7% relative to DeTRND2018_JJA, DeTRND2018_

JUN, DeTRND2018_JUL, and DeTRND2018_AUG, respectively. The variation using five different initial dates is much smaller than that using four different temperature trends (Fig. 2d). The difference of precipitation in DeTRND2018_JUL is smallest among four experiments, while the difference of air temperature at 1,000 hPa is the largest among them. These results indicate that the changes in precipitation due to warming do not necessarily correspond to the low-level temperature changes.

Changes in SST influence the low-level moisture because most water vapor is derived from the ocean around Japan. In addition, the atmospheric moist stability is modulated by changes in the vertical profiles of equivalent potential temperatures and saturated equivalent potential temperatures. Our experiments indicate that changes in the moist stability (i.e., $\theta_{e,1000} - \theta_{e,600}$ in the table in Fig. 2) contribute to changes in precipitation amounts. DeTRND2018_AUG (DeTRND2018_JUN) shows the largest (smallest) changes in stability and results in the largest (smallest) increase in precipitation. Hibino et al. (2018) pointed out that, in the future climate, the effect of moistening due to global warming on extreme precipitation in Japan could be cancelled out by the suppression of convection due to the enhancement of thermal stability.

According to the JRA-55 reanalysis data, the increases in air temperature at 1,000 hPa are 0.96, 0.75, 1.11, and 1.04 K in JJA, June, July, and August, respectively. If we assume 7% increase for every degree according to the Clausius–Clapeyron relation, the percentages are 6.7%, 5.3%, 7.8%, and 7.3%, respectively. Approximately 6.7% increase in precipitation is in the expected range. However, our results indicated that the changes in heavy precipitation are also influenced by the changes in atmospheric moist stability, which can be additional uncertainty sources in changes in heavy precipitation due to global warming. Therefore, evaluations of not only atmospheric warming but also changes in atmospheric moist stability due to global warming are necessary to quantitatively assess the impact of global warming on long-lasting heavy precipitation events, such as the heavy rain event of July 2018.

Additional experiments are conducted assuming a warmer climate than the current climate and using five initial dates. Here, the JJA temperature trends are extrapolated by the past temperature trend for same term (39 yr) and added into 2018. Mean total precipitation increases by 6.1% relative to CTL2018 in the warmer condition (see Fig. ES1 in the online supplemental material).



Table

EXP (5 runs mean)	θ_e 1000		θ_e 1000- θ_e^* 600		Total precipitation	T1000(given)	SST(given)
		CTL-DeTRND		CTL-DeTRND	CTL-DeTRND (percentage)	CTL-DeTRND	CTL-DeTRND
CTL2018	345.32 K	*	3.19 K	*	*	*	*
DeTRND2018_JJA	342.61 K	2.72 K	2.68 K	0.52 K	7.4 %	0.96 K	0.78 K
DeTRND2018_JUN	343.48 K	1.84 K	2.76 K	0.43 K	6.5 %	0.75 K	0.62 K
DeTRND2018_JUL	342.42 K	2.91 K	3.13 K	0.06 K	2.7 %	1.11 K	0.70 K
DeTRND2018_AUG	341.55 K	3.77 K	2.10 K	1.09 K	10.7 %	1.04 K	1.00 K
DeTRND2018 mean	343.07 K	2.81 K	2.67 K	0.53 K	6.7 %	-	-

Fig. 2. (a) Interannual variation of regional-mean air temperature at 1,000 hPa at 120°–145°E, 30°–40°N in JJA. A red line represents a linear trend from 1980 to 2018. (b) Difference of total precipitation between the ensemble means of CTL2018 and DeTRND2018. Blue (orange) colors indicate that the precipitation amount in CTL2018 is larger (smaller) than that in DeTRND2018. (c) Time sequence of regional-mean overland precipitation in central and western Japan. Black and blue lines represent regional-mean accumulated precipitation simulated by the CTL2018 and DeTRND2018 runs, respectively. Bold lines represent the corresponding ensemble means. Shadings and bars show the regional-mean hourly precipitation: the observation (green), CTL2018 (gray), and DeTRND2018 (blue). (d) Mean total precipitation and standard deviations simulated by each experiment. (table) Differences of several indices between CTL2018 and DeTRND2018. T1000, θ_e 1000 and θ_e^* 600 represent temperature at 1,000 hPa, equivalent potential temperature at 1,000 hPa, and saturated equivalent potential temperature at 600 hPa, respectively.

CONCLUSIONS. The contribution of historical global warming on the heavy rain event of July 2018 in Japan was quantitatively evaluated by using NHRCM02 forced by the JRA-55 reanalysis data. The NHRCM02 well simulated the horizontal distribution and timing of heavy rainfall over western and eastern Japan. Sensitivity experiments, in which linear trends of summer-mean and each monthly-mean temperature from 1980 to 2018 are eliminated from the boundary conditions, showed the increases in total precipitation due to recent warming. Total precipitation in the CTL2018 runs is approximately 6.7% (+2.7% to +10.7%) larger than that in the ensemble-mean DeTRND2018 runs. These changes in precipitation are induced by not only changes in atmospheric temperature, which relates to Clausius–Clapeyron relationship, but also changes in the SST and atmospheric moist stability. Either way, our results indicate that historical warming definitely contributed to the increase in total precipitation of the heavy rain event of July 2018 in Japan. This study employs a storyline approach to control for the specific weather phenomena associated with this extreme event. Future work is required to assess the change in frequency of background synoptic conditions causing the heavy rain event of July 2018 in Japan.

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