Enhancement of Extremely Heavy Precipitation Induced by Typhoon Hagibis (2019) due to Historical Warming

Hiroaki Kawase,1 Munehiko Yamaguchi,1 Yukiko Imada,1 Syugo Hayashi,1 Akihiko Murata,1 Tosiyuki Nakaegawa,1 Takaumi Miyasaka,2,1, and Izuru Takayabu1
1Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan
2Japan Meteorological Business Support Center, Tsukuba, Japan

Abstract

Impacts of historical warming on extremely heavy rainfall induced by Typhoon Hagibis (2019) are investigated using a storyline event attribution approach with the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM). Control experiments based on JMA mesoscale analysis data well reproduce the typhoon’s track, intensity, and heavy precipitation. First, two non-warming experiments are conducted: One excludes both 40-year atmospheric and oceanic temperature trends from 1980 to 2019, and the other excludes the oceanic trend only. A comparison between control and non-warming experiments indicates that historical warming strengthens typhoons and increases the amount of total precipitation by 10.9% over central Japan. The difference between CTL and non-warming experiments without both atmospheric and oceanic temperature trends is larger than that without just the oceanic trend (7.3%). Additional sensitivity experiments without Japan’s topography indicate that topography enhances not only total precipitation but also the changes in total precipitation due to historical warming. Through the storyline event attribution approach, it is concluded that historical warming intensifies strength of Typhoon Hagibis (2019) and enhances the extremely heavy precipitation induced by the typhoon.

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1. Introduction

Tropical cyclones (hereafter, referred to as TCs) are typical extreme phenomena and cause heavy precipitation, strong winds, and storm surges. Japan is frequently influenced by TCs formed in the western North Pacific, called typhoons. In October 2019, Typhoon Hagibis (2019) hit eastern Japan, including the Tokyo Metropolitan area, and induced extremely heavy precipitation there. Takemi and Unuma (2020) investigated environmental factors causing heavy rainfall during the passage of Typhoon Hagibis (2019). They pointed out that the combination of a nearly moist-adiabatic lapse rate, moist absolute instability, abundant moisture content, and high relative humidity throughout the troposphere resulted in the heavy rainfall.

Previous studies have investigated the impacts of global warming on TCs since the warmer sea surface temperature (SST) and plenty of moisture develop TCs. Studies on the detection and attribution of TCs and future TC changes are summarized in each oceanic basin (Knutson et al. 2019, 2020; Lee et al. 2020; Cha et al. 2020). The number of typhoons approaching Japan will decrease in the future climate, while the precipitation amount induced by strong typhoon will increase (Watanabe et al. 2019; Hatusuzuka et al. 2019; Miyasaka et al. 2020). A pseudo-global warming (PGW) experiment is one method of evaluating the impacts of global warming in the future climate on past TCs. This approach has been applied to typhoons hitting Japan such as Typhoons Vera (1959), Songda (2004), Talas (2011), Canthu (2016), and Lionrock (2016) (Ito et al. 2016; Takemi et al. 2016; Kanada et al. 2017a, 2017b; Nayak et al. 2019; Takemi 2019). These studies indicated that extreme typhoons got stronger under the future global warming scenario. Takemi (2019) pointed out that increased precipitable water led to increased rainfall produced by Typhoon Talas (2011) despite the stabilized atmospheric condition in the future climate; Takemi (2019) also indicated that global warming could enhance long-lasting heavy rainfall caused by slow-moving typhoons.

The PGW approach evaluating the impact of historical climate changes on individual extreme events is a kind of storyline event attribution (hereafter, referred to as storyline EA), which investigates the impact on an event intensity, in distinction from the risk-based EA, which investigates the impact on an event frequency (Shepherd et al. 2018). Storyline EAs aimed at TC-induced extremes show significant changes in global, regional, rainfall amounts, wind speeds, and storm surges (Takayabu et al. 2015; Patricola and Wehner 2018; Reed et al. 2020). Takayabu et al. (2015) stated that Typhoon Haiyan (2013), which made landfall in Philippines, could become stronger than in the hypothetical preindustrial condition.

Typhoon Hagibis (2019), which slowly approached and passed through Japan, brought heavy precipitation for more than 24 hours in eastern Japan. This study applies the storyline EA to Typhoon Hagibis (2019) and investigates the impacts of historical warming on Typhoon Hagibis (2019) and the typhoon-induced heavy precipitation. Additionally, we discuss the sensitivity of the typhoon-induced precipitation to historical atmospheric and oceanic temperature changes, and the effect of topography.

2. Experimental design

The basic methodology follows that of Kawase et al. (2020), who applied the storyline EA to the Heavy Rain Event of July 2018 in Japan. Numerical experiments were conducted using the Japan Meteorological Agency Nonhydrostatic Model (JMA-NHM; Saito et al. 2007) with 5 km grid spacing. The specifications of NHM used in this study are summarized in Table S1. The initial and lateral boundary conditions of control experiments (hereafter, referred to as MA) are obtained from the JMA mesoscale analysis data (hereafter, referred to as MA). A model domain and the topography around the Kanto-Koshin region are shown in Fig. 1. We conducted ensemble experiments with four initial conditions—00UTC, 03UTC, 06UTC and 09UTC—on 9 October 2019.

The Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al. 2015) shows a rapid atmospheric warming around Japan since 1980 (Fig. S1). Non-warming experiments are based on the MA in which the regional mean atmospheric temperature at each vertical level and oceanic temperature trends from 1980 to 2019 are excluded (hereafter, referred to as NonW40), which are derived from JRA-55 and Global Sea Surface Temperature Analysis Data (COBE-SST) (Ishii et al. 2005), respectively (Table 1). Sensitivity

Corresponding author: Hiroaki Kawase, Meteorological Research Institute, 1-1, Nagamine, Tsukuba 305-0052, Japan. E-mail: hkawase@mri-jma.go.jp.

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experiments using only SST trends are referred to as NonW40_SST. Five types of temperature trends are prepared: monthly means of August, September, and October; and three-monthly means of August-September-October (ASO) and September-October-November (SON). The ensemble experiments using five different time windows were conducted to reduce uncertainty in the trend estimation. The total number of ensemble experiments is 20. Vertical profiles of the temperature trends are shown in Fig. 1c. Here, we excluded the trend in only November when the number of typhoons rapidly decreases. The relative humidity in NonW40 is the same as that in CTL as with previous studies (e.g., Takemi 2019). The geopotential height is modified to be suitable to atmospheric temperature changes.

Takemi and Unuma (2020) pointed out that topography-induced ascent was considered to be the trigger of convection causing heavy precipitation. We conducted CTL and NonW40 without Japan’s topography (hereafter, referred to as CTL_NOTP and NonW40_NOTP, respectively) to investigate the impact of Japan’s topography on the precipitation changes due to historical warming.

The uncertainty of historical warming is crucial for studies on the attribution of extreme events to global warming. We also evaluate the impact of historical warming since the preindustrial period on Typhoon Hagibis (2019) using the Database for Policy Decision-Making for Future Climate Change (d4PDF; Mizuta et al. 2017), which includes 100 ensembles of historical and non-warming experiments. This study used extension data of d4PDF from 2008 to 2017 (Imada et al. 2019). We conduct the experiments using the MA in which the differences in regional mean temperature between the historical and non-warming experiments in August, September, October, ASO, and SON are excluded (hereafter, NonW_d4PDF) (Table 1).

To detect the central position of the typhoon at a given time, we first calculate a sea level pressure (SLP) averaged over 5 × 5 grids (i.e., 25 km × 25 km). Then the central grid of the 5 × 5 grids domain with the minimum mean SLP is defined as the central position of the typhoon.

Hourly radar/rain gauge–analyzed rainfall provided by the JMA is used to compare with precipitation simulated by CTL.

3. Results

3.1 Simulation skills

Large amounts of precipitation are calculated by CTL around the path of Typhoon Hagibis (2019) and over the mountains in the Kanto-Koshin region (Fig. 2a). The total precipitation from 00 UTC on 10 October to 23 UTC on 13 October 2019, is well simulated by CTL compared to the observation (Figs. 2b and 2c). The regional mean total precipitation in CTL is 26.2 mm (approximately 10%) less than the observation (Table 2). The typhoon tracks in CTL follow the best-track data of the JMA until the typhoon passes through the Kanto-Koshin region (Fig. 2a). The typhoon’s landfall and the peak of precipitation are, however, delayed by 5−6 hours in CTL. If the peak of the observed precipitation is modified to fit CTL, the time series of hourly precipitation simulated by CTL is similar to that observed (Fig. 3). East of Japan, the simulated typhoon passes through a slightly more southerly path as compared to the best-track data. NonW40 simulates typhoon tracks similar to those in CTL (Fig. 2a).

The differences between the simulated and observed minimum
Fig. 2. Total precipitation from 00 UTC on 10 October to 23 UTC on 13 October 2019; typhoon tracks; and differences in total precipitation between CTL and non-warming experiments. (a) Total precipitation in CTL and typhoon tracks in CTL and NonW40. Triangles, black circles, and red circles represent the JMA best-track data, CTL, and NonW40, respectively. Large triangle and black circle represent locations of typhoon in best-track data and one CTL run, respectively, on 12 UTC 12 October 2019. (b) Radar/rain gauge–analyzed rainfall. (c) Ensemble mean total precipitation in CTL. (d) Ensemble mean total precipitation in CTL_NOTP. (e–h) Differences in total precipitation between CTL (CTL_NOTP) and four sensitivity experiments. (e) NonW40, (f) NonW40_SST, (g) NonW40_NOTP, and (h) NonW_d4PDF. Here, CTL and non-warming experiments show the averages of 4 and 20 runs, respectively. Blue shading represents that the amount of precipitation is larger in CTL than in the sensitivity experiments.
SLPs, which represent the strength of the typhoon, are 5 and 3 hPa when the typhoon reached around 28.5°N and made landfall in Japan, respectively (Table 2). These differences are comparable to the intervals of the SLPs analyzed in the best-track data. Considering the current status of TC intensity prediction accuracy (e.g., DeMaria et al. 2014; Yamaguchi et al. 2018), an error of less than 5 hPa is a high accuracy.

### 3.2 Impact of historical warming on typhoon-induced precipitation, typhoon strength, and moisture

The total precipitation is widely greater on CTL than that in NonW40, while precipitation slightly decreases at the left (west) of the typhoon track in Japan (Fig. 2e). The total precipitation in NonW40 is less than that in CTL, especially around the peak of precipitation (Fig. 3). The total precipitation in NonW40_SST is also shown to be less than that in CTL (Fig. 2f and Table 2), indicating that the lower SST can inhibit the heavy precipitation induced by Typhoon Hagibis (2019).

Minimum SLPs of typhoons are higher in NonW40 than those in CTL, not only when the typhoon exists over the Pacific Ocean but also when the typhoon makes landfall in Japan (Fig. 4a and Table 2), which means that Typhoon Hagibis (2019) was strengthened due to historical warming. It is noteworthy that minimum SLPs in NonW40_SST are comparable to those in NonW40 north of 30°N. It is pointed out that a high SST due to global warming is most important for the development of strong typhoons (Takemi et al. 2016; Kanada et al. 2020). NonW40, on the other hand, sim-

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**Table 2.** Given temperature and SST changes, minimum SLPs of the typhoon around 28.5°N and 35°N, and regional mean total precipitation over the Kanto-Koshin region.

| Experiment name      | 1000 hPa temperature change | SST change | Minimum SLP [hPa] (standard deviation) | Regional mean precipitation over Kanto-Koshin region |
|----------------------|-----------------------------|------------|---------------------------------------|----------------------------------------------------|
|                      | 28.5°N          | 35°N       |                                        | amount [mm]                                        |
| **Observation**      | –               | –          | 935 (0.39)                            | 262.1                                              |
| **CTL**              | –               | –          | 930.2 (0.39)                          | 235.9                                              |
| **NonW40**           | –0.95           | –0.88      | 930.0 (1.57)                          | 212.9                                              |
| **NonW40_SST**       | –0.95           | –0.88      | 930.0 (1.57)                          | 220.0                                              |
| **NonW d4PDF**       | –1.37           | –1.30      | 930.5 (0.70)                          | 207.8                                              |
| **CTL NOTP**         | –               | –          | 930.6 (0.22)                          | 173.8                                              |
| **NonW40_NOTP**      | –0.95           | –0.88      | 938.8 (1.63)                          | 162.9                                              |

\* Four runs mean  
\*\* Twenty runs mean
ulates larger precipitation changes than does NonW40_SST (Table 2). The atmospheric temperature changes also affect the typhoon-induced precipitation in addition to the strengthened Typhoon Hagibis (2019).

We calculated the maximum total precipitable water during the whole calculation term (hereafter, referred to as maxTPW) in each grid. High maxTPW over 90 mm appears along the typhoon track in CTL (Fig. 4b). The maxTPW increases by approximately 7% (light and deep orange) around the Kato-Koshin region and partly increases by more than 10% (purple) along the typhoon track (Fig. 4c) in NonW40. The percentages of increase in maxTPW on the right side of the typhoon relative to the moving direction is larger than that on the left side; this is consistent with precipitation changes (Fig. 2e). The percentage of change in water vapor estimated by the Clausius-Clapeyron relation is approximately 6.65% in NonW40 when the regional mean air temperature rises by 0.95 K in NonW40 (Table 2).

In NonW40_SST, changes in the horizontal distribution of maxTPW completely differ (Fig. S2), although the minimum SLPs in NonW40_SST are comparable to those in NonW40. The remarkable difference in maxTPW appears only along the typhoon path and maxTPW differs by 3−4% over the Kanto-Koshin region due to SST warming. The impact of SST changes on maxTPW is limited to around the typhoon’s path.

We focus on the duration from 06 UTC to 21 UTC 12 October 2019, when the typhoon approaches and makes landfall in Japan and heavy precipitation occurred in the Kanto-Koshin region. Heavy precipitation occurs north of the typhoon, especially over the mountainous areas, and is enhanced near the center of the typhoon, and north and east of the typhoon (Fig. 5b). In contrast, precipitation decreases along the northwestern boundary of heavy precipitation areas.

Upward flow at 700 hPa prevails over the Kanto-Koshin region and east of the Kanto-Koshin region (Fig. 5c). The windward and leeward sides of Japan’s mountains produce strong upward and downward flows, respectively. The upward and downward flow anomalies appear on the right and left sides of the typhoon relative to the moving direction in NonW40 (Fig. 5d), where the upward and downward flows prevail in CTL, respectively (Fig. 5c). These changes are consistent with the precipitation changes (Fig. 5b). On the leeward side of the mountains, the inhibition of precipitation related to enhanced downward flow would exceed the increase in precipitation related to moistening due to warming.

4. Discussion

4.1 Topographic effects on precipitation changes due to historical warming

In CTL_NOTP, the horizontal distribution of total precipitation is smoother than that of CTL because there is no topography-induced precipitation (Fig. 2g). However, CTL_NOTP simulates large amounts of precipitation north of typhoon’s track, which is related to the local front on the north side of the typhoon when the typhoon transforms into an extratropical cyclone (Araki 2020). Araki (2020) also quantitatively evaluated the impact of topography on the heavy precipitation and discussed the mechanism of the enhanced precipitation. Our experiments also indicated that the total precipitation is enhanced approximately 26% by the topography in the Kanto-Koshin region (Table 2).

The horizontal patterns of precipitation changes by historical warming are similar to those in the experiments with topography (Fig. 2g). On the other hand, we found that the experiments with topography enhanced the precipitation induced by Typhoon Hagibis (2019) over the Kanto-Koshin region more than did the experiments without topography. The difference in the regional mean precipitation over the Kanto-Koshin region is 6.8% between CTL_NOTP and NonW40_NOTP, which is less than the difference between CTL and NonW40 (10.9%). The value of 6.8% is
similar to the percentage of change in water vapor estimated by the Clausius-Clapeyron relation in NonW40 (6.65%), as stated above. The enhancement of precipitation near the center of the typhoon due to historical warming (Knutson et al. 2020) and the enhancement of topography-induced precipitation related to the increased water vapor flux can synergistically lead to the increase in heavy precipitation of Typhoon Hagibis (2019).

4.2 Uncertainty in the definition of historical warming

We have evaluated the impact of historical warming on Typhoon Hagibis based on the JRA-55. However, the JRA-55 includes not only climatic changes due to increased greenhouse gases but also natural decadal variability, such as the Pacific Decadal Oscillation. Uncertainty in the estimation of historical warming is crucial for studies on the attribution of extreme events to global warming. Lastly, we utilize the d4PDF and evaluate the impact of anthropogenic global warming since the preindustrial period on Typhoon Hagibis (2019).

The horizontal distribution of changes in total precipitation in NonW d4PDF is quite similar to that in NonW40 (Figs. 2e and 2h), although the atmospheric temperature changes are different from those in the JRA-55 (Fig. 1c). Precipitation increases by 13.6% over that in the Kanto-Koshin region (Table 2), which is larger than that estimated by the JRA-55. This is because the temperature differences in NonW d4PDF are larger than those in NonW40 (Fig. 1c). Precipitation slightly decreases on the left (west) side of the typhoon, as with the other experiments.

The ensemble mean minimum SLP in NonW d4PDF is 939.5 hPa and 956.9 hPa around 28.5°N and 35°N, respectively, which are comparable to NonW40, although the differences in SST in NonW d4PDF are approximately 0.4 K larger than those in NonW40 (Table 2). The discrepancy in the relationship between changes in the strength of the typhoon and changes in the SST would be derived from changes in the atmospheric stability (Takemi and Unuma 2020; Kawase et al. 2020). Changes in the atmospheric temperature of d4PDF show larger warming in the upper troposphere (Fig. 1c), meaning that atmospheric stability increases due to historical warming. This stabilization can weaken the impacts of SST warming and moistening on the strength of typhoons.

Similar patterns of changes in typhoon-induced precipitation were simulated by using two types of historical warming, i.e., 40- and 50-year trends in the JRA55 and climate changes from the preindustrial period up to the present in d4PDF, despite different vertical profiles of air temperature. These results indicate that historical warming including the effects of increased anthropogenic greenhouse gases, contributes to the enhancement of heavy precipitation induced by Typhoon Hagibis (2019).

5. Summary

This study investigated impacts of historical warming on extremely heavy precipitation induced by Typhoon Hagibis (2019) using a storyline EA approach. The control experiments well reproduced the typhoon’s track, intensity, and the amounts of precipitation. Sensitivity experiments without atmospheric and oceanic trends from 1980 to 2019 showed that the strength of Typhoon Hagibis (2019) was intensified and the typhoon-induced precipitation was increased by 10.9% over the Kanto-Koshin region due to historical warming. Sensitivity experiments without just the oceanic temperature trends also showed precipitation changes (7.3%), which is smaller than 10.9%. The experiments without Japan's topography, which showed a 6.8% increase in precipitation, indicated that the impact of historical warming on precipitation changes could be enhanced by mountains in the Kanto-Koshin region.

Previous studies pointed out the slowdown of TC related to the slowdown of the subtropical jet due to global warming (Yamaguchi and Maeda 2020; Yamaguchi et al. 2020; Kanada et al. 2020). However, it will be a further study because our experiments only modify the vertical profiles of air temperature and SST. The storyline EA can quantitatively evaluate the impact of global warming on the typhoon. To probabilistically evaluate the impacts of historical warming on typhoons approaching Japan, risk-based EAs using large global ensemble experiments are needed (e.g., Stott et al. 2004; Imada et al. 2014, 2020; Shiogama et al. 2016). Furthermore, higher-resolution experiments without convective parameterization are required to represent small-scale convections (Takayabu et al. 2015). Although some future works remain, the present study undoubtedly shows that historical atmospheric and oceanic warming contributes to the intensification of extremely heavy precipitation induced by Typhoon Hagibis (2019).

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Supplements

Supplement 1 includes one supplemental table and two supplemental figures.

References

Araki, K., 2020: Numerical simulation of heavy rainfall event associated with typhoon Hagibis (2019) with different horizontal resolutions. CAS/JSC WGNE Research Activities in Earth System Modelling, 50, 3.03–3.04.

Cha, E. J., T. R. Knutson, T. C. Lee, M. Ying, and T. Nakagawa, 2020: Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region—Part II: Future projections. Tropical Cyclone Res. Rev., 9, 75–86, doi:10.1016/j.tcr.2020.04.005.

DeMaria, M., C. Sampson, J. Knaff, and K. Musgrave, 2014: Is tropical cyclone intensity guidance improving? Bull. Amer. Meteor. Soc., 95, 387–398.

Hatsuzuka, D., T. Sato, K. Yoshida, M. Ishii, and R. Mizuta, 2020: Regional projection of tropical-cyclone-induced extreme precipitation around Japan based on large ensemble simulations. SOLA, 16, 23–29, doi:10.2151/sola.2020-005.

Imada, Y., H. Shiogama, M. Watanabe, M. Mori, M. Ishii, and M. Kimoto, 2014: The contribution of anthropogenic forcing to the Japanese heat waves of 2013. In “Explaining extreme events of 2013 from a climate perspective”. Bull. Amer. Meteor. Soc., 95, S52–S54.

Imada, Y., M. Watanabe, H. Kawase, H. Shiogama, and M. Arai, 2019: The July 2018 high temperature event in Japan could not have happened without human-induced global warming. SOLA, 15A, 8–12, doi:10.2151/sola.15A-002.

Imada, Y., H. Kawase, M. Watanabe, M. Arai, H. Shiogama, and I. Takayabu, 2020: Challenges of risk-based event attribution for heavy regional rainfall events. NJP Climate Atmos. Sci., 3, doi:10.1088/2631-8755/ab8d1f.

Ishii, M., A. Shouji, S. Sugimoto, and T. Matsumoto, 2005: Objective analyses of sea-surface temperature and marine meteorological variables for the 20th century using ICOADS and the KOBE collection. Int. J. Climatol., 25, 865–879.

Ito, R., T. Takemi, and O. Arakawa, 2016: A possible reduction in the severity of typhoon wind in the northern part of Japan under global warming: A case study. SOLA, 12, 100–105, doi:10.2151/sola.2016-023.

Kanada, S., T. Takemi, M. Kato, S. Yamasaki, H. Fudeyasu, K. Tsukuboki, O. Arakawa, and I. Takayabu, 2017a: A multi-model intercomparison of an intense typhoon in future,
warmer climates by four 5-km-mesh model. *J. Climate, 30*, 6017–6036, doi:10.1175/JCLI-D-16-0715.1.

Kanada, S., K. Tsuboki, H. Aiki, S. Tsujino, and I. Takayabu, 2017b: Future enhancement of heavy rainfall events associated with a typhoon in the midlatitude regions. *SOLA, 13*, 246–251, doi:10.2151/sola.2017-045.

Kanada, S., K. Tsuboki, and I. Takayabu, 2020: Future changes of tropical cyclones in the midlatitudes in 4-km-mesh downscaling experiments from large-ensemble simulations. *SOLA, 16*, 57–63, doi:10.2151/sola.2020-010.

Kawase, H., Y. Imada, H. Tsuguti, T. Nakaegawa, S. Naoko, A. Murata, and I. Takayabu, 2019: The heavy rain event of July 2018 in Japan enhanced by historical warming. *Bull. Amer. Meteor. Soc., 101*, S109–S114, doi:10.1175/BAMS-D-19-0173.1.

Knutson, T., S. J. Camargo, J. C. L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2019: Tropical cyclones and climate change assessment: Part I. Detection and attribution. *Bull. Amer. Meteor. Soc., 100*, 1987–2007, doi:10.1175/BAMS-18-0189.1

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyakoda, and K. Takahashi, 2015: The JRA-55 Reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan, 93*, 5–48, doi:10.2151/jmsj.2015-001.

Lee, T. C., T. R. Knutson, T. Nakaegawa, M. Ying, and E. J. Cha, 2020: Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region—Part I Observed changes, detection and attribution. *Tropical Cyclone Res. Rev., 9*, 1–22, doi:10.1016/j.tcrv.2020.03.001.

Mizuta, R., and co-authors, 2017: Over 5000 years of ensemble future climate simulations by 60-km global and 20-km regional atmospheric models. *Bull. Amer. Meteor. Soc., 98*, 1383–1398, doi:10.1175/BAMS-D-16-0099.1.

Nayak, S., and T. Takemi, 2019: Dynamical downscaling of Typhoon Lionrock (2016) for assessing the resulting hazards under global warming. *J. Meteor. Soc. Japan, 97*, 69–88, doi:10.2151/jmsj.2019-003.

Reed, K. A., A. M. Stansfield, M. F. Wehner, and C. M. Zarzycki, 2020: Forecasted attribution of the human influence on Hurricane Florence. *Science Advances, 6*, doi:10.1126/sciadv.aaw2953.

Saito, K., J. Ishida, K. Aranami, T. Hara, T. Segawa, M. Narita, and Y. Honda, 2007: Nonhydrostatic atmospheric models and operational development at JMA. *J. Meteor. Soc. Japan, 85B*, 271–304, doi:10.2151/jmsj.85B.271.

Shepherd, T. G., and co-authors, 2018: Storylines: An alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change, 151*, 555–571, doi: 10.1007/s10584-018-2317-9.

Shiogama, H., and co-authors, 2016: Attributing historical changes in probabilities of record-breaking daily temperature and precipitation extreme events. *SOLA, 12*, 225–231, doi: 10.2151/sola.2016-045.

Stott, P. A., D. A. Stone, and M. R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature, 432*, 610–613.

Takayabu, I., and co-authors, 2015: Climate change effects on the worst-case storm surge: A case study of Typhoon Haiyan. *Environ. Res. Lett., 10*, 064011, doi:10.1088/1748-9326/10/6/064011.

Takemi, T., R. Ito, and O. Arakawa, 2016: Robustness and uncertainty of projected changes in the impacts of Typhoon Vera (1959) under global warming. *Hydrol. Res. Lett., 10*, 88–94, doi:10.3178/hrl.10.88.

Takemi, T., and T. Unuma, 2020: Environmental factors for the development of heavy rainfall in the eastern part of Japan during Typhoon Hagibis (2019). *SOLA, 16*, 30–36, doi:10.2151/sola.2020-006.

Watanabe, S., A. Murata, H. Sasaki, H. Kawase, and M. Nosaka, 2019: Future projection of tropical cyclone precipitation over Japan with a high-resolution regional climate model. *J. Meteor. Soc. Japan, 97*, 805–820, doi:10.2151/jmsj.2019-045.

Yamaguchi, M., H. Owada, U. Shimada, M. Sawada, T. Irimichi, K. D. Musgrave, and M. DeMaria, 2018: Tropical cyclone intensity prediction in the Western North Pacific basin using SHIPS and JMA/GSM. *SOLA, 14*, 138–143.

Yamaguchi, M., J. C. L. Chan, I. Moon, K. Yoshida, and R. Mizuta, 2020: Global warming changes tropical cyclone translation speed. *Nature Commun., 11*, doi:10.1038/s41467-019-13902-y.

Yamaguchi, M., and S. Maeda, 2020: Slowdown of typhoon translation speeds in autumn influenced by the Pacific oscillation and global warming. *J. Meteor. Soc. Japan, 98*, 1321–1334.