Influence of Warm SST in the Oyashio Region on Rainfall Distribution of Typhoon Hagibis (2019)

Satoshi Iizuka¹, Ryuichi Kawamura², Hisashi Nakamura¹, ³, ⁴, and Toru Miyama¹

¹National Research Institute for Earth Science and Disaster Resilience, Tsukuba, Japan
²Department of Earth and Planetary Sciences, Kyushu University, Fukuoka, Japan
³Research Center for Advanced Science and Technology, University of Tokyo, Tokyo, Japan
⁴Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

Abstract

Typhoon Hagibis (2019) caused widespread flooding and damage over eastern Japan. The associated rainfall maxima were primarily observed on the windward mountain slopes along with the west of the leading edge of a low-level front. Concomitantly, a significant positive value in sea surface temperature anomalies (SSTAs) was observed in association with an ocean eddy over the Oyashio region, together with anomalous warmth over the entire western North Pacific. The present study examines the role of the SSTAs in the rainfall distribution associated with Hagibis, to deepen our understanding of the influence of the midlatitude ocean on tropical cyclones and associated rainfall. Our sensitivity experiments demonstrate that the observed warm SSTAs had the potential to displace the rainfall caused by Hagibis inland and thereby acted to increase precipitation along the Pacific coast of northeastern Japan. Our results suggest that midlatitude SSTAs on ocean-eddy scales can also influence the synoptic-scale atmospheric front and associated heavy rainfall.

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1. Introduction

Typhoon Hagibis (2019) made landfall in the main island of Japan on October 12, 2019. The highest daily precipitation recorded, 922.5 mm, was observed on the day of the typhoon’s landfall by the Hakone Automatic Meteorological Data Acquisition System (AMeDAS) station of the Japan Meteorological Agency (JMA). Furthermore, nearly 30% of the climatological annual rainfall was observed only within 24 h in some municipalities within the Gunma, Saitama, Tokyo, Miyagi, and Iwate prefectures (Fig. S1) (JMA 2019). The heavy rainfall caused widespread flooding and damage over eastern Japan. This rainfall event urged the ongoing need to deepen our understanding for further improvement of prediction skill of the impact of tropical cyclone (TC) landfall.

The importance of high sea surface temperature (SST) in the formation and intensification of TCs has been well known (Gray 1968; Emanuel 1986). It has also been suggested that TC rainfall rate and area both increase with SST in the tropics (Lin et al. 2015). In midlatitudes, however, environmental conditions are different as characterized by cool SSTs and strong baroclinicity. Kim et al. (2018) pointed out that stronger vertical wind shear significantly contributes to an increase in TC rainfall area in rendering it more asymmetric, while SST rarely affects the TC rainfall area.

Figure 1a shows SST distribution on October 11, before Hagibis made landfall in Japan. Ito and Ichikawa (2021) demonstrated that the warm SST anomalies (SSTAs) over the western North Pacific (WNP) accelerated the movement of Hagibis toward Japan. Kawase et al. (2021) documented that the historical warming of both the atmosphere and ocean over the WNP sustained the intensity of Hagibis and increased the associated rainfall. In addition to the anomalous warmth observed uniformly over the WNP, marked positive SSTAs were observed over the Kuroshio off the southern coast of the main island of Japan and over the Kuroshio-Oyashio Extension (KOE) off the east coast of Japan. The former was associated with the Kuroshio large meander (Sugimoto et al. 2020), whereas the latter with a warm-core eddy over the Oyashio (Fig. 1c). Fujiiwara et al. (2020) pointed out that moisture supply from the warm Kuroshio can influence TC intensity under a particular synoptic condition. Unlike most of the studies that focus on the influence of warm (sub-) tropical SSTs on TC development, this study examines the influence of midlatitude SST on the rainfall induced by Hagibis through numerical experiments to deepen our understanding of the impacts of the midlatitude ocean on TCs.

2. Data and model

The analysis data from the JMA Meso Scale Model (MSM) were used to describe synoptic features of the heavy rainfall event due to Hagibis. To validate the simulations, the observations were derived from the best track of the Regional Specialized Meteorological Center Tokyo and radar/rain gauge-analyzed precipitation data provided by JMA.

This study uses the Weather Research and Forecasting (WRF) model (version 4.1.1) (Skamarock et al. 2019). The configuration of the simulations used in the present study are described in the Supplement.

The meteorological initial and lateral boundary conditions were sourced from the Global Forecast System of the National Centers for Environmental Prediction at a grid resolution of 0.25° at 6 h interval. Merged satellite and in situ data Global Daily Sea Surface Temperature (MGDSST), provided by JMA (Sakurai et al. 2005), was used as the lower boundary condition for the control simulation (referred to as CTL-simulation) (Table S1). To assess the response of the Hagibis-induced rainfall to the midlatitude SST, the simulations were performed for 42 h from 12UTC on October 11 before eastern Japan started to receive the rainfall. The SST given at the initial time was not updated throughout the simulations.

To examine the impacts of SSTAs on the precipitation associated with Hagibis, another WRF experiment was carried out under the same meteorological initial and lateral boundary conditions as used for CTL-simulation, but with the climatological-mean MGDSST over the 30-y period, from 1982 to 2011, was prescribed as the lower boundary condition (referred to as CLM-simulation). Another experiment was conducted using SST that was eliminated over the Kuroshio (Fig. S2a) to examine the impacts (referred to as KC-simulation). Additionally, to investigate the impacts of the SSTAs in the Oyashio region on precipitation, we conducted the other simulation prescribing the SST whose gradient had been artificially smoothed only over the specific domain, as indicated by a green box in Fig. 1b (referred to as SMTH-simulation).
windward side of the mountains along the southern coast of eastern Japan (Figs. 2a and 2b) due to the orographic effect acting on the southeasterlies (Fig. S1). After landfall, heavy rainfall spread northward along the east coast of Japan (Figs. 2c and 2d) under the influence of local mountains and a low-level front (LLF) (Figs. 2k and 2l) (JMA 2019).

Takemi and Unuma (2019) documented that both precipitable water vapor and convective available potential energy were anomalously high near the path of Hagibis, favoring heavy rainfall. The convective available potential energy was very high over the mountainous areas where rainfall was observed.

Figures 2a−2d show the time evolution of the 6 h accumulated rainfall (mm) measured by JMA radar-AMeDAS from 00, 06, 12, and 18 UTC, respectively, on 12 October. Black line with cross mark indicates the JMA best track for Hagibis. (a)−(d) Same as in (a)−(d), respectively, but for vertically integrated water vapor (kg m$^{-2}$) (shading) and its transport (kg m$^{-1}$ s$^{-1}$) (arrows) from the surface to 300 hPa, and geopotential height at 500 hPa (contours) of the analysis data. Contour interval is 50 m. (e)−(h) Same as in (a)−(d), respectively, but for air-sea thermal contrast ($^\circ$C) (shading), surface wind at 10 m (m s$^{-1}$) (arrows), magnitude of 975 hPa $\theta$ gradient (K 100-km$^{-1}$) (thick green lines) more than 12 K 100-km$^{-1}$, and sea level pressure (contour) from the analysis data. Contour interval is 10 hPa.

3. Results

3.1 Overview of Typhoon Hagibis

Figures 2a–2d show the time evolution of the 6 h accumulated rainfall from 00 UTC to 18 UTC on October 12. As Hagibis approached Japan, large amounts of rainfall were observed on the windward side of the mountains along the southern coast of eastern Japan (Figs. 2a and 2b) due to the orographic effect acting on the southeasterlies (Fig. S1). After landfall, heavy rainfall spread northward along the east coast of Japan (Figs. 2c and 2d) under the influence of local mountains and a low-level front (LLF) (Figs. 2k and 2l) (JMA 2019).

Takemi and Unuma (2019) documented that both precipitable water vapor and convective available potential energy were anomalously high near the path of Hagibis, favoring heavy rainfall. The convective available potential energy was very high over the mountainous areas where rainfall was observed.
water accompanied by high relative humidity extending throughout the depth of the troposphere and a lower-troposphere lapse rate exceeding the moist adiabatic lapse rate contributed to the heavy rainfall associated with Hagibis. Figures 2e−2h show the time evolution of water vapor and its transport both integrated from the surface to 300 hPa as well as geopotential height at 500 hPa derived from the MSM analysis. Humid air was observed almost uniformly around the center of Hagibis before its landfall (Figs. 2e and 2f), but the distribution gradually became axially asymmetric (Figs. 2g and 2h) as an indication of its transition into an extratropical cyclone.

The interaction of a TC with a pre-existing baroclinic zone has been known to result in its extratropical transition (Harr and Elsberry 2000; Jones et al. 2003; Kitabatake 2008). Before the landfall of Hagibis, a near-surface front was observed along the Pacific coast of eastern Japan, extending northeastward into the Oyashio region (Figs. 2i−2l). The front over the Oyashio region had been associated with a pre-existing extratropical cyclone (JMA 2019). To the south of this front, negative values of air-sea thermal contrast were observed as an indication that the moist southerlies associated with Hagibis were warmer than the underlying ocean. Above the stable boundary layer, deep convection is likely to occur in a conditionally unstable warm air mass in the mid-troposphere (Kitabatake 2008). On the contrary, positive values of air-sea thermal contrast were observed both on the western side of Hagibis and to the north of the LLF under the cool low-level northerlies.

3.2 Control simulation

Figure 3 compares the accumulated rainfall for 24 h from 00UTC on 12 October between the observations (Fig. 3a) and CTL-simulation (Fig. 3b). The comparison indicates that the
rainfall maxima on the windward slope of the mountains have been reasonably reproduced in the CTL-simulation. The temporal evolution of the simulated 6 h accumulated rainfall (Figs. S3a–S3d) is similar to the observations (Figs. 2a–2d). In the simulation, however, precipitable water is somewhat overestimated (Figs. S3e–S3h) than in the MSM analysis (Figs. 2e–2h), due possibly to the lower central pressure of the simulated Hagibis (Fig. S4). Still, compared to the MSM analysis (Figs. 2e–2l), the model reasonably reproduces the extratropical transition of Hagibis, characterized by the asymmetric distribution of precipitable water and the LLF (Figs. S3e–S3l).

While the rainfall maxima south of 38°N were observed mostly on the windward slope of the mountains, a swath of heavy rainfall north of 38°N was located to the west of the LLF (Fig. 4). As Hagibis moved northward, the LLF developed just inland of the east coast (Fig. 4e), extending along the coast up to approximately 40°N (Fig. 4f). Along this front, low-level southeasterlies lead to the frontogenetical shear over the LLF along the coast (Figs. 5b and 5f). The cool air mass advected by the northeasterlies is warmed up due to turbulent mixing within the atmospheric boundary layer around the LLF (Figs. S5b–S5d), inducing the frontolysis over the LLF (Figs. 5e and 5f). The tilting term linked with updraft (Fig. S5d) acts as frontolysis on the onshore side but frontogenesis on the offshore side (Figs. 5d and 5f). The warm, moist airflow from the southeast is lifted up over the cool, dry airflow from the northeast over the frontal zone, yielding latent heat release. In the coastal region (Figs. 5a and 5f), the frontogenetical contributions of the confluence, shear and diabatic terms are largely offset by the strong frontolytic effect by the tilting term. On the offshore side of the front, by contrast, all the terms but the diabatic term contribute positively to frontogenesis.

3.3 Sensitivity experiment

Figure 3d presents the accumulated rainfall for 24 h from 00UTC on 12 October in the CLM-simulation to reveal the impacts of SSTAs over the WNP on the precipitation associated with Hagibis. Its difference between the CTL- and CLM-simulations is widespread over eastern Japan (Fig. 3e), including a notable rainfall difference resulting from the onshore shift of the heavy precipitation area along the east coast north of 38°N. This onshore shift of the heavy precipitation area is related to the corresponding
shift of the LLF (Figs. 3c and 3d). We argue that the warm SSTAs over the WNP (Fig. 1a) had the potential to push the rainfall caused by Hagibis inland.

Figures 6a–6i show time evolution of the differences in surface heat fluxes (SHF) as the sum of sensible and latent heat flux, $\theta$ and moisture at the 975-hPa level between the CTL- and CLM-simulations. At 00UTC on 12 October, the differences in $\theta$ and moisture as well as SHF are accompanied by the cyclonic circulation associated with Hagibis (Figs. 6a, 6d, and 6g), which is attributable to its stronger intensity simulated under the above-normal SST over the WNP (Fig. S4). Furthermore, the warmer SST over the WNP acts to increase near-surface temperature and moisture associated with the southeasterlies off eastern Japan (Figs. 6f and 6i). The associated differences in southeasterly moisture flux off the east coast of Japan eventually yield the onshore shift of LLF in the CTL-simulation relative to CLM-simulation (Figs. 5f, 5g and 5i), leading to an increase in rainfall along the Pacific coast of eastern Japan relative to the CLM-simulation.

The warm positive SSTAs over the Kuroshio also contribute partially to an increase in rainfall along the coast (Fig. S4). However, the corresponding differences from the KC-simulation are much less compared with those from the CLM-simulation, suggesting that the positive SSTAs over the WNP south of the Kuroshio could be more influential in the intensity.

Meanwhile, at 06UTC on 12 October, remarkable $\theta$ and moisture differences are also evident offshore of the east coast north of 38°N (Figs. 6e and 6h), in association with a significant increase in SHF around [42°N, 144°E] over the Oyashio region in the CTL-simulation relative to the CLM-simulation (Fig. 6b). The SHF difference is not significant at 00UTC on 12 October (Fig. 6a), when the northeasterlies are relatively weak (Fig. 6d). Until 12UTC on 12 October, the SHF difference is still significant (Fig. 6c), while both $\theta$ and moisture increase further under the enhanced northeasterlies along the east coast north of 38°N (Figs. 6f and 6i). The anomalous $\theta$ is also accompanied by the stronger southerlies and onshore winds (Fig. 5i), yielding onshore shift of the LLF. This suggests that the onshore LLF shift resulted from both the warm southeasterlies associated with Hagibis and the warmer northeasterlies in response to the higher SST over the Oyashio region.

To further investigate the impacts of the SSTAs in the Oyashio region on the coastal precipitation, we present the accumulated rainfall for 24 h from 00UTC on 12 October in the SMTH-simulation (Fig. 3g), in addition to its difference in the CTL-simulation relative to the SMTH-simulation (Fig. 3h). Though less pronounced, the onshore shift of LLF (Fig. 3i) and the corresponding increase in the accumulated rainfall (Fig. 3h) along the east coast north of 38°N are similar to their counterpart from the CLM-simulation (Figs. 3e and 3f). However, the precipitation difference south of 38°N is not significant. The time evolution of the $\theta$ and moisture differences between CTL- and SMTH-simulations and
the corresponding SHF difference (Figs. 6j−6r) demonstrate that the warmer northeasterlies in response to the higher SST over the Oyashio region are influential along the east coast (Fig. 5j), leading to the onshore shift of the LLF (Fig. 3i) through the slight onshore shift of the maxima of the net frontogenesis, although the relative importance among the individual terms does not significantly change between the CTL- and SMTH-simulations (Figs. 5f and 5h).

Furthermore, we have conducted additional sensitivity experiments where the amplitude of the positive SSTAs observed in the Oyashio region (Fig. 1b) was artificially increased or decreased while flipping its sign. The simulated anomalies in the accumulated rainfall in the coastal region of northeastern Japan north of 38°N are positive (negative) in response to the positive (negative) SSTAs, and the amplitude of the rainfall anomaly tends to increase with that of the SSTAs (Fig. 7). The accumulated precipitation over the region marked with the green box in Fig. 7 for each of the simulations tends to increase with the SSTA over the Oyashio region (Table S1). The fraction over land also shows a similar increasing tendency. However, the relationship is not necessarily linear because the orographic effect acting on the southeasterlies is sensitive to the shift of LLF. These experiments demonstrate the high sensitivity of the rainfall anomaly in the coastal region to SST over the Oyashio region, seemingly through the corresponding sensitivity of the position of the LLF (not shown). We therefore argue that the anomalous warmth of the Oyashio may contribute, at least in part, to the extreme 24-h precipitation by Hagibis observed along the coast of northeastern Japan, which was even in excess of the climatological monthly rainfall in October.

4. Summary

During the passage of Typhoon Hagibis (2019), the extreme rainfall was observed mostly on the windward slope of the mountains, along with the region located to the west of the LLF. At the same time, in addition to the anomalous warmth uniformly over the WNP, SST over the Oyashio region was significantly higher than its climatology in association with a warm-core ocean eddy.
We have assessed the impacts of the SSTAs on the rainfall distribution associated with Hagibis through numerical experiments. Our experiments have demonstrated that the warm SSTAs around the Oyashio were likely to have the potential to push the LLF inland and thereby act to enhance the rainfall along the Pacific coast of northeastern Japan. In fact, our additional sensitivity experiments have also demonstrated a clear tendency for the LLF to shift inland (offshore) under warmer (cooler) SST around the Oyashio region, influential the coastal rainfall. We therefore consider that the anomalous warmth of the Oyashio as well as of the WNP during the autumn of 2019 was likely to contribute to the observed extreme rainfall.

Despite substantial improvement of TC track forecast in recent decades, forecasting local precipitation associated with the landfall of a TC system still remains challenging. This may be attributable partially to difficulty in forecasting the position of an associated front that forms during the transformation of the TC into an extratropical cyclone. Additionally, the currently available satellite-based SST datasets are unable to accurately reproduce the observed fine-scale spatiotemporal SST distributions over the KOE (Kawai et al. 2015). Thus, uncertainties in SST data may also lead to forecast errors of precipitation distribution associated with TCs, including their transformation stage into extratropical cyclones.

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Supplements

Supplement: Supplement describes the configuration of the simulations including one table and five figures.

References

Atallah, E. H., and L. F. Bosart, 2003: The extratropical transition and precipitation distribution of Hurricane Floyd (1999). *Mon. Wea. Rev.*, 131, 1063–1081, doi:10.1175/1520-0493(2003)131<1063:TETAPD>2.0.CO;2.

Colle, B. A., 2003: Numerical simulations of the extratropical transition of Floyd (1999): Structural evolution and responsible mechanisms for the heavy rainfall over the Northeast United States. *Mon. Wea. Rev.*, 131, 2905–2926, doi:10.1175/1520-0493(2003)131<2905:NSOTET>2.0.CO;2.

Emanuel, K. A., 1986: An air-sea interaction theory for tropical cyclones. Part I: Steady-state maintenance. *J. Atmos. Sci.*, 43, 585–604, doi:10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2.

Fujiiwara, K., R. Kawamura, and T. Kawano, 2020: Suppression of tropical cyclone development in response to a remote increase in the latent heat flux over the Kuroshio: A case study for Typhoon Chaba in 2010. *SOLA*, 161, 151–156, doi:10.2151/sola.2020-026.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, 96, 669–700, doi:10.1175/1520-0493(1968)096<0669:GVOTOO>2.0.CO;2.

Harr, P. A., and R. L. Elsberry, 2000: Extratropical transition of tropical cyclones over the western North Pacific. Part I: Evolution of structural characteristics during the transition process. *Mon. Wea. Rev.*, 128, 2613–2633, doi:10.1175/1520-0493(2000)128<2613:ETOTCO>2.0.CO;2.

Fig. 7. Differences in rainfall (mm) accumulated in 24-h from 00UTC on 12 October between the SSTA and CTL-simulations. SSTA shown in Fig. 1b is multiplied by (a) −0.5, (b) −1.5, (c) −2.5, (d) +0.5, (e) +1.5, and (f) +2.5. The 24-h accumulated rainfall averaged over the green box (38.8°N–40.4°N, 141.5°E–142.5°E) in the individual simulations are shown in Table S1.
Ito, K., and H. Ichikawa, 2021: Warm ocean accelerating tropical cyclone Hagibis (2019) through interaction with a mid-latitude jet. SOLA, 17A, 1–6, doi:10.2151/sola.17A-001.

JMA, 2019: A preliminary report on heavy rainfalls and strong winds by Typhoon Hagibis (2019). (Available online at http://www.data.jma.go.jp/bosai/report/2019/201910/2001_09012_1.html, accessed 1 July 2020).

Jones, S. C., P. A. Harr, A. Jim, L. F. Bosart, P. J. Bowyer, J. L. Evans, D. E. Hanley, B. N. Hanstrum, R. E. Hart, F. Lalauvette, M. R. Sinclair, R. K. Smith, and C.Thorncroft, 2003: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions. Wea. Forecasting, 18, 1052–1092, doi:10.1175/1520-0434(2003)018<1052:TETOTC>2.0.CO;2.

Kawai, Y., T. Miyama, S. Iizuka, A. Manda, M. Yoshioka, S. Katagiri, Y. Tachibana, and H. Nakamura, 2015: Marine atmospheric boundary layer and low-level cloud responses to the Kuroshio Extension front in the early summer of 2012: Three-vessel simultaneous observations and numerical simulations. J. Oceanogr., 71, 511–526, doi:10.1007/s10872-014-0266-0.

Kawase, H., M. Yamaguchi, Y. Imada, S. Hayashi, A. Murata, T. Nakaegawa, T. Miyasaka, and I. Takayabu, 2021: Enhancement of extremely heavy precipitation induced by Typhoon Hagibis (2019) due to historical warming. SOLA, 17A, 7–13, doi:10.2151/sola.17A-002.

Kim, D., C. Ho, D. R. Park, J. C. L. Chan, and Y. Jung, 2018: The relationship between tropical cyclone rainfall area and environmental conditions over the subtropical oceans. J. Climate, 31, 4605–4616, doi:10.1175/JCLI-D-17-0712.1.

Kitabatake, N., 2008: Extratropical transition of tropical cyclones in the western North Pacific: Their frontal evolution. Mon. Wea. Rev., 136, 2066–2090, doi:10.1175/2007MWR1958.1.

Lin, Y., M. Zhao, and M. Zhang, 2015: Tropical cyclone rainfall area controlled by relative sea surface temperature. Nat. Commun., 6, 6591, doi:10.1038/ncomms7591.

Powell, S. W., and M. M. Bell, 2019: Near-surface frontogenesis and atmospheric instability along the U.S. east coast during the extratropical transition of Hurricane Matthew (2016). Mon. Wea. Rev., 147, 719–732, doi:10.1175/MWR-D-18-0094.1.

Sakurai, T., Y. Kurihara, and T. Kuragano, 2005: Merged satellite and in-situ data global daily SST. Proc. Int. Geoscience and Remote Sensing Symposium, Seoul, South Korea, IEEE, 2606–2608, doi:10.1109/IGARSS.2005.1525519.

Skamarock, W., J. B. Klemp, J. Dudhia, D. O. Gill, Z. Lin, J. Berner, W. Wang, J. G. Powers, M. G. Duda, D. M. Barker, and X.-Y. Huang, 2019: A description of the Advanced Research WRF version 4. NCAR Tech. Notes, 145 pp., doi:10.5065/1dfh-6p97.

Sugimoto, S., B. Qiu, and A. Kojima, 2020: Marked coastal warming off Tokai attributable to Kuroshio large meander. J. Oceanogr., 76, 141–154, doi:10.1007/s10872-019-00531-8.

Takem, T., and T. Unuma, 2019: 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.

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