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Typhoon-induced precipitation characterization over northern Japan: a case study for typhoons in 2016

Sridhara Nayak*  and Tetsuya Takemi

Abstract

In August 2016, northern Japan was struck by apparently unusual occurrence of the landfall of four typhoons and experienced record-breaking heavy precipitations. This study analyzed the extreme precipitations carried out by these four typhoons to understand their internal structure over northern Japan by computing the probability distributions of precipitation durations with their peak intensities exceeding a range of percentile thresholds starting from 70 to 99%. The main focus was on the duration and size of the extreme precipitations together with the precipitation structure over northern Japan during the passage of each of these four typhoons through different latitudinal locations. To our knowledge, this is the first study to examine the long-lasting and widespread extreme precipitations carried by individual typhoon and such information are crucial for prevention of and protection from typhoon-related hazards over Japan. We find that the typhoons landfalled over Hokkaido region exhibit similar characteristics of precipitation duration, while the typhoon landfalled over Tohoku region shows relatively long-lived precipitation durations. However, all the four typhoons show a robust feature in the precipitation sizes over northern Japan. The occurrence of heavy precipitations with intensity higher than $20\text{--}30\text{ mm h}^{-1}$ is more frequent and last 6 to 9 h over northern Japan. These features may explain the excessive precipitations caused by each typhoon. The important information contained in this study is the duration and size of the precipitations induced by the typhoons vary depending on the landfalling region. However, the precipitation characteristics associated with all the three typhoons landfalled over Hokkaido show mostly robust features. This study gives a first step towards a description of the spatio-temporal characteristics of typhoon-induced precipitations and has an overall implication towards the future research that is needed for the assessment of typhoon-induced precipitation-related disasters in future warming climate.

Keywords: Precipitation characterization, Precipitation size, Precipitation duration, Typhoon, Radar-AMeDAS

Introduction

Tropical cyclones (TCs) are gigantic, destructive, and deadly disaster-spawning weather phenomena that bring very heavy precipitations and widespread flooding to coastal regions. According to the study of Pfahl and Wernli (2012), a high percentage of precipitation extremes (up to 80%) is directly related to cyclones over the Mediterranean region, Newfoundland, near Japan, and over the South China Sea. Su et al. (2012) reported

that the tropical cyclones over Taiwan bring about 70% of extreme precipitations in July–October season. Kama-hori and Arakawa (2018) evaluated typhoon-induced precipitation over Japan from the rain gauge observation for the period 1981–2010 and highlighted that the largest annual precipitation amount, which is 15% or more of the total annual precipitation, over western Japan is due to the TC activities. Thus, characterization of tropical cyclone-induced precipitation has been the focus of many studies not only for an individual tropical cyclone (e.g., Lin and Jeng 2000; Ishikawa et al. 2013; Chaithong et al. 2018) but also for the climatological period (e.g.,

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Cheung et al. 2018; Kim and Jain 2011; Su et al. 2012; Kamahori and Arakawa 2018).

Over the year, a large number of typhoons form over the western North Pacific region, and some of them became highly destructive, for example, Typhoon Vera (1959), Typhoon Mireille (1991), Typhoon Songda (2004), Typhoon Haiyan (2013), Typhoon Jebi (2018), and Typhoon Hagibis (2019) and caused severe and widespread damages by extreme precipitations (Oku et al. 2010; Mori et al. 2014; Mori and Takemi 2016; Takemi et al. 2016a, 2016b; Ito et al. 2016; Kanada et al. 2017; Takemi 2018; Takemi et al. 2019; Takemi 2019; Takemi and Ito 2020; Takemi and Unuma 2020). Such extreme typhoons strongly cause flash floods, landslides, and mudslides over large areas in a short period of time (Emanuel 2005; IPCC 2013, 2014; Takemi et al. 2016c; Guan et al. 2018). In the context of characterization of extreme precipitation events over Japan, several studies have been conducted in order to assess the spatial and temporal variability of precipitation amounts in different scales mostly either at the climatological period (e.g. Kanada et al. 2010, 2017) or at the baiu seasonal period (e.g., Duan et al. 2017; Yokoyama et al. 2017). Few studies have also been conducted for individual extremely heavy precipitation events over Japan to understand the precipitation distribution and their characteristics at convective and synoptic scale (Ishikawa et al. 2013; Takemi 2018; Kato et al. 2018; Tsuguti et al. 2019). However, to understand the severity of such disastrous events, studies are limited to get the information about the internal temporal-spatial precipitation structure in individual typhoons and particularly the duration and size of the precipitation within the typhoons.

In August 2016, northern Japan was stuck by apparently unusual occurrence of the landfall of four typhoons named as Typhoon Chanthu (T1607), Mindulle (T1609), Lionrock (T1610), and Kompasu (T1611). These were the series of typhoons moving northward near Japan, and three of them (except Typhoon Lionrock) landed on Hokkaido based on the Regional Specialized Meteorological Center (RSMC) Tokyo's best-track datasets. It was the first time till date that three typhoons landed on Hokkaido in a year. Typhoon Lionrock landed in the Pacific Ocean side of the Tohoku region in northern Japan. It was also for the first time in the history among the records (since 1951) available at Japan Meteorological Agency (JMA). All these typhoons made landfall with strong winds and brought heavy precipitations to the landfall regions and destroyed many lives and properties.

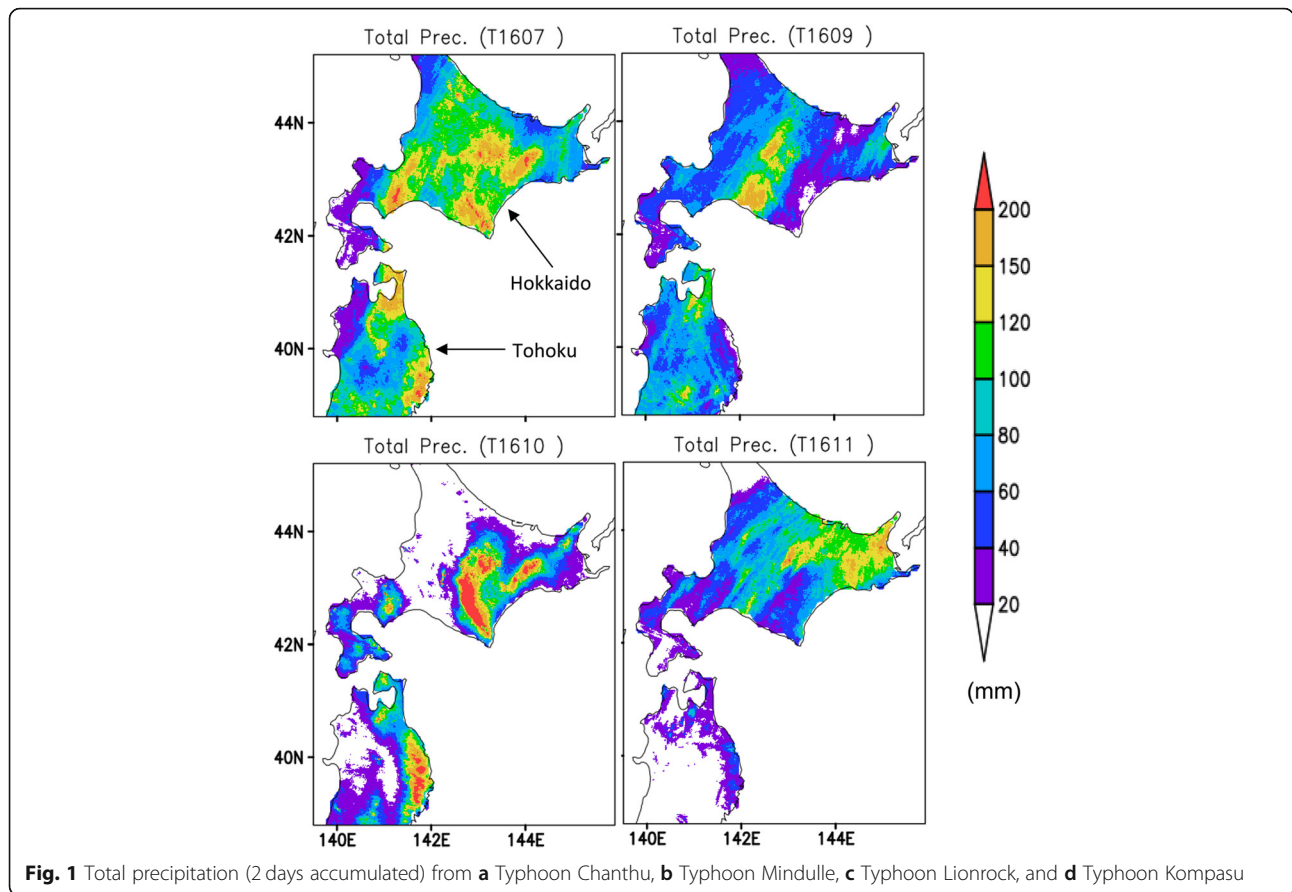
However, neither model nor observational data have yet been analyzed for individual typhoons that can explain the long-lasting and widespread extreme precipitations carried by a typhoon, and such information are crucial for prevention of and protection from typhoon-

related hazards over Japan. Such assessments are also important in storm impacts for the proper interpretation of precipitation information, particularly to determine and map the vulnerability of the typhoon landfall region. In addition, the space and duration analysis of extreme precipitations provides robust results to determine the possible impacts and the monitoring of climate risks. We thus attempted to investigate the temporal and spatial characteristics of precipitation produced by typhoons to explore (1) the distribution, extremes, duration, size, and frequency of the precipitation induced by each typhoon, (2) the duration and size of heavy precipitations together with the precipitation duration versus peak intensity characteristics in each typhoon, and (3) the precipitation structure over northern Japan during the passage of each typhoon through different latitudinal locations. For this purpose, we used rain gauge-radar precipitation analysis data. The four typhoons in 2016 were chosen here, because they produced record-breaking heavy precipitations in northern Japan. These cases are considered to be appropriate examples to understand the spatio-temporal characteristics of typhoon-induced extreme precipitations in northern Japan. In addition, recent analysis precipitation data produced by merging rain gauges and radars have a high spatial resolution, which is useful to quantitatively characterize extreme precipitations.

Data and methods

We analyzed the hourly observations of precipitation from the Radar Automated Meteorological Data Acquisition System (Radar-AMeDAS) analyzed precipitation datasets at 1 km resolution for each typhoon separately from each grid points over land in northern Japan (Fig. 1). The Radar-AMeDAS observations are the radar/rain gauge-analyzed precipitation product available at 1 km grid over Japan which provides the composite radar-derived rainfall maps calibrated with rain gauges based on radar observation of rainfall intensity. We analyzed the Radar-AMeDAS data for 2 days for each typhoon separately keeping the typhoon landfall time (over Japanese land) as the center of the total selected duration. An overview of the lifetime period of each typhoon and the time period used in this study is described in Table 1. The total sample points over the land were about 6 M for each typhoon obtained from 560×840 grid points at 48 h.

In this study, we reproduced the Kendon et al. (2012) methodology using all the grids points (land only) for each typhoon separately. We investigated the distribution, extremes, frequency, duration, and size of the precipitations induced by each typhoon with different thresholds (50th to 99th precipitation percentile). To compute the duration of the precipitations, we identified the independent precipitation durations above a



threshold in the hourly time series at each grid point. An independent duration is defined as continuous periods of precipitation exceeding the threshold. Then, we computed the mean and maximum intensity of precipitations in each duration and stratified the precipitation durations with intensity exceeding various precipitation thresholds in different duration bins with 1 h interval. Finally, the probability distributions are computed in each duration bin. To compute the size of the precipitations, we identified the independent precipitation cells above a threshold over the land at each hour. An independent cell is defined as the connected grids (diagonals are excluded) with precipitation intensity exceeding the threshold. We computed the mean and maximum intensity of precipitations in each cell and stratified the precipitation cells with intensity exceeding various precipitation thresholds in different cell bins with 1 km

internal. Finally, the probability distributions are computed in each cell bin. The peak intensity in each precipitation duration is also examined to explore the relationship between the heaviest precipitation and its entire duration. To understand such temporal structure of the peak intensified precipitations carried by each typhoon, we computed the joint probability distribution of precipitation durations with their peak intensities exceeding a range of percentile thresholds starting from 70 to 99%. Mathematically,

$$P(A \cap B) = P(A) \cdot P(B) \tag{1}$$

where P is the probability, A is the collection of independent precipitation durations, and B is the peak intensity at each precipitation duration.

Table 1 Overview of each typhoon and time periods used in this study

Typhoon name	Lifetime duration (in year 2016)	Maximum wind speed	Minimum pressure	Time period used (in year 2016)
Chanthu (T1607)	18UTC 13Aug–18UTC 17Aug	55 knots	980 hPa	00UTC 16Aug–23UTC 17Aug
Mindulle (T1609)	06UTC 19Aug–03UTC 23Aug	60 knots	975 hPa	12UTC 21Aug–11UTC 23Aug
Lionrock (T1610)	12UTC 21Aug–15UTC 30Aug	90 knots	940 hPa	12UTC 29Aug–11UTC 31Aug
Kompasu (T1611)	00UTC 20Aug–18UTC 21 Aug	35 knots	994 hPa	06UTC 20Aug–05UTC 22Aug

Results

Precipitation distribution

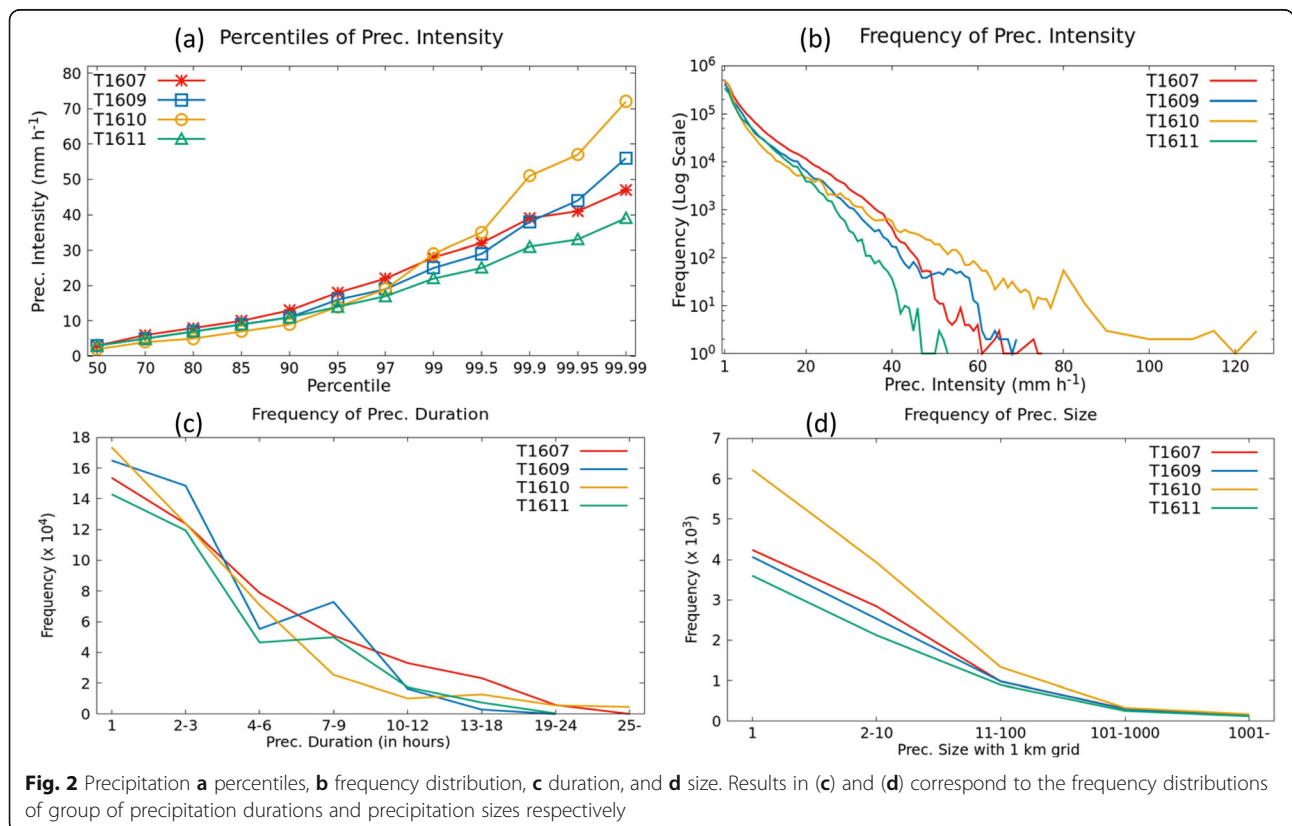
The spatial distribution of total precipitation amounts during the passage of each typhoon over northern Japan is shown in Fig. 1. The results indicate that all the four typhoons brought heavy precipitations to the northern Japan. T1607 and T1610 brought total precipitations of greater than 200 mm to the landfall regions in Hokkaido and Tohoku regions, as already shown in the previous studies of Kanada et al. (2017) and Nayak and Takemi (2019a, 2019b). T1609 and T1611 brought relatively less precipitation and greater than 150 mm to some areas over Hokkaido.

Figure 2 shows the extremes, frequencies, durations, and size of hourly precipitations (≥ 1 mm) induced by each typhoon evaluated on the land regions shown in Fig. 1. The extremes are analyzed at different percentiles of precipitation intensities starting from 50th to 99.99th for each typhoon (Fig. 2a). We find that the extreme precipitation intensities (up to 95th percentile) carried by all the four typhoons are almost the same. The 99th percentile of all the four typhoons correspond to 20–30 mm h⁻¹ precipitation intensity, while the 99.99th value of T1610 corresponds to 72 mm h⁻¹, and those of other three typhoons correspond to 40–60 mm h⁻¹. The frequency distribution of the precipitation intensities induced by each typhoon is shown in Fig. 2b. We find that

the frequencies of precipitations with intensity up to ~ 30 mm h⁻¹ are similar for all the four typhoons. Stronger precipitations brought by T1610 have intensities above 120 mm h⁻¹, while that carried by other three typhoons have intensities 55–75 mm h⁻¹. Figure 2c shows the frequency distribution of group of precipitation durations induced by each typhoon. It shows that the precipitations carried by all the four typhoons are mostly short-lived and last up to 3 h, while some precipitations last up to 12 h. All the four typhoons also carried long-lived precipitations which last up to a day or longer, although the precipitations that last more than a day are not so frequent. Figure 3d represents the frequency of group of precipitation sizes brought by each typhoon. It shows that all the four typhoons brought more frequent localized precipitations (within 10 km²) than widespread precipitations (> 100 km²). It is noticed that all the three landfalling typhoons (i.e., the cases except T1610) over Hokkaido show similar characteristics of precipitation sizes.

Precipitation intensity

Figure 3 depicts the mean intensities in the different group of durations and sizes of typhoon-induced precipitations. It shows that most frequent short-lived precipitations correspond to about 6–10 mm h⁻¹ mean intensity (Fig. 3a–d), while the long-lived precipitations



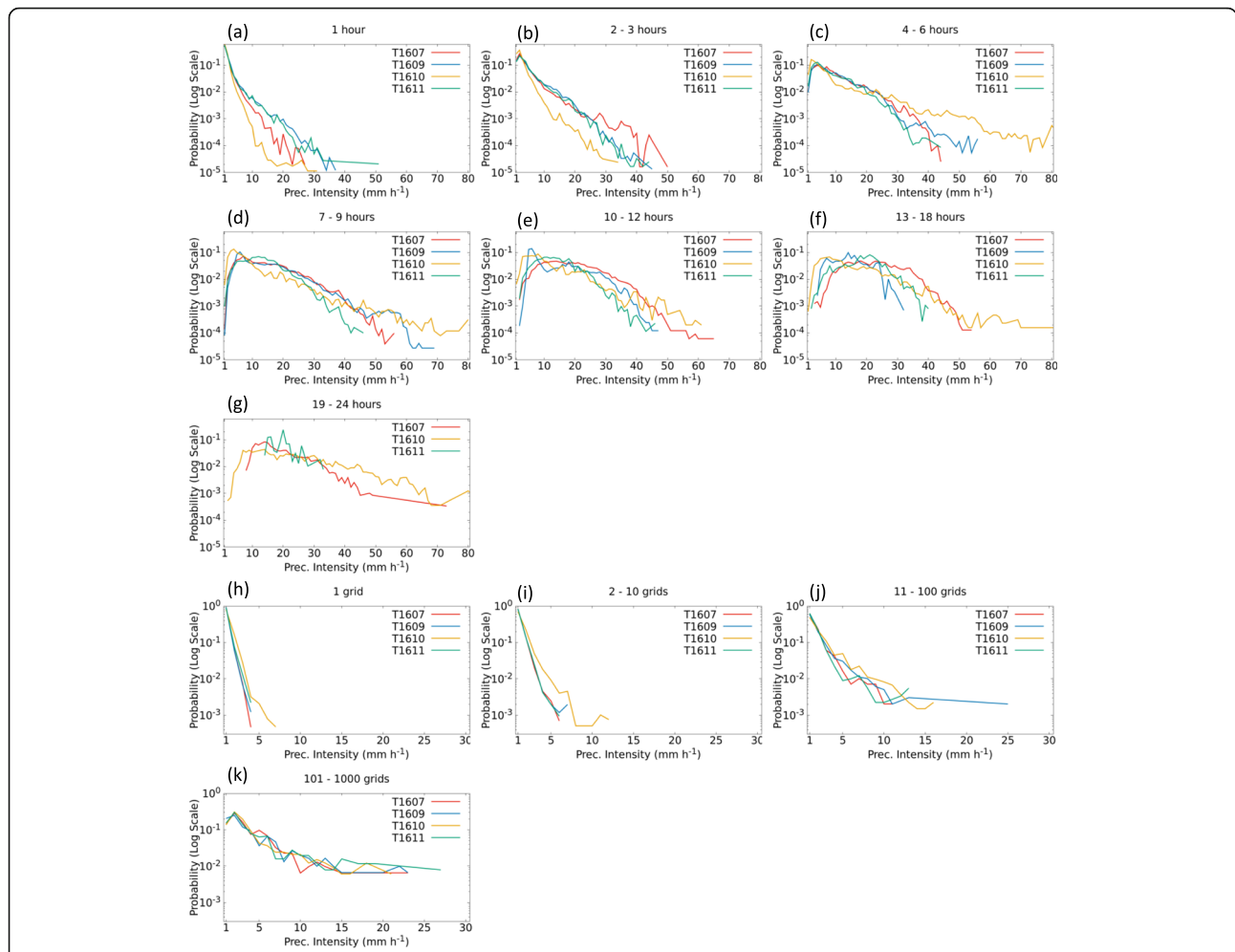


Fig. 3 Probability of intensity of precipitation (a–g) duration and (h–k) size

have intensity 15–20 mm h⁻¹ (Fig. 3f, g). Longer duration (19–24 h) precipitations correspond up to ~ 20 mm h⁻¹ except for T1609 (Fig. 3g). The T1609 brought up to 18 h duration precipitation with mean intensity up to 30 mm h⁻¹, whereas the T1611 carried relatively longer durations (up to a day), but with same intensity. On the other hand, T1607 and T1610 brought long-lived stronger precipitations with intensity more than 70 mm h⁻¹. The results of mean intensities in the precipitation sizes indicate that the intensity increases with the size of the precipitation (Fig. 3h–k). The localized precipitations (1–10 grids) correspond to mean intensity up to 10 mm h⁻¹, while the widespread precipitation (11–1000 grids) shows higher intensity. All the four typhoons show mostly similar characteristics of mean intensity in precipitation sizes. These results indicate that longer duration precipitations are mostly stronger (Fig. 3e–g) compare to shorter duration precipitations (Fig. 3a, b), and smaller sized precipitations are weaker (Fig. 3h, i) compared to larger sized precipitation (Fig. 3j, k).

Duration of heavy precipitations

In this section, we analyzed the temporal features of the precipitations carried by each typhoon with intensity exceeding a range of percentile thresholds. This is shown in Fig. 4. Each curve in Fig. 4 depicts the probability distribution of precipitation durations with intensity exceeding a percentile threshold starting from 70 to 99%. The results indicate that the short-duration precipitations (less than 3 h) occur more frequently compare to long-duration precipitations irrespective of percentile thresholds. For T1607, T1609, and T1611, extreme precipitations with intensity higher than 99th percentile tend to be short-lived and lasted up to 4 h, while the precipitations with intensity higher than 90th percentile continued up to 6 h and that with intensity exceeding 70th percentile lasted up to 12 h. For T1609, the heavy precipitations with intensity exceeding 99th percentile continued up to 6 h, while those with intensities higher than 95th percentiles are long-lived and lasted more than 18 h. These results indicate that the typhoons landfalling over Hokkaido region show almost

same precipitation duration characteristics compared to the precipitation durations of the typhoon landfalled over Tohoku region.

Size of heavy precipitations

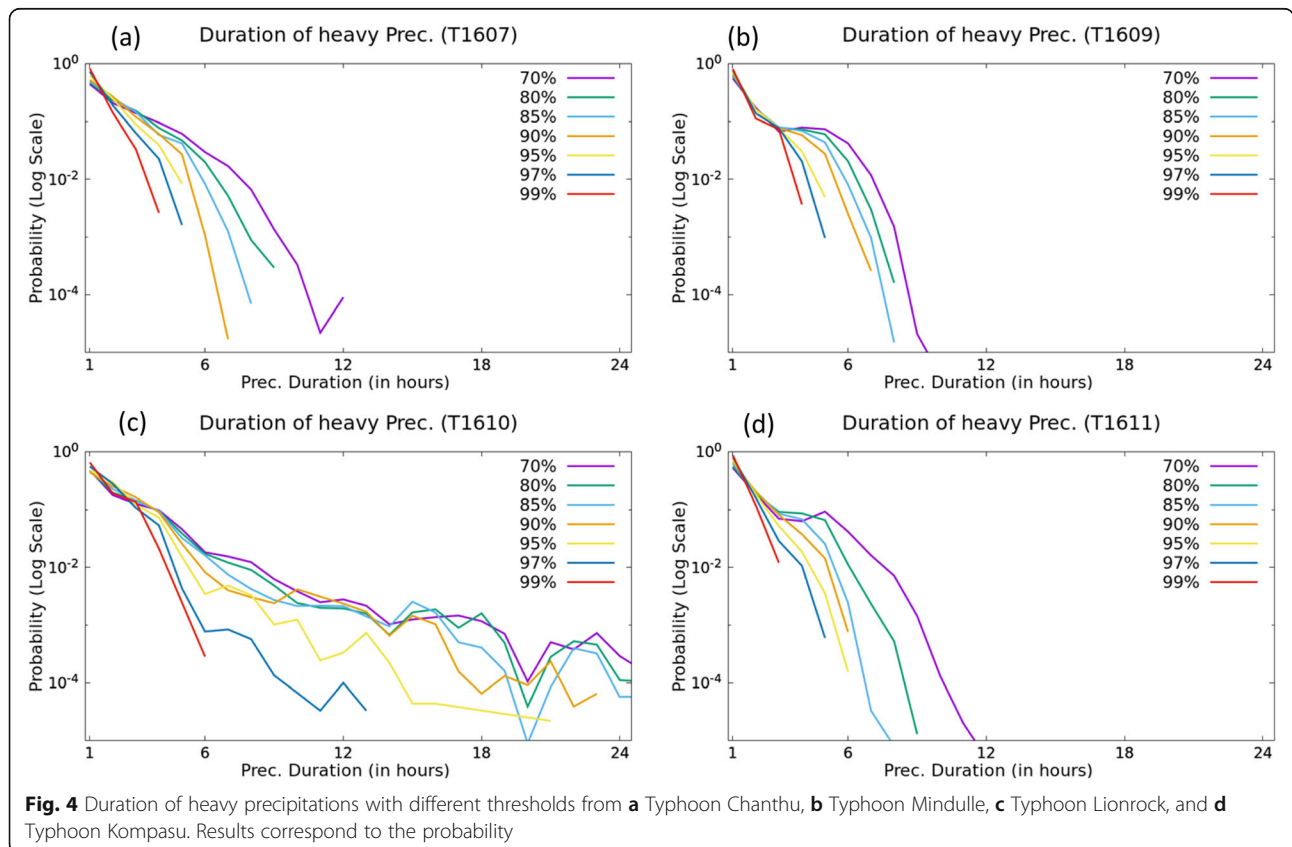
To assess the heavy precipitations in terms of its spatial structure, we investigated the size of precipitations carried by each typhoon with intensities exceeding various percentile thresholds. Figure 5 represents the probability distribution of precipitation sizes with intensity thresholds starting from 70 to 99%. We find that all the four typhoons carried more frequent localized heavy precipitations compared to the widespread precipitations brought by these typhoons. Higher frequency of localized extreme precipitations associated with each typhoon is found to have spatial scales within 20 km². There are also widespread precipitations larger than 100 km², but not so frequent (Fig. 2d). However, the precipitation sizes up to 40 km² areas with intensity exceeding 99th percentile tend to be more frequent. All the four typhoons show similar characteristics of precipitation sizes, indicating a robust feature in the spatial structure of the typhoon-induced precipitations over northern Japan.

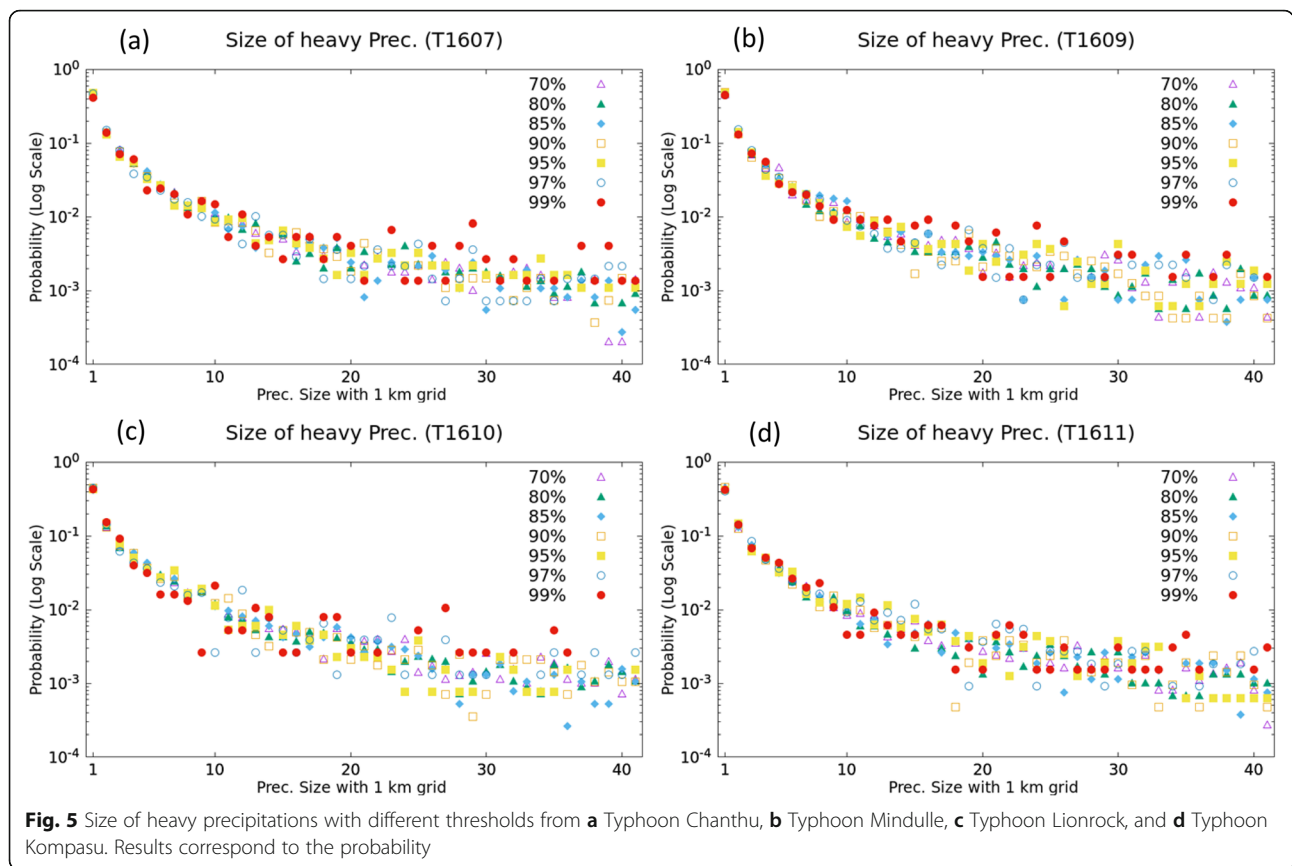
Precipitation duration versus peak intensity

In this section, we examined the duration-intensity characteristics of typhoon-induced precipitations from Eq. (1) by considering peak intensities in each precipitation duration exceeding a range of percentile thresholds (Fig. 6). We find that low peak precipitations (for instance exceeding the intensity 70th percentile) tend to be more short-lived, with a decreasing probability of high peak precipitations with increasing percentile thresholds. For the typhoons landfalled over Hokkaido, the probabilities of 8–9 h long precipitations are higher and carried high peak precipitations. These features may explain the excessive precipitations caused by each typhoon. For T1610, we find that all the peak precipitations lasted for 6 h, and their probability tends to be higher than compare to long-lived precipitation. These results indicate that all the typhoons over northern Japan carry more frequent heavy precipitations with intensity higher than 20–30 mm h⁻¹ for continuous 6 to 9 h.

Precipitation structure

To understand the precipitation structure of each typhoon, we examined the area-averaged accumulated precipitations over northern Japan during the passage of each typhoon through different latitudinal locations





starting from 35 to 45 N (Fig. 7). We find that all the four typhoons during their location below 39 N do not bring substantial precipitations to the land over northern Japan. T1607 brought the highest amount of precipitation, while T1611 brought comparably the lowest amount.

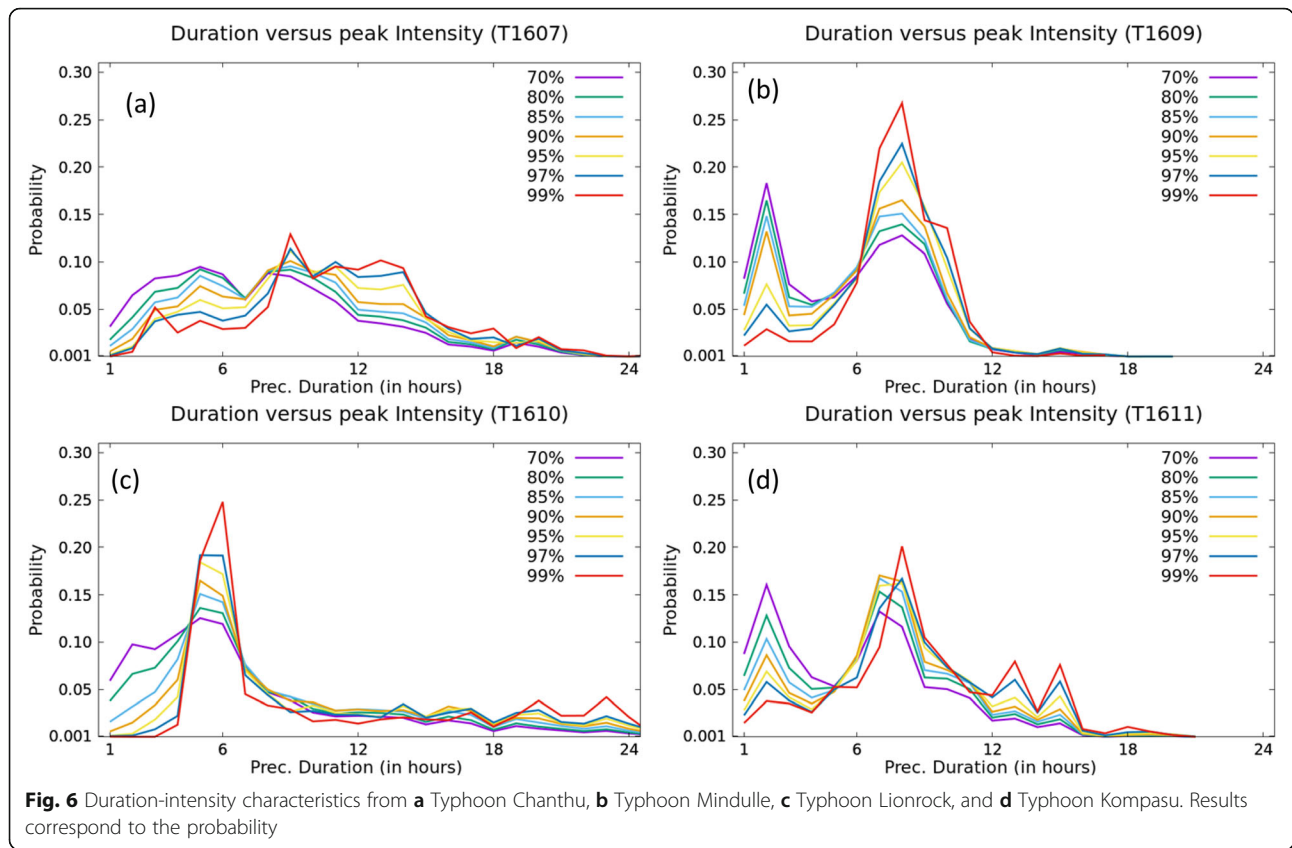
Figure 8 shows the longitudinal averaged precipitations at different latitudes starting from 39 to 45 N during the passage of each typhoon through various latitudinal locations starting from 35 to 45 N. For T1607 and T1609, a strong propagating precipitation region is observed when the typhoon locations were at 38–41 N and at 43 N, while for the T1610, the strong propagating signal was observed at 38–43 N, and for T1611, it was 39–40 N. This implies that all the four typhoons reaching 39 N carried large amount of precipitation to the land over northern Japan. It is noted that the precipitation areas generally extend to the north of the typhoon centers.

Discussion

This paper investigated the temporal and spatial characteristics of precipitations induced by four typhoons land-falled over northern Japan. We first focused on the distribution, extremes, duration, size, and frequency of the precipitations induced by each typhoon. Our results indicate that two typhoons (T1607 and T1610) carried

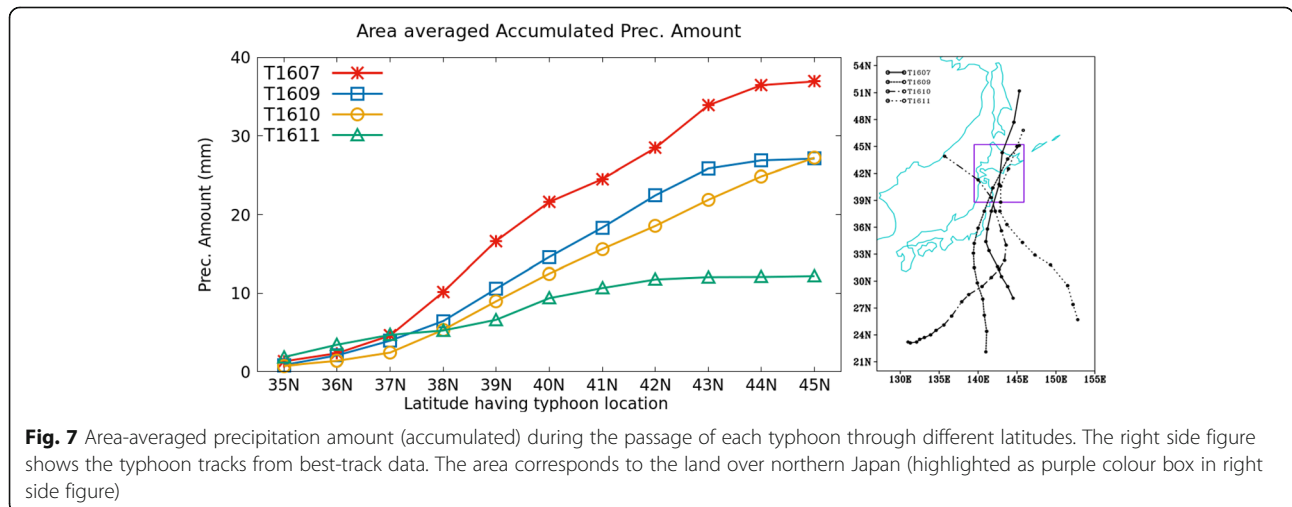
relatively high amount of precipitations (> 200 mm) to the landfall regions in Hokkaido and Tohoku regions while other two (T1609 and T1610) brought relatively less amount (> 150 mm). T1610 brought stronger precipitations with intensity above 120 mm h⁻¹, while others carried the same with 55–75 mm h⁻¹. T1610 carried long-lived localized precipitation, while T1607 and T1611 brought short-lived widespread precipitation.

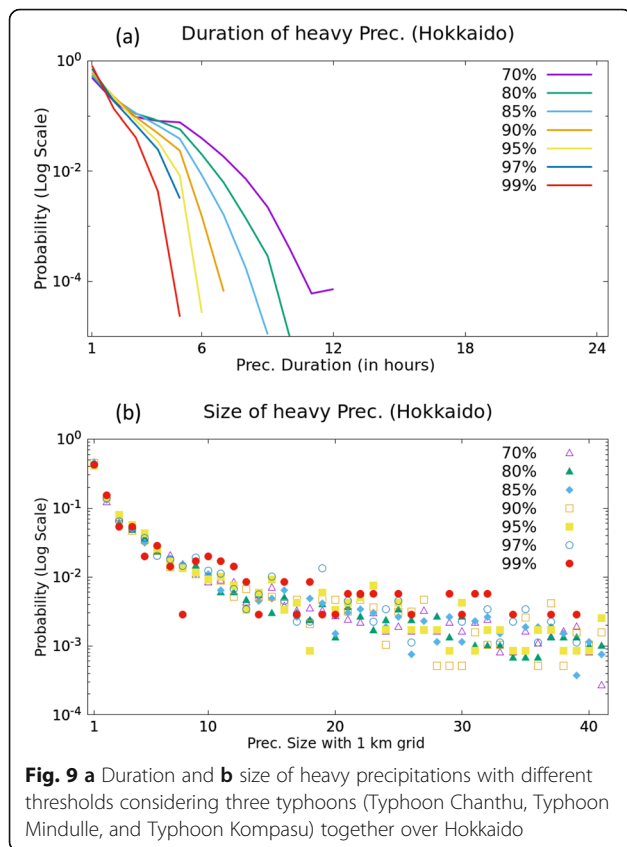
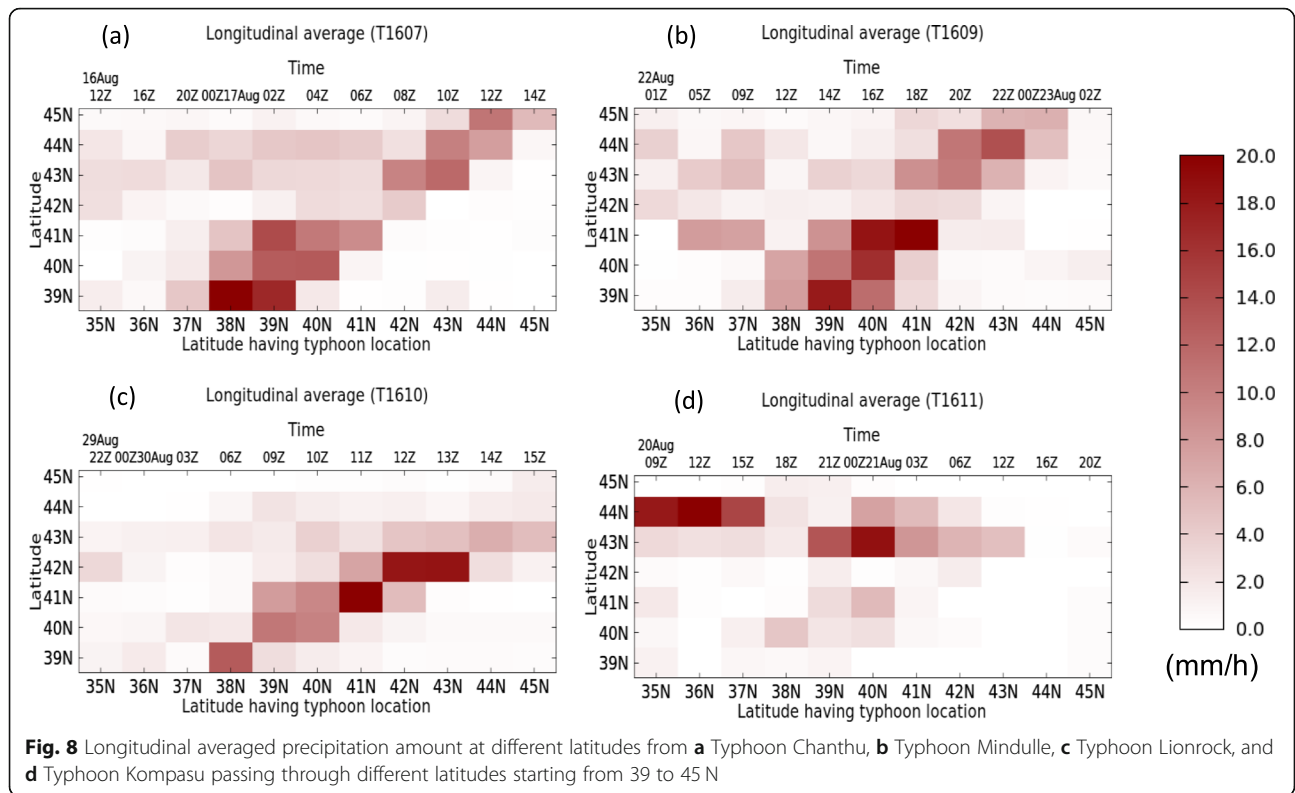
Next, we examined the duration and size of heavy precipitations associated with each typhoon. We find that the typhoons landfalled over Hokkaido region exhibit similar characteristics of precipitation duration (Fig. 4a, b, d), while the typhoon landfalled over Tohoku region shows relatively long-lived precipitation durations (Fig. 4c). However, all the four typhoons show a robust feature in the precipitation sizes over northern Japan. We also analyzed the duration and size of heavy precipitations with different thresholds starting from 70 to 99% considering three typhoons (Typhoon Chanthu, Typhoon Mindulle, and Typhoon Kompasu) together over Hokkaido and shown in Fig. 9. Results indicated that in the combined case over Hokkaido, the typhoon-induced precipitations with intensity higher than 95th percentile lasted up to 6 h, while the precipitations with intensity higher than 50th percentile tend to be long-lived and continued up to 12 h (Fig. 9a). The size of the typhoon-induced precipitations in the



combined case over Hokkaido showed more frequent localized heavy precipitations with spatial scales within 20 km² (Fig. 9b). Overall results indicated that the characteristics of precipitation duration and sizes in the combined cases are mostly same as of individual typhoon landfalled over Hokkaido. To understand the mechanism on why do the typhoons landfalled over Hokkaido region exhibit similar precipitation duration characteristics, we analyzed the atmospheric water vapor from the 3 hourly forecast

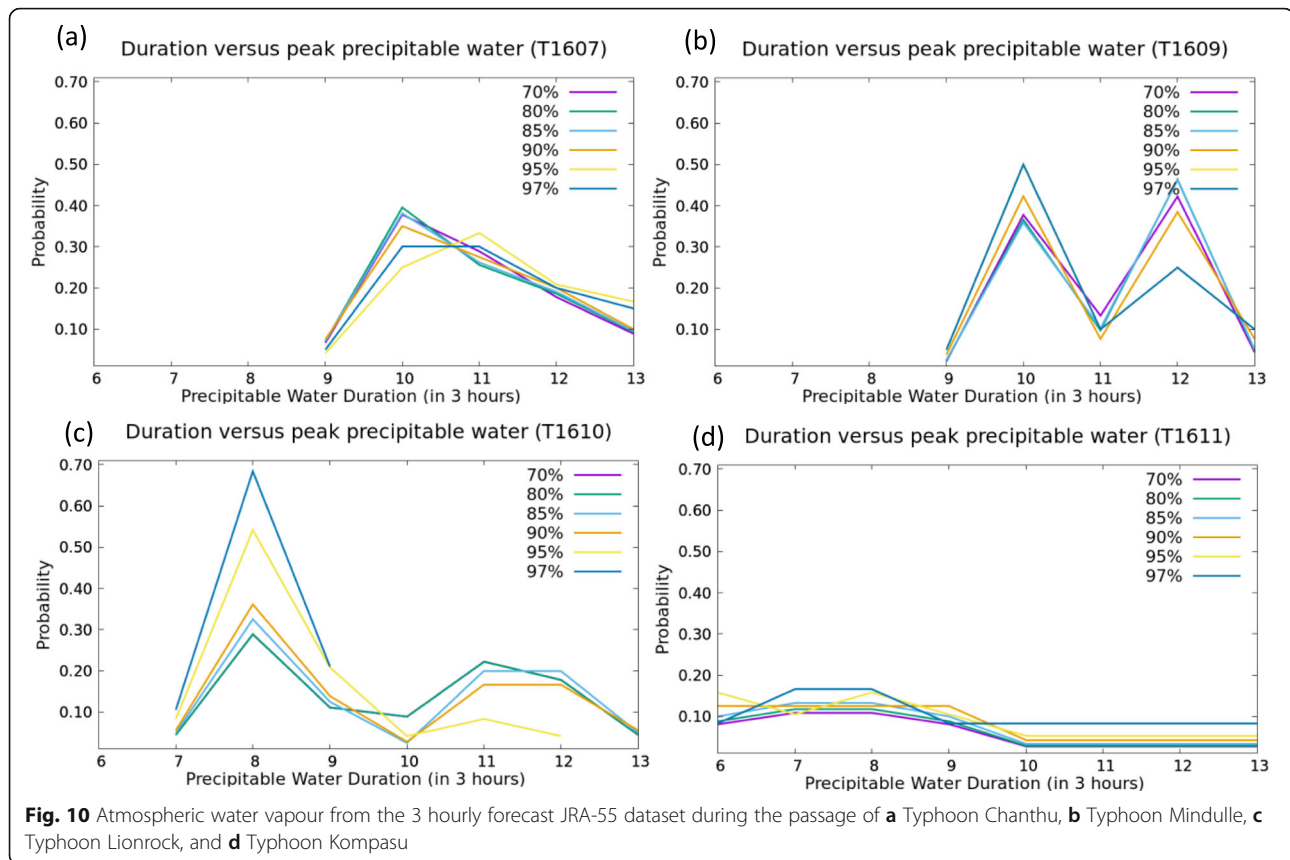
Japanese Reanalysis (JRA-55, Kobayashi et al. 2015) data of JMA during the passage of each individual typhoon over northern Japan (Fig. 10). We find that the supply of atmospheric moisture plays an important rule to maintain the precipitation duration. A closer investigation in Fig. 10 shows that all the four typhoon supplied continuous moisture and formed peak. This possibly brought continuous precipitations up to certain duration and then decreased as the moisture supply gradually decreased in time (Fig.





10). We further explored the precipitation duration versus peak intensity characteristics in each typhoon. Our results indicate that the occurrence of heavy precipitations with intensity higher than $20\text{--}30\text{ mm h}^{-1}$ (~ 99 th percentile) is more frequent and last 6 to 9 ho over northern Japan (Fig. 6). It should be noted that large amount of atmospheric moisture over any particular region is mostly available for 6–9 h for each typhoon (Fig. 10). This could be the reason that each typhoon carried heaviest precipitations for 6–9 h. The availability of moisture during T1607 and T1609 also shows peaks similar to its precipitation duration-intensity behavior (Fig. 6a, b and Fig. 10a, b). In case of T1610, the peak in moisture availability is relatively earlier compare to T1607 and T1609 (Fig. 10c), implying relatively earlier in peak duration precipitations (Fig. 6c). The moisture availability in case T1611 also shows some peaks although they are very low (Fig. 10d).

These results are important to enhance the understanding of how vulnerable the landfall region will be. Kamahori and Arakawa (2018) discussed the return period of typhoon-induced annual maximum precipitations and highlighted the occurrence of such extremes once in 50 years possible cause flashflood. Moreover, Morimoto et al. (2019) reported forest damages over northern Japan due to Typhoon Songda (2004). It is apparent that the average surface temperature across the globe is increasing, thus intensifying the extreme precipitation events (IPCC 2014; Nayak and Takemi 2019c).



Several studies also highlighted that the extreme weather events such as typhoons, floods, and heavy precipitation events over Japan would be more intense due to warming (Nayak and Dairaku 2016; Kanada et al. 2017; Nayak et al. 2018; Kawase et al. 2020). Likewise, various studies reported that typhoons in future warming climate are expected to carry more precipitations to landfall regions (Takemi et al. 2016a; Kanada et al. 2017; Nayak and Takemi 2019a). To reveal and better characterize such features, application of climate model is needed. So, we believe that our study gives a first step towards a description of the spatio-temporal characteristics of typhoon-induced precipitations and can be used to evaluate the model results for the assessment of typhoon-induced precipitation-related disasters in future warming climate.

Conclusions

In this study, we examined the long-lasting and widespread extreme precipitations carried by four typhoons in August 2016 over northern Japan from the very high spatial resolution rain gauge-radar precipitation analysis data. The results indicate that the durations of the extreme precipitations induced by the three typhoons landfalling over Hokkaido region exhibit similar features, while the typhoon landfalled over Tohoku region shows

relatively long-lived extreme precipitation durations. However, all the four typhoons show similar spatial structure of the typhoon-induced precipitations over northern Japan. All the four typhoons also carried long-lived precipitations which last up to a day or longer and more frequent localized precipitations than widespread precipitations. The frequencies of precipitations with intensity up to $\sim 30 \text{ mm h}^{-1}$ are similar for all the four typhoons. The occurrence of extremely heavy precipitations (higher than 99th percentile) carried out by all the four typhoons is mostly last up to 6–9 h. These features may explain the excessive precipitations caused by each typhoon. The results of the precipitation structure during the passage of each typhoon through different latitudinal locations indicate that all the four typhoons reproduce heavy precipitations over the land in northern Japan when they reach at 39°N. Overall, the important information contained in this study is the duration and size of the precipitations induced by the four typhoons vary depending on the landfalling region. However, the precipitation characteristics associated with all the typhoons landfalled over Hokkaido show mostly robust features. More research is needed to get a better understanding of the processes involved in typhoon-induced precipitation by using some very high resolution climate model and their response to future climate change.

Abbreviations

TC: Tropical cyclone; Radar-AMeDAS: Radar Automated Meteorological Data Acquisition System; JMA: Japan Meteorological Agency; T1607: Typhoon Chanthu; T1609: Typhoon Mindulle; T1610: Typhoon Lionrock; T1611: Typhoon Kompas; IPCC: Intergovernmental Panel on Climate Change; RSMC: Regional Specialized Meteorological Center

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Authors' contributions

SN proposed the topic, designed the study, analyzed the data, and drafted the manuscript. TT helped in the interpretation and the construction of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The Radar/Rain gauge-Analyzed Precipitation dataset supporting the conclusions of this article is obtained from the Japan Meteorological Agency (JMA, www.jmbasc.or.jp).

Competing interests

The authors declare that they have no competing interest.

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