

Risk-based versus storyline approaches for global warming impact assessment on basin-averaged extreme rainfall: a case study for Typhoon Hagibis in eastern Japan

Tanaka, Tomohiro
Graduate School of Engineering, Kyoto University

Kawase, Hiroaki
Meteorological Research Institute, Japan Meteorological Agency

Imada, Yukiko
Atmosphere and Ocean Research Institute, the University of Tokyo

Kawai, Yuki
Consulting Business Division Human Resources & Organization Business Unit, Mitsubishi UFJ Research and Consulting Co., Ltd

他

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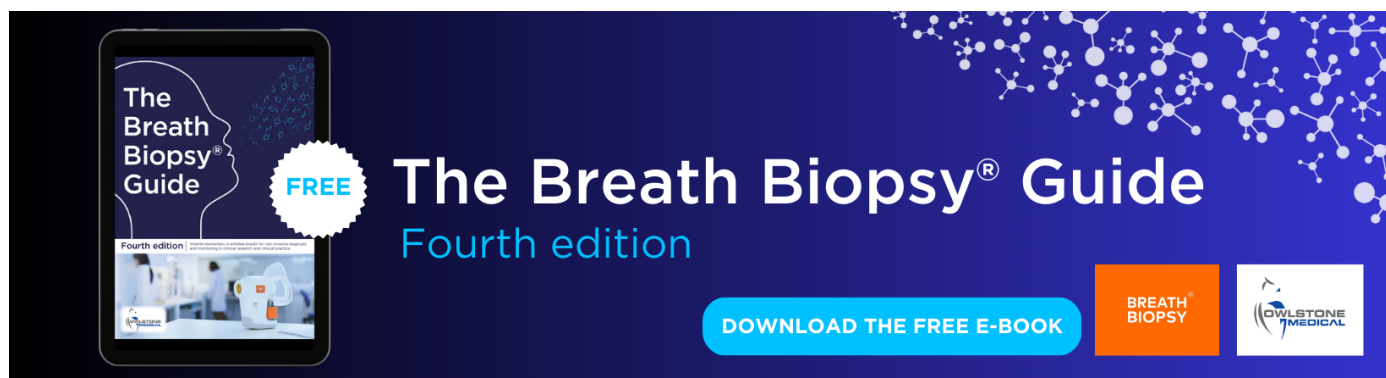
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Risk-based versus storyline approaches for global warming
impact assessment on basin-averaged extreme rainfall: a case
study for Typhoon Hagibis in eastern JapanTomohiro Tanaka^{1,*}, Hiroaki Kawase², Yukiko Imada³, Yuki Kawai⁴ and Satoshi Watanabe⁵¹ Graduate School of Engineering, Kyoto University, Japan² Meteorological Research Institute, Japan Meteorological Agency, Japan³ Atmosphere and Ocean Research Institute, the University of Tokyo, Japan⁴ Consulting Business Division Human Resources & Organization Business Unit, Mitsubishi UFJ Research and Consulting Co., Ltd, Japan⁵ Faculty of Social and Cultural Studies, Kyushu University, Japan

* Author to whom any correspondence should be addressed.

E-mail: tanaka.tomohiro.7c@kyoto-u.ac.jp**Keywords:** pseudo global warming, d4PDF, Typhoon Hagibis, storyline approach, risk-based approachSupplementary material for this article is available [online](#)

Abstract

Two methods exist to address the degree to which past extreme events and associated disasters will be intensified due to climate change: storyline approaches and risk-based approaches. However, the risk-based approach applied to weather similar to the target event (typhoons, a stationary weather front,...etc) becomes theoretically similar to the storyline approach. We examine this theory for the climate change impact of a real event, Typhoon Hagibis, which caused devastating flood damage to eastern Japan in 2019, while focusing on basin-averaged accumulated rainfall (BAAR) in major eastern river basins. A risk-based approach was conducted to determine the future change of BAAR by calculating the quantile change corresponding to Hagibis from the probability distribution of typhoon-induced events in a large ensemble climate simulation dataset database for Policy Decision-making for Future climate change (past, +2K and +4K future climates). A storyline approach for Typhoon Hagibis was realized using a pseudo global warming (PGW) experiment with a 5 km non-hydrostatic model. The projected BAAR in the two approaches were consistent for all target basins, supporting the robustness of the calculated changes in extreme catchment precipitation. This presents an important practical benefit: one can assess future climate change impact on a past symbolic event using either PGW experiments or large ensemble climate projections for the target weather.

1. Introduction

In East Asia, extreme weather events such as heavy rainfall, which are caused by a stationary weather front (Baiu front) and typhoons, are followed by various meteorological disasters such as river floods, landslides, and coastal floods. In recent years, Japan has experienced the continuous occurrence of catastrophic flood disasters, such as Baiu-front-induced heavy rainfall in 2018 and Typhoon Hagibis in 2019 (Ministry of Land, Infrastructure, Transport and Tourism 2019a, 2019b, Tanaka *et al* 2021). Typhoon Hagibis caused serious flood damage and resulted in the second highest insurance loss among

past water-related disasters (The General Insurance Association of Japan 2020). The expected impact of similar events under future climatic conditions is of high public concern (Li *et al* 2019, Takemi 2019, Gbode *et al* 2021).

Event attributions (EA), which are impact assessments of past global warming on realized extreme events, can be performed in either of two ways: a risk-based or storyline approach (Shepherd 2016). Both methods are extended to future global warming as well (Shepherd *et al* 2018). The former estimates the frequency of a variable of interest (e.g. heavy rainfall or exceptionally high temperature) for the event probabilistically (e.g. as a 99% or 99.5%

quantile) and assesses the climate change impact as the change in that quantile often using the largest available ensembles of climate projection datasets (Otto *et al* 2012, King *et al* 2015, Kamae *et al* 2021). Otto *et al* (2012) examined the EA for the 2010 Western Russian heat wave using large ensemble simulations and concluded that the occurrence probability of such events would increase, supporting Coumou *et al* (2015). King *et al* (2015) also showed increasing probability of high temperature in Central England. As above, the risk-based approach quantifies the occurrence probability of the target events. However, when it comes to determining the uniqueness of the event, a storyline approach, such as the pseudo global warming (PGW) technique, plays a critical role (Lackmann 2015, Gutmann *et al* 2018, Nayak *et al* 2019) because the probability distribution of the risk-based approach includes extreme events developed by physical processes other than the actual mechanism of occurrence of the event. Kamae *et al* (2021) addressed this difficulty for future projections of extreme rainfall by analyzing the future changes of physical mechanisms behind in a case study of atmospheric rivers.

Shepherd (2016) argued that both approaches are not mutually exclusive and can be viewed within the common framework of detecting the climate change signal of target variables such as temperature, rainfall, and snowfall. The storyline approach of a particular extreme event corresponds to the tail of the target probability distribution in the risk-based approach; therefore, one can bring together climate-oriented and weather-oriented perspectives. This idea is theoretically applicable to EA studies as well as future climate projections of specific extreme events. The database for Policy Decision-making for Future climate change (d4PDF) was developed (Mizuta *et al* 2017) with large ensembles ($\sim 10^3$ years in total) of high-resolution (~ 20 km) simulations around Japan, as well as six sea surface temperature (SST) ensembles representing the coverage of Climate Model Intercomparison Project 5. Comparing d4PDF ensembles and storyline PGW techniques based on regional climate models (RCMs), Shepherd's argument can be discussed in a real application.

If projections from the two approaches are consistent, we can obtain more robust results for future changes in extreme precipitation. In addition, the more feasible and easily accessible method can be chosen depending on the situation. The risk-based approach can quantify the occurrence probability of an event of interest but requires vast amount of data; therefore, when it is more feasible to collect ensemble data such as d4PDF for an event of interest, its statistical analysis may be used as a substitute for PGW and vice versa. Further, if one is interested in the whole story of the event (e.g. the development of the storm event) in addition to extreme rainfall, PGW is

advantageous because it provides narrative, physically self-consistent pathways (Shepherd *et al* 2018). Determining the agreement between PGW and the risk-based approach, which has not yet been verified in the literature, will also improve the robustness and reliability of estimated impacts. The objective of this study is therefore to examine the consistency between PGW (storyline) experiments and d4PDF (risk-based) experiments, using a case study of Typhoon Hagibis for two different levels of global warming conditions: +2K and +4K of the global mean temperature.

2. Extreme basin-averaged rainfall of Typhoon Hagibis in warmer climates

2.1. Target area and experimental design

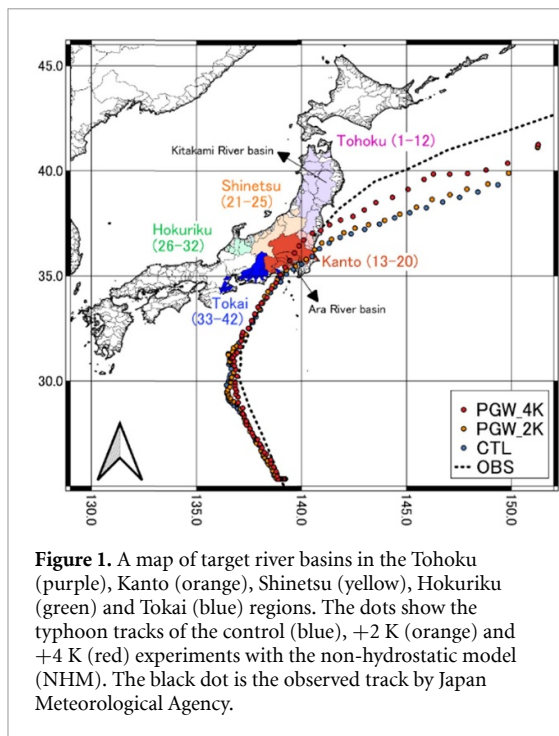
To provide primary flood risk information of Typhoon Hagibis that heavily damaged the Japanese society, this study focuses on areal extreme precipitation, particularly the maximum N -hour river basin-averaged accumulated rainfall (BAAR) which is a fundamental proxy to extreme floods that considers flood travel time.

Among 109 major river basins in Japan (classified as Class A by the Ministry of Land, Infrastructure, Transportation and Tourism, Japan), 42 river basins located in eastern Japan were selected as the target area (colored river basins in figure 1). Target accumulation duration N refers to the river improvement plan of each river system ranging from 6 to 72 h (specifically, 24 or 48 h in 35 out of 42 river basins), considering flood travel time (Ministry of Land, Infrastructure, Transportation and Tourism). Table S1 contains a list of river basins and their properties.

The BAAR in the target river basins in the present (control) and in warmer climate conditions is simulated with the non-hydrostatic model (NHM) (Saito *et al* 2007) as a storyline approach, while a risk-based approach is conducted using current quantiles from typhoon-induced heavy rainfall as well as +2K and +4K experiments extracted from a typhoon track dataset as detailed below. We then explore whether storyline- and risk-based approaches fall within the common framework (Shepherd 2016). The experimental design used in this study is illustrated in figure 2.

2.2. Brief description of d4PDF

Three climate experiments in d4PDF are used in this study: historical (PAST), 2-K warming (+2K), and 4-K warming (+4K) climates. Each experiment consists of a 60 year simulation and was performed with the atmospheric global climate model developed by the Meteorological Research Institute at 60 km resolution. Global climate simulations were dynamically downscaled with the non-hydrostatic RCM



(NHRCM) at a resolution of 20 km (Sasaki *et al* 2008). The PAST experiment had 50 ensembles for different perturbations of SST and sea ice to the observation from 1951 to 2010, making 3000 year data. The PAST experiments were extended to 2019 (Imada *et al* 2020). For the +2K and +4K experiments, six climatological SST warming patterns were added to the observed SSTs after removing the long-term trend component, each of which had 15 ensembles of different initial conditions and SST perturbations, giving a 900 year data in each of the six future SST ensembles. The greenhouse gases are set to the value in 2040 and 2090 of the RCP8.5 scenario, respectively (Mizuta *et al* 2017, Fujita *et al* 2019). This dataset is used in the risk-based approach as well as the climate difference in PGW experiment (figure 2).

2.3. Storyline approach by PGW experiment with NHM

Kawase *et al* (2021) performed storyline EA of Typhoon Hagibis running NHM in actual and non-warming climates and revealed that historical warming since the preindustrial period enhanced the total precipitation amount by 13.6%. The storyline approach was extended to warmer climate conditions. The hindcast simulations of Typhoon Hagibis have the same NHM setting as Kawase *et al* (2021). The initial and lateral boundary conditions are obtained from Japan Meteorological Agency mesoscale analysis data. We conduct time-lagged ensemble experiments with four initial conditions—00UTC, 03UTC, 06UTC, and 09UTC—on October 9, 2019. The PGW experiment is conducted using the climate differences between the present climate from 2010 to 2019 and the +2 K/+ 4 K climates in the d4PDF. Since

the d4PDF is a time-slice experiment, the climate in warmer conditions is extracted from all 60 years of all ensembles in the d4PDF.

This study used the regional mean anomaly of air temperature and geopotential height at each pressure level and SST around Japan (25N–40N, 130E–135E) to obtain PGW conditions, since the spatial distribution of anomaly, especially zonal and meridional wind anomaly, can change the atmospheric circulation and influence the typhoon tracks more than the regional means. In our PGW experiments, the relative humidity in the +2K and +4K experiments is the same as that in the PAST one and the amount of water vapor increases due to atmospheric warming. Therefore, our PGW experiment considers the changes in water vapor due to warming, SST warming, and the vertical profile of temperature changes, i.e. future changes in atmospheric stability. The climatic anomaly is different among months. To cover uncertainties derived from monthly and three-monthly mean anomalies, we applied five climatic anomaly data, calculated in August, September, October, August to October and September to November, to the PGW experiments. In summary, the control run by Kawase *et al* (2021) and the +2K/+4K climate experiments has four and twenty ensembles, respectively. Note that the comparison of sample variance or the whole histogram is not feasible because the number of ensembles is different between the control and +2K/+4K climate experiments. Rather, this study focuses on the ensemble mean changes of BAAR.

In a previous study of PGW experiments for Typhoon Hagibis, Kanada *et al* (2021) used the Cloud Resolving Storm Simulator version 3.4 (Tsuboki and Sakakibara 2002), while their PGW experiments used the climate difference given by the Meteorological Research Institute-Atmospheric General Circulation Model version 3.2, which is a different dataset from d4PDF. This study aligns the climate difference condition between the storyline and the risk-based approach by setting the climate difference given by d4PDF to the NHM. The details of the experimental design are summarized in table S2.

Figure 3 shows the comparison of BAAR between the observation and the control run by Kawase *et al* (2021). The observed BAAR is calculated from radar/rain gauge-analyzed precipitation which is a 1 km grid precipitation dataset created by combining radar precipitation and ground precipitation by Japan Meteorological Agency (Ishizuka and Matsuyama 2018). The control run reproduces the spatial heterogeneity and overall magnitude of BAAR over the study basins, presenting the validity of the NHM for Typhoon Hagibis in terms of catchment-scale extreme rainfall. As detailed in Kawase *et al* (2021), this experiment also represented the overall spatial pattern of precipitation and other meteorological indices of Typhoon Hagibis. Some biases

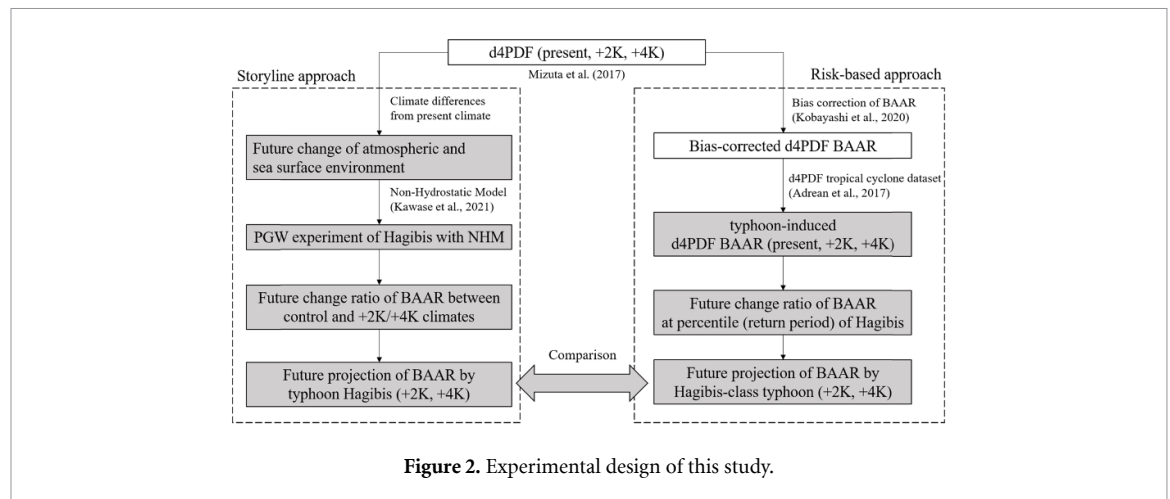


Figure 2. Experimental design of this study.

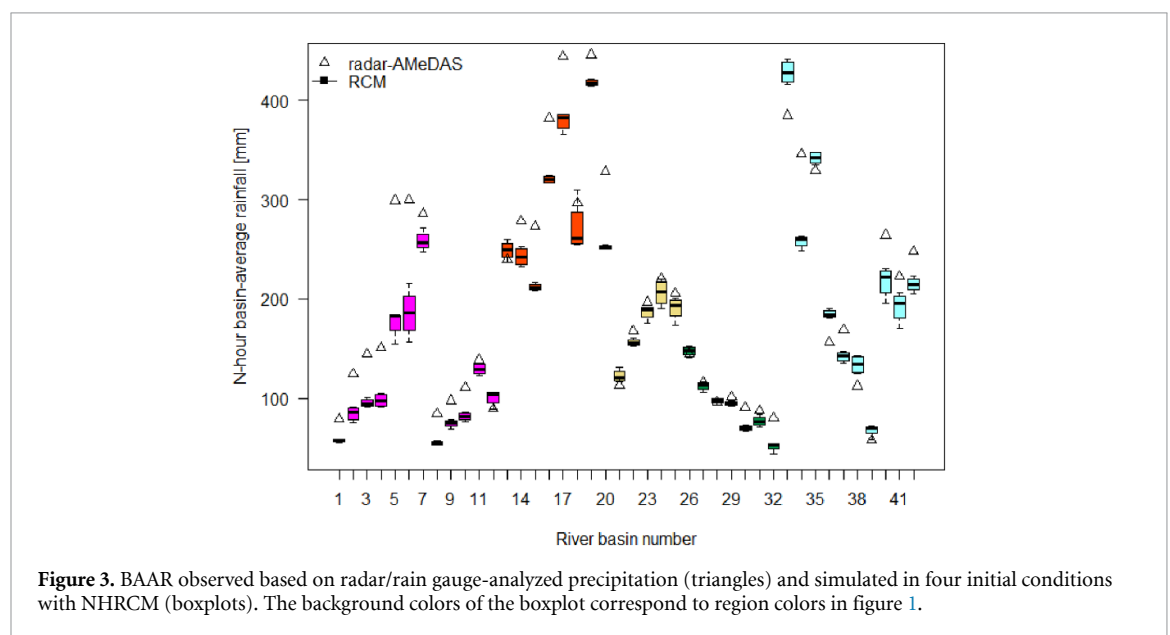


Figure 3. BAAR observed based on radar/rain gauge-analyzed precipitation (triangles) and simulated in four initial conditions with NHRCM (boxplots). The background colors of the boxplot correspond to region colors in figure 1.

exist in northern Japan (Tohoku and Kanto regions are shown in violet and orange, respectively) due to typhoon track discrepancy after passing the Kanto region (see figure 1). This study derives the change ratio between the control and warmer climate experiments and multiplies it by the observed BAAR both in the storyline and risk-based approaches. This method is common in bias correction and follows the trend preservation assumption (Hempel *et al* 2013).

2.4. Risk-based approach by typhoon-induced rainfall events in d4PDF

We use bias-corrected BAAR by Kobayashi *et al* (2020) using the quantile mapping method (Panofsky and Brier 1968) for the present and +4K climates and newly added the +2K climate experiment applying the same bias correction (see more details in text S1 and examples of bias correction result in figure S1). From this dataset, typhoon-induced BAAR, defined as rainfall events during which the tropical cyclone has a latitude between 30 and 50 degrees north and a longitude of 125 to 150 degrees east, is extracted using

the d4PDF tropical cyclone track database in each climate experiment (Webb *et al* 2019). The cumulative probability of the observed BAAR in each river system during Typhoon Hagibis is estimated from the reconstructed dataset. Finally, future projections in the +2K and +4K climate experiments are given as the corresponding quantiles (see examples in figure S2). Through this process, the risk-based approach using large ensembles of d4PDF is specified for extreme precipitation induced by typhoons. We expect that future projections at high percentiles correspond to those obtained by the PGW experiment of Typhoon Hagibis.

3. Comparison of future projection of annual maximum BAAR between the storyline and risk-based approaches

Figure 4 shows the future projections of BAAR for the 42 river basins in the +2K experiment using the storyline approach with PGW (dynamical downscaling with NHM) and the risk-based approach with +2K future climate in d4PDF. The boxplot shows

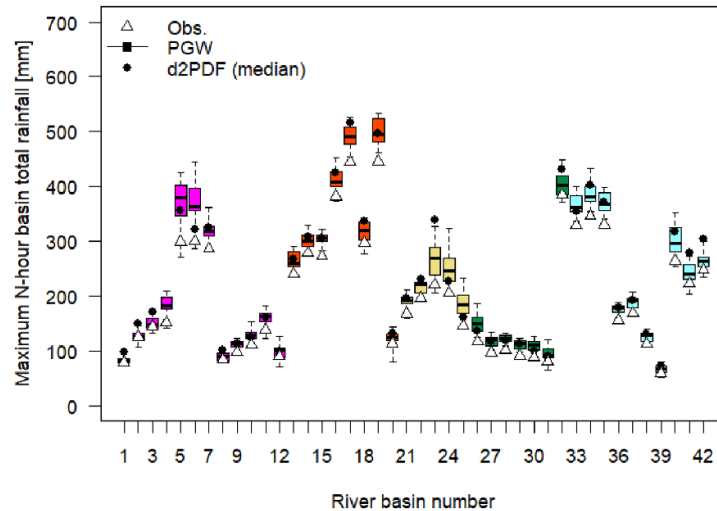


Figure 4. BAAR projected in the risk-based (circles) and storyline (boxplots) approaches in the +2 K climate. The boxplots represent 20 ensembles with five SSTs and four initial conditions. The circles show quantiles corresponding to Typhoon Hagibis among typhoon-induced d4PDF. The triangles are the observation (same as figure 3). The background colors of the boxplot correspond to region colors in figure 1.

the spread of the PGW experiments with different climate differences and initial conditions, while the black circles represent the median of six future SST ensembles in +2K future climate d4PDF. It is evident that in both approaches, the BAAR in the warmer experiments is larger than that in the observations (triangles). The Wilcoxon test demonstrates that the increase of BAAR in the +2K climate from the observation is statistically significant at 95% confidence in 34 out of 42 river basins (the single sample *t*-test does in 38 out of 40 river basins where normality was verified by the Shapiro–Wilk test at 95% confidence), indicating the impact of global warming on the intensified rainfall for the target typhoon due to warmer SSTs (Mizuta *et al* 2017, Kawase *et al* 2021). Note that bias corrections are applied to BAARs in both the storyline and risk-based approaches, as mentioned above. Although the increasing ratio varied over the target area, PGW was in agreement with +2K future climate d4PDF overall, indicating a consistent assessment of the impact of heterogeneous climate change on extreme rainfall.

In the PGW as shown in figure 1, the typhoon tracks in the control and +2K experiments are consistent while the +4K PGW experiment differs around the Kanto Region. The increasing ratio between the control and +4K experiments may result not only from climate change impact but also by the inconsistency of tracks between the two scenarios. Therefore, we compared the two experiments across approaches only where the typhoon tracks are consistent.

We define a track as divergent when the longitudes of two typhoon tracks are 1° away from each other. A

river basin is targeted only if over 90% of a typhoon's total rainfall has already occurred before the tracks diverge. Figure 5 shows the future projection of the BAAR for the target 16 river basins using the two approaches. The target basins (the western Kanto and Tokai regions) are colored darker in figure 1. Obviously, future changes in BAAR are far clearer in the +4K climate. The Wilcoxon test demonstrates that the increase of BAAR in the +4K climate from the observation is statistically significant in all river basins at 95% confidence (the single sample *t*-test as well in all 40 river basins where normality was verified by the Shapiro–Wilk test at 95% confidence). The future projections for the target basins in the storyline and risk-based approaches agree well with each other.

Figure 6 shows the boxplot of the increasing difference between target river basins from the control scenario and warmer climates in the storyline (red) and risk-based (blue) approaches compared with the Clausius–Clapeyron (C–C) scaling (7% increase in rainfall per temperature increase) (red triangles). Both approaches are generally in agreement with C–C scaling, similar to Kawase *et al* (2021), implying that the trend of rainfall intensification averaged in all BAARs is caused by the thermodynamic effect of global warming. On the other hand, the increasing ratio of BAAR in each catchment was varied as observed in figures 4 and 5, and some were much greater than the C–C scaling possibly due to local effects, such as topographical effects, as pointed out in previous studies (Tu and Chou 2013, Molnar *et al* 2015, Kawase *et al* 2021). It is worth emphasizing that such variability was in agreement between the storyline and risk-based approaches.

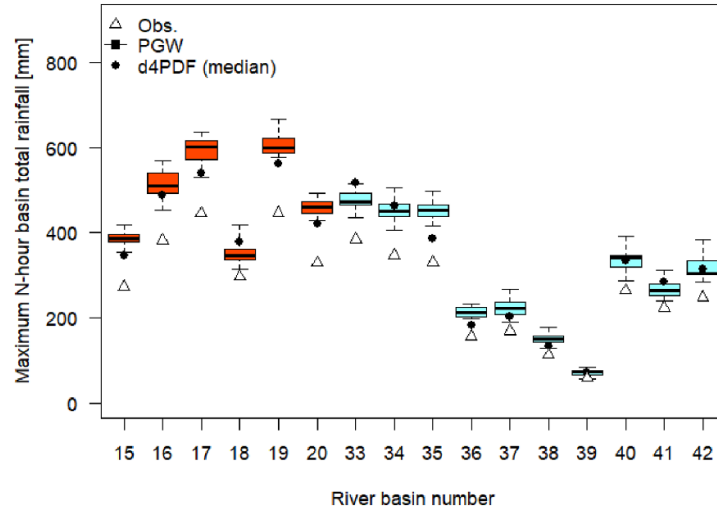


Figure 5. BAAR projected in the risk-based (circles) and storyline (boxplots) approaches in the +4K climate. The boxplots represent 20 ensembles with five SSTs and four initial conditions. The circles show quantiles corresponding to Typhoon Hagibis among typhoon-induced d4PDF. The triangles are the observation (same as figure 3). The background colors of the boxplot correspond to region colors in figure 1.

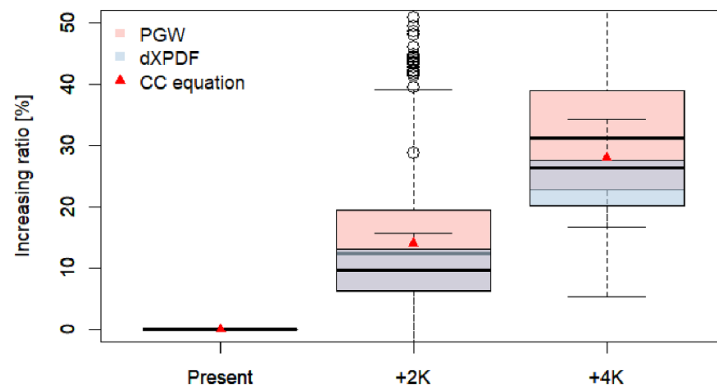


Figure 6. Comparison of increasing ratio of *N*-hour BAAR values in warmer climates in the storyline approach (red) and the risk-based approach (blue). The red triangles show the C–C scale assuming 7% increase of rainfall per 1° increase in temperature.

4. Summary and discussions

The storyline impact assessment using the PGW method based on d4PDF was compared with the quantile changes resulting from the risk-based approach. Both showed overall agreement in the intensification of BAAR in all target river basins compared to the +2K and +4K experiments as long as the typhoon track in the PGW was consistent with the control experiment. This indicates that dynamic components like internal variability (Deser *et al* 2014) are fixed and only thermodynamic components affect the intensification of extreme rainfall (Shepherd *et al* 2018).

The agreement between PGW and the risk-based approach delivers practical benefits and improves the robustness and reliability of the estimated impact. Multiple options for climate change impact assessment of extreme events can be selected based on data availability: if large ensemble data such as d4PDF are

available and sufficient for a target event, one can use the risk-based approach; otherwise, PGW can provide reasonable impact assessments of the target event.

This study has a few limitations to be addressed in the future research. As discussed in section 3, the typhoon track plays a significant role in catchment-scale heavy rainfall. Indeed, future projections between the two approaches were inconsistent when major rainfall in a catchment occurs after a track in the control run departs from that in the PGW experiments (see details in text S2 and figures S3 to S4). This is probably because of the track discrepancy between the control and PGW experiments. The changes in cumulonimbus convections around typhoon due to the oceanic warming can change the speed of typhoon through an interaction with a mid-latitude westerly jet (Ito and Ichikawa 2021), which might change the track of typhoon. As shown in Kanada *et al* (2021), the typhoon tracks of the target typhoon event can be improved by using the Japan Meteorological Agency

global objective analysis dataset with a horizontal resolution of $0.25^\circ \times 0.20^\circ$ (Japan Meteorological Agency 2019) as boundary conditions. Another limitation is that, although this study showed the consistency of BAAR in the two approaches in various river basins over Japan, we need to compile more events to consolidate the conclusion. With the accumulation of the PGW experiment cases for other historical typhoons, this should be verified. Despite these obstacles, this study demonstrated unprecedented and promising results regarding the consistency of climate change signals in catchment-scale extreme rainfall during Typhoon Hagibis between the storyline and risk-based approaches.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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