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Assessing the impacts of global warming on meteorological hazards and risks in Japan: Philosophy and achievements of the SOUSEI program

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Abstract:

We review the philosophy and achievements of the research activity on assessing the impacts of global warming on meteorological hazards and risks in Japan under Program for Risk Information on Climate Change (SOUSEI). The concept of this research project consists of assessing worst-class meteorological hazards and evaluating probabilistic information on the occurrence of extreme weather phenomena. Worst-case analyses for historical extreme typhoons and probabilistic analyses on Baiu, warm-season rainfalls, and strong winds with the use of high-performance climate model outputs are described. Collaboration among the fields of meteorology, hydrology, coastal engineering, and forest science plays a key role in advancing the impact assessment of meteorological hazards and risks. Based on the present research activity, possible future directions are given.

KEYWORDS meteorological hazard; extreme weather; global warming; impact assessment

INTRODUCTION

Extreme weather phenomena such as tropical cyclones (TCs), heavy rainfall, and strong winds have profound impacts on social infrastructure and human society. Such extreme phenomena are meteorological hazards that sometimes spawn disasters. Climate change is considered to influence the frequency and severity of extreme weather phenomena, as detailed in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013). Based on the future projections, disaster risks by TCs are anticipated to increase globally (IPCC, 2014).

In assessing disaster risks, better estimates on meteorological hazards are necessary. Because the occurrence of disasters depends on the local characteristics of geographic, atmospheric, artificial, and social environment, meteorological hazards should also be examined at local scales. In addition, from a viewpoint of disaster risk assessment, it is very important to estimate quantitatively the severity of meteorological hazards such as rainfall amount and wind speed, because disaster occurs when the intensity and/or duration of extreme weather exceed a certain extreme threshold. We should also be aware of the fact that rainfalls and winds critically depend on local topographic features and relative distances from meteorological disturbances. Furthermore, probability estimates on the development of meteorological disturbances should also be provided in order to assess the probability for the occurrence of extreme weather.

Based on these considerations, one group, named “Risk Assessment of Meteorological Disasters under Climate Change”, in Theme-D “Precise Impact Assessments on Climate Change” under Program for Risk Information on Climate Change (the SOUSEI program during FY2012-FY2016) is designed to assess the impacts of climate change on meteorological hazards and risks over Japan. Here we describe the philosophy and concept of the meteorological disaster group under the SOUSEI program. We then review the achievements of the present research project and discuss the current status by comparing the results with those in other studies.

RATIONALE

The present research concept consists of evaluating worst-class meteorological hazards and estimating probabilistic information on the occurrence of extreme phenomena. For these purposes, we use the data from climate model simulations for the present climate and future climate conditions conducted under Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012), Innovative Program of Climate Change Projection for the 21st Century (KAKUSHIN) (Kitoh et al., 2009), and the SOUSEI program. Data both from general circulation models (GCMs) and regional climate models (RCMs) are used. Figure 1 shows the concept of the present research project under the SOUSEI program. Table S1 in the Supplement lists the participants of the meteorological disaster group. The impacts of meteorological hazards on local disasters are assessed through collaborating with the hydrological and coastal research groups (Mori et al., 2016).

In Japan, typhoons, extra-tropical cyclones, stationary fronts, and thunderstorms are major meteorological hazards that would spawn disasters. Based on the statistics on natural disasters by Cabinet Office (2015), typhoons and frontal rainfalls are among the worst-class hazards in Japan. Actually, typhoons and frontal rains are ranked in Japan as producing the costliest insurance losses among all the meteorological disasters during the period from 1970 to 2015 (Swiss Reinsurance Company, 2016). Thus, we focus on typhoons and frontal rainfalls.

In considering worst-class meteorological hazards, past disaster-spawning events are regarded as a baseline.
the present climate is also reproduced in a future climate as typhoons, which cannot be quantitatively reproduced in AGCM for future warmed climate and obtained 12 super-typhoons simulated in 20-km-mesh Atmospheric GCM 2-km-mesh downscaling experiments for the 30 strongest in the 20-km-mesh GCM. Tsuboki rainfall in a 5-km-mesh RCM is better represented than that For example, Kanada et al. (2010) clearly indicated that the approach with an RCM plays a critical role in quantitatively the future climate. For this purpose, a dynamical downscaling matological atmospheric conditions between the present and class events, it is useful to estimate the difference in the cli-

Japan, Typhoon Vera (1959) (so called Isewan Typhoon) caused devastating damages including more than 5000 fatalities, while Typhoon Mireille (1991) caused the most costly insurance loss among the TCs in the Pacific region during the period from 1970 to 2015 (Swiss Reinsurance Company, 2016). Evaluating the effects of climate change on the severity of typhoons is of primary importance in preventing and mitigating natural disasters under global warming. During the SOUSEI program, we conduct quantitative analysis on the climate change impacts on Typhoon Vera (1959), Typhoon Mireille (1991), Typhoon Songda (2004), Typhoon Talas (2011), and Typhoon Haiyan (2013). Although there are other damaging typhoons in Japan before Typhoon Vera (1959) such as Muroto Typhoon (1934), Makurazaki Typhoon (1945), Typhoon Kathleen (1947), and Typhoon Marie (1954) (known as Toyamaru Typhoon) (National Astronomical Observatory of Japan, 2015), the cases examined are limited to the typhoons after 1958. This is because the data used as the initial and boundary conditions for the numerical simulations are the long-term reanalysis data of Japan Meteorological Agency, called JRA-55 (Ebita et al., 2011; Kobayashi et al., 2015), which are available after 1958.

To assess the impacts of climate change on specific worst-class events, it is useful to estimate the difference in the climatological atmospheric conditions between the present and the future climate. For this purpose, a dynamical downscaling approach with an RCM plays a critical role in quantitatively representing extreme weather through resolving physical processes and topographical features at a high resolution. For example, Kanada et al. (2010) clearly indicated that the rainfall in a 5-km-mesh RCM is better represented than that in the 20-km-mesh GCM. Tsuboki et al. (2015) conducted 2-km-mesh downscaling experiments for the 30 strongest typhoons simulated in 20-km-mesh Atmospheric GCM (AGCM) for future warmed climate and obtained 12 super-typhoons, which cannot be quantitatively reproduced in AGCMs.

In contrast, it is not obvious whether a specific storm in the present climate is also reproduced in a future climate as a storm with changes in its intensity but without any pronounced changes in its track as well as the genesis location. Furthermore, a past specific event will not be reproduced in the present-climate runs; this is an issue related to realization in climate simulations. Thus, if we consider worst-class hazards based on the past extreme events, we need to use another method in addition to dynamical downscaling.

An effective method to assess the impacts of climate change on a specific event is a pseudo-global warming (PGW) experiment developed by Schär et al. (1996) and Sato et al. (2007). The PGW experiment is designed to add climate change components to the analysis fields of the past events. Climate change components are defined as the increments of the future climate from the present climate in GCM runs. The performance and reliability of the PGW method was verified for the atmospheric condition and precipitation over East Asia in June under climate change (Yoshikane et al., 2012). The PGW method has been applied for various types of weather phenomena including Baiu rainfall (Kawase et al., 2009), snowfall in Japan (Hara et al., 2008), marine boundary layer clouds over the eastern Pacific (Lauer et al., 2010), a severe flooding event over the United States (Lackmann, 2013), winter precipitation in Colorado (Rasmussen et al., 2011), and tornadic storm events over the United States (Trapp and Hoogewind, 2016). Lauer et al. (2013) examined the uncertainties of the PGW method using multiple CMIP5 models in assessing climate change impacts in the Hawaii region and successfully identified robust signals of future changes in the Hawaii climate. These studies investigated the climate change impacts for persistent anomalous weather.

In contrast, there are few studies that examined the impacts of climate change on a specific extreme event. For example, Lackmann (2015) estimated the impacts of climate change on Hurricane Sandy (2012). Takayabu et al. (2015) investigated, by conducting ensemble downscaling simulations under the actual and the pre-industrial condition, the effects of global warming on the storm surge induced by Typhoon Haiyan (2013) and showed that the worst-class storm surge will become severer under global warming. In this way, the PGW method is currently being applied for analyzing an extreme event. One possible shortcoming of the PGW method for an extreme event analysis would be the arbitrariness in the choice of the PGW increments. Climatological mean PGW increments may not always be adequate in determining the environmental conditions for extreme events. This issue is still an open question for future studies.

In the present studies, we employ the PGW experiment approach to investigate the climate change impacts on specific extreme events. To reproduce past events, we use the long-term reanalysis dataset, JRA-55. Dynamical downscaling and PGW experiments are conducted with the use of the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008).

Probability information on the occurrence of meteorological hazards provides quantitative confidence and/or uncertainties for projected changes in extreme events. To evaluate statistical significance, a large number of projection runs (of the order of 100 or more) are required. Moreover, high-resolution data (of the order of 1 km) are desirable to evaluate quantitatively the impacts at regional scales. However,
owing to the limitation of computational resources, it is still not possible to meet the needs on both sample size and spatial resolution. Therefore, we currently take priority in high-resolution over sample size by primarily using the 20-km-mesh AGCM simulations (MRI-AGCM version 3.2, Mizuta et al., 2012, 2014; Kioth et al., 2016) and the down-scaled 5-km-mesh simulations with the Non-Hydrostatic RCM (NHRCM) (Nakano et al., 2012; Murata et al., 2015). High-resolution is important since the representation of topography and rainfall amount/wind speed critically depends on how topography is reproduced at the model resolutions (Takemi, 2009; Oku et al., 2010). The 20-km-mesh AGCM data are primarily used for analyzing atmospheric conditions and circulations, while the 5-km-mesh RCM data are used for quantitative assessment of rainfalls and winds. In addition, we also use an ensemble of 60-km MRI-AGCM runs with multiple cumulus schemes and multiple SST patterns in order to obtain statistical information. The future climate with the MRI-AGCM are under the Representative Concentration Pathways (RCP) 8.5 scenario.

The advantage in using the MRI-AGCM data is emphasized here for its highest-level performance. Kusunoki (2016) demonstrated that the 20-km-mesh and 60-km-mesh MRI-AGCM runs provide better performance in reproducing precipitation, especially in summer, and the seasonal march of Baiu front over East Asia than those obtained from the CMIP5 GCMS. Therefore, although the MRI-AGCM runs were conducted only for a single future scenario, i.e., RCP8.5, we consider that the better performance of MRI-AGCM gives better reliability in assessing the impacts of climate change on meteorological hazards.

Another point to note in using high-resolution data is related to model numerics. In general, meteorological models include various types of numerical filters and diffusions and thus may not accurately resolve physical phenomena exactly at the model grid. The resolution that can effectively resolve physical phenomena is considered to be about 6 times the grid spacing or greater (Takemi and Rotunno, 2003; Skamarock, 2004; Bryan, 2005). Furthermore, considering that typhoons and heavy rainfalls are generated by cumulus activity, resolving non-hydrostatic effects (Weisman et al., 1997) is also important. From these considerations, it is emphasized that a resolution of a few kilometers (so called convection-permitting resolution, Trapp et al., 2007; Zhang et al., 2007) is at least necessary for evaluating quantitatively meteorological hazards in regional scales. Therefore, in this research project, the 5-km NHRCM data are mainly used, and downsampling experiments at grids of one or a few kilometers are conducted.

RESULTS FROM THE SOUSEI PROGRAM

Worst-scenario analysis

Worst-case analysis has been conducted for Typhoon Vera (1959), Typhoon Mireille (1991), Typhoon Songda (2004), and Typhoon Talas (2011), which caused significant disasters over Japan within the past 60 years or so.

Since rainfall amount and wind speed induced by typhoons critically depend on their tracks, examining how rain and wind are sensitive to the typhoon tracks is important to identify worst tracks for spawning disasters. Ishikawa et al. (2013) proposed a methodology to control typhoon tracks by extracting and relocating typhoon vortices that are separated from the background field through a potential vorticity (PV) inversion technique (Davis and Emanuel, 1991). With this methodology, we are able to generate a large number of typhoon ensembles with different tracks and to identify a typhoon track that produces the most significant hazard as the worst scenario. Oka et al. (2014) applied the PV inversion methodology in generating typhoon ensembles to investigate the maximum probable rainfall over the Kii Peninsula produced by Typhoon Talas (2011).

Typhoon Vera (1959) has been extensively investigated in the present research project. Shimokawa et al. (2014) developed a new typhoon bogusing method based on the PV inversion technique to control the track of a simulated typhoon and applied the method to investigate the impacts of global warming on the storm surge due to Typhoon Vera (1959). Their method was extended by Murakami et al. (2015) who evaluated the risk of coastal disaster resulting from the multiple hazards due to a Vera-class typhoon and showed that the middle part of Ise Bay is more dangerous than the inner part of Ise Bay.

Mori and Takemi (2016) and Takemi et al. (2016a) conducted PGW experiments for Typhoon Vera (1959) by prescribing monthly-mean warming increments from 4 ensembles of the 20-km AGCM runs (Mizuta et al., 2014) on the JRA-55 analysis fields of September 1959. In determining the PGW conditions, the relative humidity increment was not added, because of no significant future change in relative humidity (Takemi et al., 2012). The wind increment was also not added, because differences in wind fields largely change typhoon tracks and negatively affect the impact assessments on natural hazards (Mori et al., 2014). It was demonstrated that the typhoons at the times of their maximum intensity and landfall are unanimously intensified under the PGW condition. The robustness of the intensification of this extreme typhoon has been further investigated through multi-model inter-comparisons (Kanada et al., 2016).

Typhoon impacts are also investigated through collaborating with forest scientists. Forest trees play an important role in determining surface heat/moisture fluxes to the atmosphere and thereby controlling water cycle. Furthermore, forest trees are one of the important players in the global carbon budget. Thus, assessing the damaging impacts of typhoons on forest trees is an important issue in forest sciences. According to Takano et al. (2016), Typhoon Marie (1954) caused the severest damage to forest trees in the record history of Japan. However, due to the availability of JRA-55, we focused on Typhoon Songda (2004), which took a track similar to that of Typhoon Marie and caused severe damage to forest trees at many places in Hokkaido (Sano et al., 2010; Hayashi et al., 2015). Ito et al. (2016) examined the influences of global warming on the severity of Typhoon Songda (2004) over Hokkaido and demonstrated that wind speed over Hokkaido decreases under the PGW conditions, owing to the rapid weakening of the future typhoons in the higher-latitude regions despite the strengthening at the typhoons’ maximum intensity in the lower latitudes. The rapid weakening of the future typhoons at higher latitudes is due to the weakening of baroclinicity under global warming. Takemi et al. (2016b) further investigated the latitudinal
dependent of the change in typhoon intensity through the PGW experiments for Typhoon Mireille (1991) and indicated that typhoon winds will be intensified in Kyushu (the southern part of Japan) and be weakened in Tohoku (the northern part of Japan). Takano et al. (2016) used the output of the numerical simulations for Typhoon Songda (2004) by Ito et al. (2016) to investigate the changes in the damages to forest trees in Hokkaido under global warming. Further analyses on forest damages in Kyushu and Tohoku by Typhoon Mireille (1991) are now being undertaken.

**Probabilistic analysis**

Probability information is important to evaluate the significance and uncertainty of the occurrence of extreme events. Although the ensemble number of the MRI-AGCM runs is not sufficient to derive reliable probabilities, uncertainty and robustness of the projected changes are derived.

Okada et al. (2016) used the outputs from the present-climate simulation and the 4 ensemble future-climate projections from MRI-AGCM to investigate the projected changes in atmospheric circulation during the Baiu season. They indicated the delayed northward shift of the Baiu front in June and the resulting decrease in rainfall in western Japan in June. According to the results with different SST conditions, they found that the projected changes in atmospheric circulation in June have a robust commonality while the changes of atmospheric condition in July and August depend on the SST conditions. Thus, the AGCM ensembles are necessary to evaluate the robustness and uncertainty of the projected changes.

Nakakita et al. (2015, 2016a) investigated the characteristics of atmospheric circulation relevant to localized heavy rainfall in summer by using the 20-km MRI-AGCM outputs as well as the 60-km MRI-AGCM ensemble data. The 5-km RCM outputs were used to quantitatively examine the rainfall amount and its relationship with the atmospheric circulation identified with the AGCM outputs. They revealed that anti-cycloonic circulation originating from the western North Pacific toward the Sea of Japan, which is favorable for the rainfall in the western part of Japan, is projected to be more frequent in the future climate and that a significant increase in rainfall is found at the 5% significance level on the Japan Sea side of the Tohoku region in July and in all regions on the Japan Sea side in August.

Kuzuha (2015) analyzed the annual maximum series of observed daily precipitation and examined probability distributions for fitting the observations. They successfully estimated daily precipitation with the 120-year return period for 51 meteorological stations.

Future changes in strong wind hazards are investigated by Zhang et al. (2014a) from the 5-km RCM outputs. They showed that wind speeds are projected to increase in southern Japan while projected to decrease in central and northern Japan. Because strong winds are primarily due to typhoons, stronger winds in the south and weaker winds in the north in the future climate seem to be consistent with the latitudinal dependence of the typhoon intensity as shown by Ito et al. (2016) and Takemi et al. (2016b). In order to assess the risks of strong winds due to typhoons, Nishijima (2016) proposed a framework for decision optimization for adaptation of civil infrastructure to climate change by applying a system assessing wind risk for residential buildings (Zhang et al., 2014a, 2014b) to multiple climate projections. The framework bases on decision graphical representation consisting of four layers that evaluate the changes in greenhouse gas concentration, air temperature, hazard, and consequence, with each layer being related with each other through a Bayesian network. At this point, Nishijima (2016) only provided the concept; however, the framework should provide a pathway to the civil infrastructure adaptation to climate change.

**DISCUSSION**

The results from the present research project are summarized in Table 1. These results are evaluated by comparing with those from other studies.

There are not many studies on extreme typhoons from a worst-scenario perspective. We have extensively conducted PGW experiments for some past extreme typhoons and inter-model comparisons to gain robust signals in their changes under global warming. Furthermore, there have been few studies on the typhoon impacts in northern Japan; we have also examined this issue by collaborating with forest scientists.

Kossin et al. (2014) identified a pronounced poleward migration of the location of TC maximum intensity with a rate of 53 km per decade in the Northern Hemisphere.

Table I. Summary of the results of the meteorological disaster group under Theme-D of the SOUSEI program. GCM20, GCM60, and RCM5 refer to 20-km-mesh MRI-AGCM, 60-km-mesh MRI-AGCM, and 5-km-mesh RCM, respectively

| Analysis category | Meteorological hazard | Input dataset | Results |
|-------------------|----------------------|---------------|---------|
| Worst-scenario analysis | Typhoon | GCM20, JRA-55 | Increased intensity of typhoons at their maturity and the landfall. Typhoon impacts are more severe in the southern and the Pacific side of Japan, but may be reduced in northern Japan. |
| Probabilistic analysis | Baiu | RCM5, GCM20, GCM60, CMIP5 | Delayed northward shift of Baiu front. Reduction of rainfall in June in western Japan. |
| Warm-season rainfall | RCM5, GCM20, GCM60 | Increased risks of the occurrence of heavy rainfall in summer. |
| Strong wind | RCM5 | Increased risks of strong winds in southern Japan and decreased risks in central and northern Japan. Regional characteristics of residential buildings should be taken into account. |
because of the poleward expansion of tropical circulation and the associated increase in potential intensity to about 30°N latitude. The PGW experiments for Typhoon Vera (1959), demonstrating increased intensity at the maximum intensity and the landfall, are consistent with the study by Kossin et al. (2014). In contrast, typhoons at higher latitudes (north of 40°N latitude) are projected to experience rapid weakening, leading to the reduction of the typhoon winds in northern Japan.

For the probabilistic analyses, the use of the data from the high-performance MRI-AGCM (Kitoh et al., 2016; Kusunoki, 2016) and the downscaled RCM (Murata et al., 2015) is the advantage of this research project, although the ensemble number is limited and the future scenario is only RCP8.5. With the use of the high-performance climate data, we were able to provide the changes in the atmospheric circulation during the Baiu period and the warm-season rainfall.

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SUPPLEMENTS

Table SI. List of the participants of the meteorological disaster group, “Risk Assessment of Meteorological Disasters under Climate Change”, in Theme-D “Precise Impact Assessments on Climate Change” under Program for Risk Information on Climate Change (the SOUSEI program) during FY2012-FY2016

REFERENCES

Bryan G. 2005. Spurious convective organization in simulated squall lines owing to moist absolutely unstable layers. Monthly Weather Review 133: 1978–1997. DOI: 10.1175/MWR2952.1.
Cabinet Office. 2015. White Paper on Disaster Management in Japan 2015. Cabinet Office, Government of Japan, Japan; 222.
Davis CA, Emanuel KA. 1991. Potential vorticity diagnostics of cyclogenesis. Monthly Weather Review 119: 1929–1953. DOI: 10.1175/1520-0493(1991)119<1929:PVDOC>2.0.CO;2.
Ebita A, Kobayashi S, Ota Y, Moriya M, Kumabe R, Onogi K, Harada Y, Yasui S, Miyaoka K, Takahashi K, Kamahori H, Kobayashi C, Endo H, Soma M, Okawa Y, Ishimizu T. 2011. The Japanese 55-year Reanalysis “JRA-55”: An interim report. SOLA 7: 149–152. DOI: 10.2151/sola.2011-038.
Hara M, Yoshikane T, Kawase H, Kimura F. 2008. Estimation of the impact of global warming on snow depth in Japan by the pseudo-global-warming method. Hydrological Research Letters 2: 61–64. DOI: 10.3178/hrl.2.61.
Hayashi M, Saigusa N, Oguma H, Yamagata Y, Takao G. 2015. Quantitative assessment of the impact of typhoon disturbance on a Japanese forest using satellite laser altimetry. Remote Sensing of Environment 156: 216–225. DOI: 10.1016/j.rse.2014.09.028.
IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA; 1535.
IPCC. 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, USA; 1132.
Ishikawa H, Oku Y, Kim S, Takemi T, Yoshino J. 2013. Estimation of a possible maximum flood event in the Tone River basin, Japan caused by a tropical cyclone. Hydrological Processes 27: 3292–3300. DOI: 10.1002/hyp.8930.
Ito R, Takemi T, Arakawa O. 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, Nakano M, Kato T. 2010. Climatological characteristics
of daily precipitation over Japan in the Kakushin regional climate experiments using a non-hydrostatic 5-km-mesh model: Comparison with an outer global 20-km-mesh atmospheric climate model. SOLA 6: 117–120. DOI: 10.2151/sola.2010-030.

Kanada S, Takemi T, Kato M, Yamasaki S, Fudeyasu H, Tsuboki K, Takayabu I. 2016. Study on a category-5 typhoon in future, warmer climates: A multi-model intercomparison by four 5-km models. Journal of Climate (under review).

Kawase H, Yoshikane T, Hara M, Kimura F, Yasunari T, Ailiikon B, Ueda H, Inoue T. 2009. Intermodel variability of future changes in the Baiu rainband estimated by the pseudo global warming downsampling method. Journal of Geophysical Research 114: 110. DOI: 10.1029/2009JD011803.

Kitoh A, Ose T, Takayabu I. 2016. Dynamical downsampling for climate projection with high-resolution MRI AGCM-RCM. Journal of the Meteorological Society of Japan Ser. II 94A: 1–16. DOI: 10.2151/jmsj.2015-022.

Kitoh A, Ose T, Kurihara K, Kusunoki S, Sugi M, KAKUSHIN Team-3 Modeling Group. 2009. Projection of changes in future weather extremes using super-high-resolution global and regional atmospheric models in the KAKUSHIN Program: Results of preliminary experiments. Hydrological Research Letters 3: 49–53. DOI: 10.3178/hrl.3.49.

Kobayashi S, Ota Y, Harada Y, Ebita A, Moriya M, Onoda H, Onogi K, Kamahori H, Kobayashi C, Endo H, Miyaoaka K, Takahashi K. 2015. The JRA-55 Reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan Ser. II 93: 5–48. DOI: 10.2151/jmsj.2015-001.

Kossin JP, Emanuel KA, Vecchi GA. 2014. The poleward migration of the location of tropical cyclone maximum intensity. Nature 509: 349–352. DOI: 10.1038/nature13278.

Kusunoki, S. 2016. Is the global atmospheric model MRI-AGCM3.2 better than the CMIP5 atmospheric models in simulating precipitation over East Asia? Climate Dynamics (accepted). DOI: 10.1007/s00382-016-3335-9.

Kazuhara Y. 2015. Estimating optimal stochastic probability distributions of daily precipitation considering return periods of the largest records. Journal of Japan Society of Hydrology and Water Resources 28: 59–71. DOI: 10.3178/jjshr.28.59 (in Japanese).

Lackmann GM. 2013. The south-central U.S. flood of May 2010: Present and future. Journal of Climate 26: 4688–4709. DOI: 10.1175/JCLI-D-12-00392.1.

Lackmann GM. 2015. Hurricane Sandy before 1900 and after 2100. Bulletin of the American Meteorological Society 96: 547–560. DOI: 10.1175/BAMS-D-14-00123.1.

Lauer A, Hamilton K, Wang Y, Phillips VTV, Bennartz R. 2010. The impact of global warming on marine boundary layer clouds over the eastern Pacific – a regional model study. Journal of Climate 23: 5844–5863. DOI: 10.1175/2010JCLI3666.1.

Lauer A, Zhang C, Elison-Timm O, Wang Y, Hamilton K. 2013. Downscaling of climate change in the Hawaii region using CMIP5 results: On the choice of the forcing fields. Journal of Climate 26: 10006–10030. DOI: 10.1175/JCLI-D-13-00126.1.

Mizuta R, Yoshimura H, Murakami H, Matsueda M, Endo H, Ose T, Kamiguchi K, Hosaka M, Sugi M, Yukimoto S, Kusunoki S, Kimoto A. 2012. Climate simulations using MRI-AGCM3.2 with 20-km grid. Journal of the Meteorological Society of Japan 90A: 233–258. DOI: 10.2151/jmsj.2012-A12.

Mizuta R, Arakawa O, Ose T, Kusunoki S, Endo H, Kimoto A. 2014. Classification of CMIP5 future climate responses by the tropical sea surface temperature changes. SOLA 10: 167–171. DOI: 10.2151/sola.2014-035.

Mori N, Takemi T. 2016. Impact assessment of coastal hazards due to future changes of tropical cyclones in the North Pacific Ocean. Weather and Climate Extremes 11: 53–69. DOI: 10.1016/j.wace.2015.09.002.

Mori N, Kjelland M, Nakajo S, Shibutani Y, Shimura T. 2016. Impact assessment of climate change on coastal hazards in Japan. Hydrological Research Letters 10: 101–105. DOI: 10.3178/hrl.10.101.

Mori N, Kato M, Kim S, Mase H, Shibutani Y, Takemi T, Tsuboki K, Yasuda T. 2014. Local amplification of storm surge by Super Typhoon Haiyan in Leyte Gulf. Geophysical Research Letters 41: 5106–5113. DOI: 10.1002/2014GL060689.

Murakami T, Shimokawa S, Yosho J, Yasuda T. 2015. A new index for evaluation of risk of complex disaster due to typhoons. Natural Hazards 79: 29–44. DOI: 10.1007/s11069-015-1824-5.

Murata A, Sasaki H, Kawase H, Nosaka M, Oh’izumi M, Kato T, Aoyagi T, Shido F, Hibino K, Kanada S, Suzuki-Parker A, Nagatomo T. 2015. Projection of future climate change over Japan in ensemble simulations with a high-resolution regional climate model. SOLA 11: 90–94. DOI: 10.2151/sola.2015-022.

Nakatika E, Kusano H, Kim S. 2015. Prediction on appearance frequency of atmospheric characteristics causing localized heavy rainfall during Baiu season under climate change. Journal of Japan Society of Civil Engineers Ser. B1 (Hydraulic Engineering) 71: I_373–I_378. DOI: 10.2208/jsscejhe.71.1.373 (in Japanese).

Nakatika E, Kusano H, Kim S. 2016a. Study on future change in atmospheric characteristics causing localized heavy rainfall under climate change using AGCM20km ensemble. Hydrological Research Letters (submitted).

Nakatika E, Kusano H, Touge Y, Kim S. 2016b. Future change in appearance frequency of atmospheric characteristics causing localized heavy rainfall during Baiu season using AGCM ensembles. Annuals of Disaster Prevention Research Institute 59B: 230–248.

Nakano M, Kato T, Hayashi S, Kanada S, Yamada Y, Kurikara K. 2012. Development of a 5-km-mesh cloud-system-resolving regional climate model at the Meteorological Research Institute. Journal of the Meteorological Society of Japan 90A: 339–350. DOI: 10.2151/jmsj.2012-A19.

National Astronomical Observatory of Japan. 2015. Chronological Scientific Tables. Maruzen Publishing Co., Ltd., Tokyo, Japan; 1098 (in Japanese).

Nishijima K. 2016. Concept of decision graphical framework for optimising adaptation of civil infrastructure to a changing climate. Structure and Infrastructure Engineering 12: 477–483. DOI: 10.1080/15732479.2015.1020496.

Okada Y, Takemi T, Ishikawa H, Kusunoki S, Mizuta R. 2016. Future changes in atmospheric conditions for the seasonal evolution of the Baiu as revealed from projected AGCM experiments. Journal of the Meteorological Society of Japan (under review).

Okyu Y, Yoshino J, Takemi T, Ishikawa H. 2014. Assessment of heavy rainfall-induced disaster potential based on an ensemble simulation of Typhoon Talas (2011) with controlled track and intensity. Natural Hazards and Earth System Sciences 14: 2699–2709. DOI: 10.5194/nhess-14-2699-2014.

Okyu Y, Takemi T, Ishikawa H, Kanada S, Nakano M. 2010. Representation of extreme weather during a typhoon landfall in regional meteorological simulations: A model intercomparison study for Typhoon Songda (2004). Hydrological Research Letters 4: 1–5. DOI: 10.3178/hrl.4.1.
Rasmussen RM, Liu C, Ikeda K, Gochis D, Yates D, Chen F, Tewari M, Barlage M, Dudhia J, Yu W, Miler K,Arsenault K, Grubic V, Thompson G, Gutmann E. 2011. High-resolution coupled climate runoff simulations of seasonal snowfall over Colorado: A process study of current and warmer climate. *Journal of Climate* 24: 3015–3048. DOI: 10.1175/2010JCLI3985.1.

Sano T, Hirano T, Liang N, Hirata R, Fujinuma Y. 2010. Carbon dioxide exchange of a larch forest after a typhoon disturbance. *Forest Ecology and Management* 260: 2214–2223. DOI: 10.1016/j.foreco.2010.09.026.

Sato T, Kimura F, Kitoh A. 2007. Projection of global warming onto regional precipitation over Mongolia using a regional climate model. *Journal of Hydrology* 333: 144–154. DOI: 10.1016/j.jhydrol.2006.07.023.

Schär C, Frei C, Lüthi D, Davies HC. 1996. Surrogate climate-change scenarios for regional climate models. *Geophysical Research Letters* 23: 669–672. DOI: 10.1029/96GL00265.

Shiogama S, Iizuka S, Yoshino J, Yasuda T. 2014. A new typhoon bogussing scheme to obtain the possible maximum typhoon and its application for assessment of impacts of the possible maximum storm surges in Ise and Tokyo Bays in Japan. *Natural Hazards* 74: 2037–2052. DOI: 10.1007/s11069-014-1277-2.

Shiogama H, Imada Y, Mori M, Mizuta R, Stone D, Yoshida K, Arakawa O, Ikeda M, Takahashi C, Arai M, Ishii M, Watanabe M, Kimoto M. 2016. Attributing historical changes in probabilities of record-breaking daily temperature and precipitation extremes onto regional precipitation over Mongolia using a regional climate model. *Journal of Hydrology* 533: 2214–2223. DOI: 10.1016/j.jhydrol.2016.07.023.

Skamarock WC. 2004. Evaluating mesoscale NWP models using kinetic energy spectra. *Monthly Weather Review* 132: 3019–3032. DOI: 10.1175/MWR2830.1.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W, Powers JG. 2008. A description of the Advanced Research WRF version 3. *NCAR Technical Note TN-475-STR*, National Center for Atmospheric Research, Colorado, USA: 113.

Swiss Reinsurance Company. 2016. Natural Catastrophes and Man-Made Disasters in 2015: Asia Suffers Substantial Losses. Swiss Re Sigma Reports; 47.

Takano KT, Nakagawa K, Aiba M, Oguro M, Morimoto J, Furukawa Y, Mishima Y, Ogawa K, Ito R, Takemi T. 2016. Projection of impacts of climate change on windthrows and evaluation of potential adaptation measures in forest management: A case study from empirical modelling of windthrows in Hokkaido, Japan, by Typhoon Songda (2004). *Hydrological Research Letters* (accepted).

Takayabu I, Hibino K, Sasaki H, Shiogama H, Mori N, Shibutani Y, Takemi T. 2015. Climate change effects on the worst-case storm surge: A case study of Typhoon Haiyan. *Environmental Research Letters* 10: 064011. DOI: 10.1088/1748-9326/10/6/064011.

Takemi T. 2009. High-resolution numerical simulations of surface wind variability by resolving small-scale terrain features. *Theoretical and Applied Mechanics Japan* 57: 421–428. DOI: 10.1134/ncamt.57.421.

Takemi T. 2012. Projected regional-scale changes in atmospheric stability condition for the development of summertime convective precipitation in the Tokyo metropolitan area under global warming. *Hydrological Research Letters* 6: 17–22. DOI: 10.3178/HRL.6.17.

Takemi T, Rotunno R. 2003. The effects of subgrid model mixing and numerical filtering in simulations of mesoscale cloud systems. *Monthly Weather Review* 131: 2085–2101. DOI: 10.1175/1520-0493(2003)131<2085:TREOSMM>2.0.CO;2.

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

Takemi T, Ito R, Arakawa O. 2016b. Effects of global warming on the impacts of Typhoon Mireille (1991) in the Kyushu and Tohoku regions. *Hydrological Research Letters* 10: 81–87. DOI: 10.3178/hrl.10.81.

Takemi T, Nomura S, Oku Y, Ishikawa H. 2012. A regional-scale evaluation of changes in environmental stability for summertime afternoon precipitation under global warming from super-high-resolution GCM simulations: A study for the case in the Kanto Plain. *Journal of the Meteorological Society of Japan* 90A: 189–212. DOI: 10.2151/jmsj.2012-A10.

Tayler KE, Stouffer RJ, Meehl GA. 2012: An overview of CMIP5 and the experimental design. *Bulletin of the American Meteorological Society* 93: 485–498. DOI: 10.1175/BAMS-D-11-00994.1.

Trapp RJ, Hoogewind KA. 2016. The realization of extreme tornadic storm events under future anthropogenic climate change. *Journal of Climate* 29: 5251–5265. DOI: 10.1175/JCLI-D-15-0623.1.

Trapp RJ, Halvorson BA, Diffenbaugh NS. 2007. Telescoping, multimodel approaches to evaluate extreme convective weather under future climates. *Journal of Geophysical Research* 112: 109. DOI: 10.1029/2006JD008345.

Tsukub K, Yoshikoa MK, Shinoda T, Kato M, Kanada S, Kitoh A. 2015. Future increase of supertyphoon intensity associated with climate change. *Geophysical Research Letters* 42: 646–652. DOI: 10.1002/2014GL061793.

Unuma T, Takemi T. 2016a. Characteristics and environmental conditions of quasi-stationary convective clusters during the warm season in Japan. *Quarterly Journal of the Royal Meteorological Society* 142: 1232–1249. DOI: 10.1002/qj.2726.

Unuma T, Takemi T. 2016b. A role of environmental shear on the organization mode of quasi-stationary convective clusters during the warm season in Japan. *SOLA* 12: 111–115. DOI: 10.2151/sola.2016-025.

Weisman ML, Skamarock WC, Klemp JB. 1997. The resolution dependence of explicitly modeled convective systems. *Monthly Weather Review* 125: 527–548. DOI: 10.1175/1520-0493(1997)125<0527:TRDOEM>2.0.CO;2.

Yoshikane T, Kimura F, Kawase H, Nozawa T. 2012. Verification of the performance of the pseudo-global-warming method for future climate changes during June in East Asia. *SOLA* 8: 133–136. DOI: 10.2151/sola.2012-033.

Zhang S, Nishijima K, Maruyama T. 2014b. Reliability-based probabilistic assessment of wind risk for residential buildings under projected future climate. *Civil Engineering and Environmental Systems* 31: 98–110. DOI: 10.1080/10286608.2014.912642.

Zhang S, Nishijima K, Maruyama T. 2014a. Climate model-based probabilistic assessment of wind risk for residential buildings under projected future climate. *Civil Engineering and Environmental Systems* 31: 98–110. DOI: 10.1080/10286608.2014.912642.

Zhang S, Nishijima K, Maruyama T. 2014b. Reliability-based modeling of typhoon induced wind vulnerability for residential buildings in Japan. *Journal of Wind Engineering and Industrial Aerodynamics* 124: 68–81. DOI: 10.1016/j.jweia.2013.11.004.

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