Hydrological Research Letters **10**(4), 119–125 (2016)
Published online in J-STAGE (www.jstage.jst.go.jp/browse/hrl). DOI: 10.3178/hrl.10.119

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-scenario 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 in 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) (Tayler *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 SI 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. In

Received 29 August, 2016
Accepted 3 November, 2016
Published online 10 December, 2016

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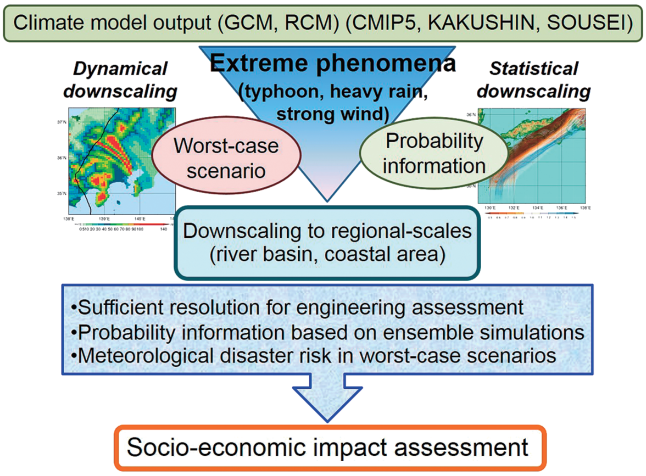

Figure 1. Conceptual diagram of the research in the assessment of meteorological hazards and risks under climate change in the SOUSEI program

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; Kitoh *et al.*, 2016) and the downscaled 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 downscaling 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. Oku *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 dependence 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-cyclonic 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 I. 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.

REMARKS AND FUTURE DIRECTIONS

The philosophy and achievements in the studies of assessing the impacts of global warming on meteorological hazards and risks in Japan under the SOUSEI program were reviewed. The concept of the research project consists of assessing worst-class meteorological hazards and evaluating probabilistic information on the occurrence of extreme phenomena. Collaboration among the fields in meteorology, hydrology, coastal engineering, and forest science plays a critical role in advancing the impact assessment of meteorological hazards and risks.

There are still remaining issues. One is to evaluate the worst-case scenario for heavy rainfalls in warm season. PGW experiments for extreme rainfalls will be a step forward to resolve this issue. The second is to quantitatively assess the probability of extreme events from a large number of climate projection samples. In-depth analyses on the data from the Database for Policy Decision making for Future climate change (d4PDF) (Shiogama *et al.*, 2016) are required. Nakakita *et al.* (2016b) conducted preliminary analyses on warm-season rainfall and atmospheric circulation features using the d4PDF dataset. Furthermore, higher-resolution RCM data are desirable to assess the impacts of climate change on smaller-scale phenomena such as thunderstorms and the associated heavy rainfalls and strong winds, advancing the study on the environmental conditions for summertime local rainfalls in Tokyo (Takemi, 2012).

Recently, heavy-rainfall-producing stationary convective systems have caused severe disasters such as the landslide in Hiroshima in August 2014 and the flooding in Ibaraki in September 2015. Future changes in the characteristics of such stationary convective systems will be a next research issue. Automated identification algorithms for stationary convective systems (Unuma and Takemi, 2016a, 2016b) can be applied if high-resolution, high-frequency rainfall outputs from climate projections are available, which will provide future projections in heavy rainfall due to stationary convective systems under global warming.

ACKNOWLEDGMENTS

The reviewers' comments are acknowledged in improving the original manuscript. This work was conducted under the SOUSEI program of MEXT.

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

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