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Impact assessment of coastal hazards due to future changes of tropical cyclones in the North Pacific Ocean

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ABSTRACT

Tropical cyclones generate severe hazards in the middle latitudes. A brief review and applications of dynamical and statistical downscaling of tropical cyclone (TC) are described targeting extreme storm surge and storm wave hazard assessment. First, a review of the current understanding of the changes in the characteristics of TCs in the past and in the future is shown. Then, a review and ongoing research about impact assessment of tropical cyclones both dynamical downscaling and statistical model are described for Typhoon Vera in 1959 and Typhoon Haiyan in 2013. Finally, several examples of impact assessment of storm surge and extreme wave changes are presented. Changes in both TC intensity and track are linked to future changes in extreme storm surge and wave climate in middle latitude.

1. Introduction

Tropical cyclones (TCs) are one of the major meteorological hazards as a cause of flooding, landslides, damaging winds, high waves, and storm surges. Depending on their size, intensity, track, and translation speed, TCs affect wide regions in the tropical, the sub-tropical, and the mid-latitude regions. After reaching a certain intensity, TC is specifically called a typhoon in the western North Pacific, a hurricane in the northeastern Pacific and in the North Atlantic, and a cyclone in the north Indian Ocean. Such intense TCs have spawned devastating damages from the past up to the present; recent examples include Hurricane Katrina in 2005, Cyclone Nargis in 2008, Typhoon Morakot in 2009, Hurricane Sandy in 2012, Typhoon Haiyan in 2013, and Tropical Cyclone Pam in 2015. For the purpose of mitigating and preventing disasters due to such intense storms, timely and proper warning based on accurate numerical weather prediction is prerequisite. Although numerical weather prediction of such destructive TCs is still a scientific challenge, some studies have recently shown that extended-range predictions of TCs beyond two weeks can be conducted under certain synoptic-scale conditions (Nakano et al., 2015; Xiang et al., 2015). Given the progress in quantitative weather forecasting of the track and intensity of TCs, the accuracy of warning for anticipated disasters will be improved.

From the perspective of mitigating and preventing disasters, long-term projections of TCs under climate change are also important. Global warming in the future is expected to affect the characteristics of TCs, in particular their frequency, intensity, and track. Such future changes of TCs would give significant impacts on natural disasters. Therefore, in order to mitigate and prevent TC-related disasters in the long term we need to assess the characteristics of TCs under global warming and the resulting impacts of future TCs on natural disasters.

Among the intense TCs in recent years, Cyclone Nargis (2008), Hurricane Sandy (2012), Typhoon Haiyan (2013), and Tropical Cyclone Pam (2015) caused significant coastal disasters. Because most of the major urban areas in the world are located in the coastal regions, intense TCs that make landfall or pass near the coastal regions affect a large number of people and social infrastructures. With the continuous growth of populations and social infrastructures in coastal urban regions in the future, intense TCs will increasingly be a threat to the human society especially in coastal regions. The impact assessment of coastal hazards due to anticipated changes of intense TCs under future climate change is of great concern. Because of the rapidly growing population in Asia (United Nations, 2012), TCs in the western North Pacific and in the Indian Ocean more significantly affect the economic and industrial activities as well as human lives than those in other ocean basins. Here we focus on TCs in the western North Pacific, i.e., typhoons.

The direct consequence of sea-level rise is inundation of low-lying coastal areas, which is a long-term concern and a gradual process of climate change effects. The Intergovernmental Panel on Climate Change (IPCC) the Fifth Assessment Report (AR5) (2013)

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states that climate change exacerbates the vulnerability of coastal regions to other extreme and impulsive physical processes, such as storm surges and storm waves. Future changes in storm surge and ocean wave climates are a dynamic side issue of how climate change influences coastal regions (e.g. Mori et al., 2010; Hemer et al., 2013). If extreme weather events become stronger in the future, it is necessary to seriously consider the effects of these dynamic phenomena to prevent and reduce the impact of coastal disasters. The wave hindcasts in the Atlantic Ocean show more significant wave height increase in the region off the Canadian coast and the northwest of Ireland but less significant change in the North Sea and in the region off the Scandinavian coast. In addition, the long-term changes to storm surge and storm waves are important considerations for structures near the coastal zone. For example, a coastal breakwater is designed with a maximum storm surge level and pressure from a maximum wave condition, a so-called design wave, for a predetermined design lifetime. Generally, coastal areas that will be most affected by increases in storm surge are the heavily populated mega-delta regions of East Asia, South-East Asia, South Asia and the Gulf of Mexico.

Tropical cyclone (TC) activity has major impacts on the delta regions located in the subtropical to mid-latitude zones. In these regions, 1-hPa decrease in atmospheric pressure corresponds to 1-m change in the barotropic effect to storm surge, and wind-induced surge is proportional to the square of wind speed (e.g. Nielsen, 2009). Also, wind induced surge is related to the moving speed and duration of a storm, and to the bathymetry of the bay. Therefore, storm surge is not only sensitive to TC intensity, but also to the track of the cyclone. Moreover, a certain number of TC tracks is necessary to make an assessment of storm surge risk at a particular location.

Future storm surge projections have been conducted for particular places such as Europe and East Asia. For example, Lowe and Gregory (2005) and Woth (2005) have analyzed future storm surges around the UK and in the North Sea regions, and they showed significant increases in storm surge elevations for the UK coast and the continental North Sea coast resulting from increases in the intensities of mid-latitude storms. Yasuda et al. (2014) and Zhao et al. (2014) show the impact of future storm surge changes in East Asia. For the subtropical to mid-latitude zones, however, future storm surge projections are limited due to the lack of knowledge of how TCs in these regions will change. furthermore, in these latitudes the majority of coastal regions measuring a few hundred kilometers in area have limited historical records of TC landfall. Therefore, assessing the TC risk in a particular region is difficult even considering the present climate alone. One way to overcome the limited amount of actual events is to use statistical modeling of TC events and another way is pseudo global warming experiments by a regional climate model.

Combining dynamic and statistical climate models gives a useful tool to assess the risks of future TCs and related coastal hazard. This study describes a brief review of future projections of TC characteristics due to global climate change. Then, we provide a review and ongoing research on the impact assessment of tropical cyclones for both dynamic downscaling and statistical models. Finally, we describe how TC characteristics change in the future climate changes coastal hazard based on the different approaches. A schematic flow chart of projection and impact assessment of climate change is shown in Fig. 1 (the numbers in Fig. 1 indicate the sections subsections in the manuscript).

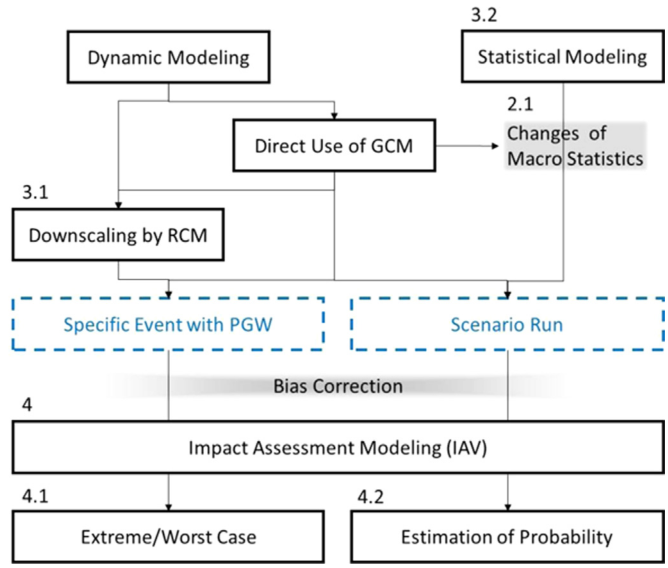

Fig. 1. Schematic flow chart of projection and impact assessment of climate change. Numbers in figure indicate the sections.

2. Past and future changes of tropical cyclones

In this section, we briefly overview the current understanding on the changes in the characteristics of TCs in the past and in the future. The current status of the understanding which has gained consensus among the broad scientific community is found in IPCC AR5 (2013). Based on the results included in IPCC (2013) and from other recent studies, we describe the characteristics on TCs in the western North Pacific from an impact assessment perspective.

2.1. Past changes of tropical cyclones

First, we give an overview on the changes of TCs in the past. For the assessment of the long-term changes in the TC activities, quantitative information on the intensity and track of TCs is necessary. Such reliable data have been available since the beginning of the satellite era starting from around the 1970s. Weather surveillance geostationary satellites give reliable data on TCs over each ocean basin, although the starting point of such observations depends on each ocean basin. For example, the observations by the Japanese Geostationary Meteorological Satellite “Himawari” over the western half of the Pacific started in 1977. Before the satellite era, aircraft observations played a role in quantifying the activity of TCs. However, without aircraft or satellite observations it is quite difficult to gain quantitative information on TCs. Therefore, data availability imposes a strong limitation on the assessment of the long-term changes in past TC activity. Although efforts have been made to archive long-term data on the TC activity back to the middle of the 19th century (International Best Track Archive for Climate Stewardship (IBTrACS), which is maintained by The National Oceanic and Atmospheric Administration (NOAA)), data that have uniformity in time and space are not available.

Because of the limited data availability, the confidence level in assessing the centennial-scale, long-term changes in TC activity in AR5 is overall low. An exception is for the activity of TCs in the North Atlantic; it is assessed in AR5 as virtually certain (i.e., the probability of 99% or greater) that the frequency of strong hurricanes in the North Atlantic has increased since the 1970s. However, firm conclusions on the changes in the frequency and intensity of TCs in the western North Pacific have not been obtained. In Kunkel et al. (2013), it is concluded that robust detection of trends in the TC activity in the Atlantic and the western North Pacific is significantly constrained by data heterogeneity and deficient quantification of internal variability, and that attribution of the past changes is challenged by a lack of consensus on the