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The evolution and intensification of Cyclone Pam (2015) and resulting strong winds over the southern Pacific islands

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ABSTRACT

Cyclone Pam (2015), a category-5 storm, in the southern Pacific in March 2015 caused severe damages over the islands states in the southern Pacific. Cyclone Pam was originated from an active convective region in the Madden-Julian oscillation (MJO) and evolved from convective clouds into a tropical cyclone. This study numerically investigated the effects of convective processes on the evolution and intensification of Cyclone Pam and the resulting strong winds with the use of the Weather Research and Forecasting (WRF) model through examining sensitivities to cloud microphysics schemes. The numerical simulations successfully reproduced the eastward propagation of the MJO and the aggregation of convective clouds that transformed to a tropical cyclone. It was found that microphysics processes affect the diabatic heating and therefore the evolution of tropical convection into a tropical cyclone. The potential instability for convective development and the actual development of deep cumulus clouds both contribute to the sensitivity of the simulated TC to the choice of the cloud microphysics schemes. Even with such sensitivity, this study successfully reproduced the cyclone track accurately in all the experiments and therefore is able to generate consistent hazard information from the cyclone.

1. Introduction

Tropical cyclones (TCs) are one of the major meteorological hazards and sometimes produce heavy rainfalls, strong winds, high waves, and storm surge. When TCs hit regions which are vulnerable to natural hazards, the impacts of TCs on human lives, social infrastructures, and economic activities will be enormous. Still recently there have been TCs that spawned devastating damages. For example, Cyclone Sidr (2017) landed on the southwestern coast of Bangladesh in November 2007, causing more than 3000 fatalities and huge economic damages (Paul, 2009). Cyclone Nargis (2008) made landfall on the Irrawaddy delta region of Myanmar in May 2008 and caused a devastating disaster that is regarded as the most damaging in the recorded history of Myanmar (Webster, 2008). Typhoon Haiyan (2013) made landfall on the Philippines in November 2013 and spawned severe storm surges over the coastal area of the Leyte Gulf. The central surface pressure of Typhoon Haiyan reached 895 hPa at its mature stage and is a category-5 storm in the Saffir-Simpson scale. To prepare for more extreme TCs, Lin et al. (2014) proposed that an extreme category above category 5, i.e., category 6 is required within the Saffir-Simpson scale. Not only to prepare for the coming TCs every year but also to respond to the anticipated increase in the intensity of TCs under future global warming, mitigating disaster risks from TCs is a critical social issue for those regions.

Another recent TC that severely affected developing countries is Cyclone Pam (2015), which developed in the southern tropical Pacific in March 2015. Cyclone Pam caused severe damages over the islands states in the southern Pacific. According to the information by Joint Typhoon Warning Center (JTWC), Cyclone Pam was a category-5 storm and its maximum wind speed reached about 75 m s^{-1}. Among the region affected, the islands of Vanuatu were severely damaged by the cyclone. The damages by Cyclone Pam are regarded as the worst natural disaster in the history of Vanuatu (Vitart and Coauthors, 2017). Because the isolated islands in the open ocean are susceptible to strong winds, high waves, and storm surges, a quantitative assessment of hazards induced by TCs is important in order to mitigate and prevent resulting disasters. The quantitative assessment of the hazard specific to this cyclone should enhance the resilience of the society of the islands states by designing appropriate measures for future cyclone hazards.

In addition, this cyclone is of meteorological interest, because Cyclone Pam developed and evolved from an active convective phase of a Madden-Julian Oscillation (MJO) signal. MJO is a large-scale cluster of convective clouds in the tropics (Madden and Julian, 1971, 1972; Zhang,

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2005) and sometimes affects the generation and evolution of tropical cyclones by changing the atmospheric conditions favorable for tropical cyclogenesis (Liebmann et al., 1994; Bessafi and Wheeler, 2006; Kim et al., 2008; Camargo et al., 2009; Chand and Walsh, 2010; Kikuchi and Wang, 2010; Huang et al., 2011; Yanase et al., 2012; Klotzbach and Blake, 2013; Klotzbach, 2014; Tsuboi and Takemi, 2014). With the use of an index that describes the potential for tropical cyclogenesis (Murakami et al., 2011), it was found that the increase in humidity is an important condition favorable for the generation of tropical cyclones in the Indian Ocean during the active periods of MJO (Tsuboi and Takemi, 2014; Tsuboi et al., 2016). Klotzbach and Blake (2013) indicated that during the convectively active phase of the MJO over the eastern and central tropical Pacific the north-central Pacific tends to have more TCs and the convectively active phase of MJO is responsible for north-central Pacific TCs that experience rapid intensification. Chand and Walsh (2010) examined the modulation of TC genesis by MJO in the central South Pacific (i.e., the Fiji, Samoa, and Tonga regions) and showed that the TC genesis is significantly enhanced during the active phase of MJO. Thus, the intensification of Cyclone Pam that occurred in the central South Pacific is considered to be significantly affected by the presence of MJO. The physical processes that lead to the intensification of Pam are therefore of scientific interest.

This study numerically investigates the evolution and intensification of Cyclone Pam (2015) that transformed from convective populations to a tropical cyclone by conducting dynamical downscaling simulations with the use of a regional meteorological model, the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008). In order to elucidate the diabatic heating processes that control the development of convective clouds, the sensitivities to the cloud microphysics schemes were investigated. Ice-phase processes are known to affect the development of TCs (Lord et al., 1984; Sawada and Iwasaki, 2007; Fovell et al., 2016). We will demonstrate how the cloud microphysics influences the evolution of convective populations and the intensification to a tropical cyclone and hence affects the assessment of hazards by the cyclone. Furthermore, previous studies indicated that a dynamical downscaling simulation with a regional meteorological model is an effective tool to assess the impacts of extreme weather phenomena on local-scale hazards (Mori and Takemi, 2016; Takemi et al., 2016a) and has been successfully used for assessing the impacts of typhoons (Ishikawa et al., 2013; Oku et al., 2014; Mori et al., 2014; Murakami et al., 2015; Murata et al., 2015; Ito et al., 2016; Takano et al., 2016; Takemi et al., 2016b, 2016c). Another purpose of this study, therefore, is to demonstrate the applicability of the dynamical downscaling approach in estimating strong wind hazards by a TC in the southern Pacific.

This paper is organized as follows. In section 2, the settings of the WRF model and the design of the numerical experiments are described. Section 3 firstly evaluates the performance of the numerical experiments and then examines the evolution of Cyclone Pam from the sensitivity experiments. We will further demonstrate hazards due to cyclone winds in Vanuatu from the dynamical downscaling experiments. We will discuss the advantages and significance of this study by comparing the previous studies in section 4 and will conclude this study in section 5.

2. Numerical model and experimental design

The numerical model used here was the WRF model-the Advanced Research WRF (ARW) version 3.3.1. The model was configured in a realistic mode to simulate the genesis, evolution, and movement of Cyclone Pam under actual meteorological conditions in March 2015.

During this period, the active convective regions of MJO propagated eastward from the western part of the Indian Ocean to the eastern part of the Pacific. Therefore, the complete description of the MJO in numerical simulations requires a vast computational domain. At the same time, convective nature of MJO requires a sufficient resolution that can represent the organization of convective clouds. However, to meet both the vast computational domain and the convection-resolving grid spacing is not affordable from a viewpoint of computational resources. Thus, two-way nesting capability was used to resolve the active convective regions of MJO and the evolution of the tropical cyclone at a convection-permitting grid spacing in a limited domain that is nested in a coarser-resolution, larger domain. The outer domain (Domain 1) covered the tropical regions from the Maritime Continent to the eastern part of the Pacific with an area of 7650 km (east-west) by 4500 km (north-south), centered at 152°E, 12°S. The inner domain (Domain 2) covered the central part of the Pacific with an area of 2500 km by 3000 km. The map projection of the computational domains was based on the Mercator.

The spatial resolutions of the simulations were set as follows. The horizontal grid spacings of Domain 1 and 2 were 6 km and 2 km, respectively. While in the vertical, the number of the model levels was 56, and the model top was set to the 20-hPa height. The vertical resolution at the lowest level was 69 m, and there were 8 levels in the lowest 1-km depth. With this vertical resolution, it was expected to sufficiently resolve the low-level inflows of the simulated tropical cyclones. The vertical resolution was gradually stretched with height. There were 20 levels in the lowest 3-km depth, and the vertical resolution at around the 3-km height was about 200 m. The vertical resolution was further stretched: about 300 m at around the 5-km height, about 500 m at around the 10-km height, and greater than 1 km above the 15-km height.

The model topography was generated with the use of the global digital elevation model data, GTOPO30, having a horizontal grid spacing of 30 arc-seconds (about 1 km), provided by the United States Geological Survey.

The physics options employed in the present simulations were chosen based on our recent studies on tropical cyclones (Mori et al., 2014; Mori and Takemi, 2016; Takemi et al., 2016b, 2016c); for example, we chose the Yonsei University scheme for boundary-layer mixing (Hong et al., 2006) and a Monin-Obukhov similarity-based scheme for surface fluxes (Jimenez et al., 2012). Among the physics processes, the cloud microphysics process affects the diabatic heating due to phase changes and thus is considered to determine the development of convective cloud. Therefore, this study focuses on the sensitivity of the simulated cyclone to the choice of cloud microphysics schemes. The schemes examined here are a single-moment, six-category scheme by Hong and Lim (2006) and two double-moment schemes, i.e., the schemes by Thompson et al. (2008) and Morrison et al. (2009). Brief descriptions of these schemes can be found in the User's Guide of the WRF model (available online at http://www2.mmm.ucar.edu/wrf/users/docs/user_guide_V3/contents.html) as well as in the technical document (Skamarock et al., 2008). In this study, we conducted three numerical experiments by changing the cloud microphysics scheme but with otherwise the same model settings. The numerical experiments with the single-moment scheme, the Thompson scheme, and the Morrison scheme are respectively referred to as WSM6, THOM, and MORR.

As the initial and boundary conditions, we used the 6-hourly, 1-degree by 1-degree resolution Final Analysis (FNL) data of National Centers for Environmental Prediction (NCEP) Operational Model Global Tropospheric Analyses. The FNL datasets includes not only three-dimensional atmospheric fields but also surface parameters such as sea surface temperature, ground surface temperature, etc. The spectral nudging for low wave-number components (i.e., wave number 2) of middle- and upper-level winds was applied in Domain 1 to keep the synoptic-scale influences on the simulated atmospheric fields. The time coefficient for the spectral nudging was set to 0.00028 s^{-1}. This coefficient was used in the studies of Mori et al. (2014), Ito et al. (2016), and Takemi et al. (2016b, 2016c) who demonstrated that by trial and error the spectral nudging with that coefficient was effective in reproducing the tracks and intensity of typhoons. For this reason, this study also used the same time coefficient.

It is noted that the present simulations use only the analysis fields but not the forecast fields. Because the analysis fields incorporate observed data through data assimilation technique, they are able to represent large-scale and/or synoptic-scale atmospheric phenomena such as