

Supplementary material for
Future Changes of a Slow-moving Intense Typhoon with
Global Warming: A Case Study using a 1-km-mesh
atmosphere–ocean coupled regional model

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Contents of this file

Text S1

Table S1

Introduction

This supplementary material provides additional information about the models and methodology.

1. Models and methodology

The model used in the present study is a high-resolution three-dimensional atmosphere–ocean coupled regional model, CReSS–NHOES (Aiki et al. 2015). Detailed specifications are summarized in Table S1.

The atmosphere model CReSS version 3.4.1 (Tsuboki and Sakakibara 2002) includes bulk-type cloud microphysics with an ice phase (Murakami 1990). No cumulus parameterization is adopted. The model applies the Deardorff scheme (Deardorff 1980) for turbulence and the Louis scheme (Louis et al. 1982) with a surface-roughness-length formulation based on Kondo (1975) for the surface boundary layer. The ocean model NHOES (Aiki et al. 2006, 2011) uses the turbulence closure model by Furuichi et al. (2012) modified from Nakanishi and Niino (2009). The atmosphere model provides heat and water fluxes and wind stress to the ocean model, and the ocean model provides sea surface temperature (SST) to the atmosphere model. The coupling interval was set to 300 s.

The horizontal domain of the coupled model spans 121°E–140.01°E and 14°N–33.01°N (Fig. 1), and is discretized with a grid spacing of 0.01° by 0.01°. The sponge layers for the all lateral boundaries were set to 0.28°. The both models used the same horizontal domain and grids. The atmosphere model has 64 vertical levels (lowest layer, 100 m; top height, approximately 28.5 km), and the time step was 2 s. The ocean model has 100 vertical levels (2 m intervals from the sea surface to 100 m depth stretch from a depth of 100 m to the ocean bottom).

The pseudo-global warming (PGW) simulations were conducted by the similar procedure to that of Kanada et al. (2019, 2017). First, a control simulation of Typhoon Trami (2018) under current climate conditions was performed (the CNTL simulation). Initial and lateral boundary conditions for the atmosphere model were provided every 6 h from the Japan Meteorological Agency global objective analysis data (GANALjp; Japan Meteorological Agency 2013) with a horizontal resolution of $0.25^\circ \times 0.20^\circ$. For the ocean model, initial and lateral boundary conditions were provided every 24 h from

the Japan Coastal Ocean Predictability Experiment reanalysis product (JCOPE2M, Miyazawa et al. 2017, 2019). Simulations started at 0600 UTC on 26 September 2018 and ended at 1800 UTC on 29 September 2018.

To make the PGW increments, the results of climate runs by MRI-AGCM version 3.2 with a horizontal resolution of 20 km (Mizuta et al. 2012) were used. The future climate runs were driven by a multi-model ensemble mean SST pattern projected by Coupled Model Intercomparison Project phase 5 (CMIP5) models under the RCP8.5 scenario (Mizuta et al. 2014). Then, changes between the periods of 1979–2003 and 2075–2099 were estimated from the results, and these changes averaged in the simulation domain were added to the initial and boundary conditions of the CNTL simulation. Future changes in the September monthly mean for SST, atmospheric temperature (T) and geopotential height (Z) were added to the initial and boundary conditions of the CNTL simulation for the PGW simulation, since the typhoon occurred in September. The change in relative humidity was not considered because recent studies have indicated little change in tropospheric relative humidity between the current and future climates (e.g., Takemi et al. 2012). Therefore, water vapor (QV) was increased to conserve the relative humidity in the PGW simulation for the warmer climate.

Because Huang et al. (2015) have reported that the vertical temperature gradient will be steeper in a warming climate (i.e., the temperature increase decreases as the depth increases in the future climate), SST increments were added to ocean temperature (T_{ocean}) from the sea surface to a depth of 100 m, decreasing linearly to be 0 at 100 m depth for the PGW simulation. To understand the sensitivity of the ocean initial conditions to TC intensity, we performed another PGW simulation (the PGWC

simulation) with different ocean boundary conditions: constant SST increments were added to all T_{ocean} from the surface to a depth of 100 m.

Table S1. Specifications of the models.

	Atmosphere Model (CReSS3.4.1)	Ocean Model (NHOES)
Horizontal domain	121-140.01°E by 14-33.01°N with a resolution of 0.01 deg by 0.01 deg (See Fig. 1)	
Vertical extents	Top height: 28.5 km (lowest dz = 100 m)	From the sea surface to the bottom of the ocean (dz = 2 m for the top 100-m)
Time step	2 sec	0.5 sec (barotropic) 15.0 sec (baroclinic)
Coupling interval	300 sec	
Coupling quantities	SST (from NHOES)	Surface heat, fresh water and momentum (from CReSS)
Surface heat and momentum exchange	Latent and sensible heats and momentum: Louis et al. (1982) with Kondo (1975), Short- and long-wave radiation: Tsuboki and Sakakibara (2002); Segami et al. (1989)	
Cloud	Simple 2-moment 3-ice bulk scheme (No cumulus convection)	N/A
Turbulence	Deardorff (1980)	Furuichi et al. (2012)
Initial and boundary conditions	Japan Meteorological Agency global objective analysis data (resolution: 0.25 and 0.2 degrees in the longitude and latitude, respectively)	JCOPE2M (Miyazawa et al. 2017, 2019) (resolution: 0.1 deg)
Initial time	0600 UTC on 26 September 2018	

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