Simulation of the December 2014 Nemuro Storm Surge and Incident Waves

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The storm surge due to the December 2014 Nemuro cyclone was hindcast using the Delft-3D/SWAN combined hydrodynamic and wave model with Japan Meteorological Agency (JMA) Mesoscale Model (MSM) reanalysis data as the surface boundary condition. Wind and pressure fields near Nemuro from the JMA MSM reanalysis data set agree with data from AMEDAS weather stations in eastern Hokkaido. The storm surge model result matches published measurements of water level and inundation extent in the town. Via application of the BOSZ Boussinesq-type wave model, the excitation of infragravity motions nearshore by this storm were found to be insignificant, but wave runup does cause an increase in the extent of inundation compared to that due to the still water storm tide hindcast by the Delft-3D/SWAN model.

To evaluate the possible effects of climate change, a hypothetical storm with 150% the intensity of the 2014 cyclone was also simulated. Though the concrete armor units protecting the town's infrastructure are strong enough to escape damage from the hypothetical storm's waves, they are not high enough to prevent waves from riding atop the storm surge into low-lying areas of the town proper and the harbor. These waves are large enough to wreck residential buildings and pose a threat to life as well as property. Coastal hazards at locations in the midlatitudes, such as Nemuro, need to be reassessed accounting for the predicted effects of climate change, and adaptation strategies formulated based on local conditions.

Key Words : *extratropical cyclone, storm surge, waves, meteorological model, armor unit, breakwater*

1. INTRODUCTION

The extratropical cyclone of December 17, 2014 caused a storm surge that flooded the downtown and port areas of Nemuro, Hokkaido Prefecture (**Fig. 1**). Inundation was up to 1.5 m deep¹, necessitating the evacuation of 1,500 residents², flooding 97 buildings up to 300 m from shore, and causing damage of over 2 billion yen³. The peak of the storm surge occurred near a neap high tide; if the same event were to occur during a spring high tide, the flooding could be much worse. Due to climate change, it is expected that tropical cyclones will affect higher latitudes⁴ and the intensity and frequency of extratropical storms near northern Japan may also increase⁵, exacerbating the

coastal flood hazard along Hokkaido's coasts and requiring both the reassessment of coastal defenses already in place and investigation of the necessity for expanded coastal defenses in populated areas.

Section 2 of this paper discusses the meteorological data used to reconstruct the pressure and wind fields of the cyclone. Section 3 details the setup of the storm surge and wave models. Section 4 compares model results with measurements. Section 5 discusses the effects of a hypothetical intense storm on coastal structures and buildings.

2. METEOROLOGICAL DATA

In order to determine the sea surface air pressure

Fig. 1. Map of large model domain. Small rectangles represent the middle and small domains. Thick black line shows the storm track of Table 1. Color represents surface air pressure [hPa] and vectors show wind at 9am JST on December 17, 2014.

and wind fields during the cyclone, 3 different data sources were considered: Japan Meteorological Agency (JMA) Mesoscale Model (MSM) forecast data with 5 km resolution and available at 1 hr intervals⁶⁾, JMA MSM reanalysis hindcast data with 5 km resolution and available at 3 hr intervals⁷⁾, and Climate Forecast System Version 2 (CFSv2) data with 20 km resolution at 1 hr intervals⁸⁾. The validity of these model results were compared with AMEDAS⁹⁾ weather station measurements at the 3 easternmost locations in Hokkaido: Attoko, Nemuro, and Nosappu. **Fig. 2** compares measured air pressure, wind speed, and wind direction with each model's results. As the CFSv2 data's spatial resolution is too coarse, it cannot resolve the storm enough to hindcast the pressure and wind speed measured at the AMEDAS stations. However, the JMA MSM forecast and reanalysis data sets each qualitatively compare well to measured data from the AMEDAS stations. Therefore, JMA MSM reanalysis data is

Fig. 2. Weather models compared to AMEDAS measurements.

used to drive the storm surge model to follow. **Fig. 1** shows the track of the cyclone along with sea level air pressure and wind fields at the time of lowest central pressure. **Table 1** lists storm track parameters derived from the JMA MSM reanalysis data set, along with the track of a hypothetical storm with 150% the intensity of the December 2014 Nemuro cyclone. This hypothetical storm is used as a proxy for the type of storm to which this region might be subject in the future due to climate change.

3. STORM SURGE AND WAVE MODEL

The hindcast pressure and wind fields are input into a combined hydrodynamic and wave model to hindcast the water level and wave heights induced by the cyclone. The hydrodynamic model used is Delft-3D¹⁰⁾ applied with only 1 layer in the vertical (thus the shallow water equations), and the spectral wave model used is SWAN¹¹⁾. Delft-3D and SWAN are run together, with the hydrodynamic model repeatedly passing water level and current fields to the wave model, which calculates the wave field including the effects of currents and storm surge. The wave model in turn passes the radiation stress field back to the hydrodynamic model, which uses this information to calculate breaking-wave-induced setup and nearshore currents.

The Delft-3D/SWAN model was run over 3 nested domains, with the large domain of 2 km resolution, the middle domain 80 m, and the small domain 16 m (**Fig. 1**). Coarse bathymetry from JODC¹²⁾ was combined with fine bathymetry from the Japan Coast Guard nautical chart of Nemuro Port¹³⁾ for the fine model domains. Land elevation in the model was derived from GSI 5 m mesh data¹⁴⁾. Tides were included as a boundary condition using the TPXO¹⁵⁾ model result, and spun up for 5 days before adding winds to the model. Delft-3D was run with 1 vertical layer. Manning's n for bed friction was specified as $n=0.1 \text{ s/m}^{1/3}$ in industrial areas, $n=0.15 \text{ s/m}^{1/3}$ in dense residential areas, and $n=0.02 \text{ s/m}^{1/3}$ over open

Table 1. Track of the December 2014 Nemuro cyclone based on JMA Reanalysis data⁷⁾.

Month	Day	Hour	Center Longitude, deg E	Center Latitude, deg N	Center Pressure, hPa	Max Wind, m/s	Center Pressure 150%, hPa	Max Wind 150%, m/s
12	16	12	134.18	32.53	997	26.25	989	39.37
12	16	15	136.50	33.42	990	30.19	978	45.28
12	16	18	139.22	34.76	986	28.78	973	43.16
12	16	21	142.46	36.48	982	30.37	966	45.55
12	17	0	144.99	38.79	973	29.78	953	44.67
12	17	3	146.17	41.09	957	32.97	929	49.45
12	17	6	146.21	42.72	949	35.74	916	53.61
12	17	9	146.03	43.43	948	33.67	916	50.50
12	17	12	146.10	44.13	948	32.82	915	49.24
12	17	15	146.07	44.41	950	29.15	919	43.73
12	17	18	146.39	44.35	953	28.48	923	42.73
12	17	21	146.45	44.30	955	26.88	925	40.32

Fig. 3. Comparison of Delft-3D modeled water elevation with measurements from the Nemuro Port tide gauge²¹⁾.

ground^{16),17)}. In order to evaluate the effect of this land-use-dependent Mannign's n , another simulation was run with uniform $n=0.02 \text{ s/m}^{1/3}$.

An important adjustment to the default SWAN setup was the use of an air-sea drag coefficient limiter of $0.003^{18),19)}$ imposed on the drag law of Wu²⁰⁾. This drag coefficient limiter is the result of multiple airborne sonde drop measurements in hurricanes¹⁹⁾, and is necessary to prevent the development of unphysical wave heights in the model.

4. STORM SURGE MODEL RESULTS

The water level measured by the Nemuro tide gauge²¹⁾ is compared with storm surge model results in **Fig. 3**. The model result captures the peak storm tide at 2.2 m above mean sea level (MSL). The application of both JMA MSM meteorological models (forecast and reanalysis) drivers for the storm surge model result in almost the same storm tide timeseries at this location. Both model results hindcast a marginally more rapid rise in storm surge than the measurement, with a peak storm tide 30 minutes earlier than the measured timeseries. Since the tide

Fig. 4. Comparison of Delft-3D maximum modeled water elevations with the measurements of Shibayama et al.²²⁾.

Fig. 5. SWAN wave height spectrum outside of Nemuro Port used as input to the BOSZ Boussinesq wave model. Radial bins are frequency [Hz], and azimuthal bins are incident wave direction [deg]. Figure made using the DIWASP toolbox for MATLAB.

gauge failed at about 1:00 pm, no measured data is available for comparison after that time.

Fig. 4 shows modeled inundation water levels compared with Shibayama et al.'s²²⁾ measurements throughout the inundated portion of Nemuro. The median value of the measurements is close to the model result, though the measurements show a larger spread. To investigate whether this could have been due to infragravity oscillations, the Boussinesq wave model *BOSZ*²³⁾ was applied to Nemuro with the same topography used by Delft-3D and with the spectrum of **Fig. 5** as the offshore wave boundary condition²⁴⁾. However, *BOSZ* computes only weak energy in the infragravity band. Therefore, the difference between modeled and measured flood elevations in **Fig. 4** is likely due to variations in flow around individual buildings and structures in the town, as these buildings were not resolved in the topographic data used by the model.

Fig. 6 shows the maximum modeled flood depth throughout the town and harbor. The extent of inundation compares well with maps of observed inundation extent published by MLITT³⁾ and Watanabe et al.²⁵⁾. As indicated by **Fig. 4**, accounting for land-use-dependent bed friction had only a small effect on modeled inundation depth by retarding flow speed and causing a 10% deeper flood to accumulate on land than in the case with a uniform Manning's n .

Figs 7 and 8 indicate that large waves did not penetrate into the flooded town. This is a reason for the lack of heavy damage and casualties due to the storm surge. However, by resolving individual waves with *BOSZ*, **Fig. 8** indicates that wave runup east of the port was large enough to overtop a berm road and cause ponding that was not resolved by the

Fig. 6. Maximum Delft-3D flood depth [m] in Nemuro.

phase-averaged result of Fig. 6.

5. URBAN HAZARD REASSESSMENT

In order to assess the hazard that Nemuro and other towns fronted by shallow offshore regions at midlatitudes might face in the future due to climate change, a hypothetical storm with 150% the central pressure drop and maximum wind speed of the December 2014 Nemuro cyclone was considered (Table 1). Fig. 3 shows that this event would cause a storm surge up to 4.6 m above MSL, resulting in inundation of low-lying parts of town by water up to 4 m deep (Fig. 9). This storm surge would submerge the town's coastal defenses, which are mostly wave-dissipating concrete blocks (Fig. 10) along with breakwaters and floodwalls with heights between 2 m and 3 m above MSL. Waves would thus propagate into town (Fig. 11) with significant wave height of 2 m in the residential area of Fig. 10, and 4.5 m high waves would strike the breakwater north

Fig. 7. Maximum SWAN significant wave height [m].

Fig. 8. Example snapshot of the wave field from the BOSZ Boussinesq-type wave model. White line indicates the mean sea level shoreline. Red line indicates maximum runup extent. Arrow indicates area of ponding due to wave runup and overtopping.

of the harbor. The propagation and breaking of waves of this size could pose a threat to the infrastructure protecting the town, and, even graver, to lives and property inside the town.

Armor stability was evaluated via Eq. (1)^{26,27} for tetrapod-armored slopes and Eq. (2)^{26,28} for tetrapod mounds in composite breakwaters.

$$\frac{H_s}{\Delta D_n} = \left(3.75 \frac{N_{od}^{0.5}}{N_z^{0.25}} + 0.85 \right) s_{om}^{-0.2} \quad (1)$$

$$\frac{H_s}{\Delta D_n} = 2.32 \left(\frac{N_{od}}{N_z^{0.5}} \right)^{0.2} + 1.33 \quad (2)$$

where $\Delta = (\rho_s / \rho_w - 1)$, with ρ_s the solid (concrete) density, ρ_w the water density, H_s the significant wave height, D_n the armor unit equivalent cube side

Fig. 9. Maximum Delft-3D flood depth [m] in Nemuro due to the hypothetical 150%-intensity storm.

Fig. 10. Residential development at the location of the star icon in Figures 6, 7, 9, and 11.

length, N_z the number of waves (equal to 7,500 for equilibrium damage), s_{om} the wave steepness, and N_{od} is the number of units displaced out of the armor layer within a strip of 1 cube side length D_n .

The locations of the triangle and rectangle icons in **Fig. 11**, along with the entire northern attached breakwater, are composed of concrete jack-type wave dissipating blocks and tetrapods of length 2.4 m protecting concrete caissons and parapets. Even at the tip of the attached breakwater, where the significant wave height would be 4.5 m, Eq. (2) gives $N_{od}=0.13$, indicating that displacement of armor units would be minimal. The 1.5 m long tetrahedron-type armor units of **Fig. 10** would be subject to a significant wave height of 2.5 m, for which Eq. (1) gives $N_{od}=0.16$. In both of these locations, the armor units in place appear to be large enough so as not to fail during the 150% intensity storm. However, the 4.6 m above MSL storm surge will allow waves to overtop these defenses and impact buildings directly.

The design maximum pressure P and force f per unit wall length due to a breaking wave incident on a vertical wall is calculated via Eq. (3)²⁹⁾ and Eq. (4)³⁰⁾

$$P = C_p \gamma_w d + 1.2 \gamma_w d \quad (3)$$

$$f = 1.1 C_p \gamma_w d^2 + 2.4 \gamma_w d^2 \quad (4)$$

where C_p is a dynamic pressure coefficient equal to 2.6 for residential buildings and 3.5 for essential facilities (hospitals, evacuation centers, etc.), γ_w is the specific weight of water, and d is the water depth at breaking. The breaking water depth is assumed to be $d=H_s/0.78$, with H_s the significant wave height.

In the residential area of **Fig. 10**, waves of 2.5 m height breaking against building walls will result in $P=103$ kPa and $f=362$ kN/m. This loading is 2 orders of magnitude larger than would be occur due to wind even during category 5 hurricane conditions²⁹⁾, so building collapses might be expected.

6. CONCLUSIONS

Fig. 11. Maximum SWAN significant wave height [m] in Nemuro due to the hypothetical 150%-intensity storm.

Storm surge due to the December 2014 Nemuro cyclone was hindcast using a combined hydrodynamic and wave model with JMA MSM reanalysis meteorological data as the surface boundary condition. The model result agrees with published measurements of water level and inundation extent in the town. To evaluate the possible effects of climate change, a hypothetical storm with 150% the intensity of the 2014 cyclone was also simulated. Though the concrete armor units protecting the town's infrastructure are strong enough to escape damage from waves, they are not high enough to prevent waves from riding atop the storm surge into low-lying areas of the town proper and the harbor. Waves propagating into the town are large enough to wreck residential buildings and pose a threat to life safety.

The type of threat facing Nemuro is not limited to this city alone, but will also affect other cities fronted by shallow coasts in Hokkaido and elsewhere at northern midlatitudes. As hurricanes and typhoons migrate poleward due to climate change⁴⁾ and the intensities of extratropical storms near Hokkaido strengthen⁵⁾, the incidence of damaging storm surge and waves at these locations is likely to become more common. However, this does not necessarily suggest that building higher breakwaters and seawalls is a practical idea. Since the population of Nemuro is declining rapidly (28,060 residents in 2014, compared to a peak of 49,896 residents in 1966)³¹⁾, managed and gradual retreat of residences from the shoreline via land use zoning might be a more practical option than public investment in shoreline protection infrastructure. Protection of port infrastructure, however, will require construction of larger breakwaters, floodwalls and gates, or toughened or elevated buildings.

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