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ESTIMATING STORM SURGE INUNDATION DAMAGE TRIGGERED BY GLOBAL WARMING ALONG JAPAN'S PACIFIC COAST

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In Japan, large populations and property are concentrated in vast, low-lying coastal lands. These areas are at increased risk of inundation by storm surges, which would be exacerbated by rising sea levels and stronger typhoons in the event of global warming. This study created a numerical model to estimate inundation damage by calculating the probability of storm surge occurrence and the area of land inundated. The model examined the Pacific coast of southern Japan to estimate the inundated area, inundated population, and damage corresponding to varying sea level increases and storm surge heights. The results indicate that the inundated area, population affected, and damage increase linearly with increasing sea levels and storm surge heights. Furthermore, low-lying land surrounding Japan's three major bays, the Seto Inland Sea, and northwestern Kyushu are at the highest risk of inundation by storm surges.

Keywords: *global warming, storm surge, inundation damage model, Japan's Pacific Coast*

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC)1), it is highly probable that sea levels will rise 18–59 cm and the frequency of strong typhoons will increase over the next 100 years due to global warming. One implication of global warming is an increasing risk of inundation damage by storm surges in Japan's coastal areas, which contain 46% of Japan's population, 47% of industrial shipments, and 77% of total commercial sales and are important socioeconomically2). A model is needed to predict storm surge inundation damage based on increasing sea levels and storm surge heights caused by global warming3). Such a model could also be used in setting targets for greenhouse gas concentrations.

Implementing preparations immediately to reduce damage by higher storm surges would require large investments and would be too costly over the short term. Since both global warming and increasing storm surge height are long-term threats, acting at a similar pace to that of global warming would be more viable and less financially burdensome. Therefore, storm surge inundation damage should be estimated based on global warming levels. Scenarios are also needed for countermeasures against increased storm surges resulting from global warming.

Since the increase in inundation damage rates will vary across Japan, damage should be determined for the entire country. This study estimated the risk of inundation caused by increased storm surge heights in high-risk areas of the Pacific coast of southern Japan. Topography, levee, and seawall datasets were created for the computational model. Inundation depth was estimated by calculating levee and seawall overflow, and inundation areas were estimated under varying sea level and storm surge heights. Graphs were made of the inundated areas, the population within these areas, and the amount of inundation damage considering increased sea level and storm surge heights due to strengthened typhoons.

2. SCOPE OF MODELLING

To predict damage caused by physical oceanographic phenomena altered by global warming, the area and population in land lower than the maximum sea level caused by storms or tsunamis are often estimated as a risk index4). However, this estimation may be insufficient. Since levees and seawalls protect most low-lying areas in Japan, estimated and actual risks could differ largely. Furthermore, the risk of storm surges associated with a certain increase in sea level and typhoon intensity is unknown.

Therefore, we created an inundation model incorporating levee and seawall overflow and inundated land area. The inundated area and population and the inundation damage are used as indicators of storm surge damage. These indicators are calculated using the inundation model for varying sea level increases and storm surge scale factors, equal to the affected storm surge height over the storm surge height in the reference year. Then, graphs are plotted for the damage indicators considering both sea level increases and storm surge scale factors.

First, datasets of land surface elevation, population, and levee, seawall, or shore protection are created. Then, water level oscillation data are compiled, and the shore protection overflow volume is calculated over time. The water depth for each mesh is calculated for varying storm surge heights using a horizontal-surface flooding model. The inundated area and population and inundation damage are calculated for the maximum water levels under each condition. Expected values are obtained by multiplying the inundated area and population and inundation damage by the probability of storm surge occurrence. The calculation is performed for varying sea level increases and storm surge scale factors. Variations in the inundated area and population, and inundation damage are clarified.

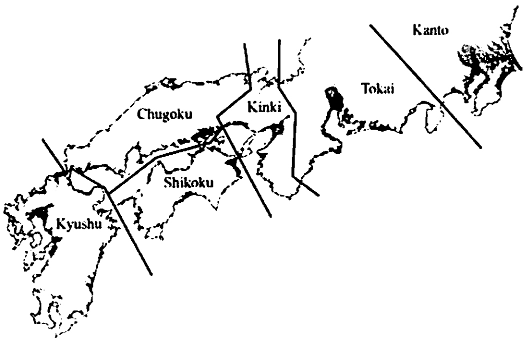

Fig.1 Area selected for the cell calculations.

Table 1 Number of cells and cell coverage rate.

Region	Cell No.	Cell area (km^2)	Cell pop. (x1000)	Total area (km^2)	Total pop. (x1000)	Cover rate (area)	Cover rate (pop.)
Kanto	66	4,657	13,586	4,804	13,694	0.969	0.992
Tokai	94	2,907	6,802	3,019	6,868	0.963	0.990
Kinki	75	1,404	8,333	1,507	8,429	0.932	0.989
Chugoku	97	1,715	3,391	1,989	3,551	0.862	0.955
Shikoku	55	1,066	1,924	1,277	2,005	0.835	0.960
Kyushu	148	3,122	5,203	3,855	5,444	0.810	0.956
Total	535	14,871	39,239	16,451	39,991	0.904	0.981

Notes: The total area includes the area < 15 m above sea level and the total population is the number of people living within this area in each region.

Global warming may increase storm surge damage across the country. This study analyzed regions along the Pacific Ocean that have relatively high risks of storm surges: the Kanto, Tokai, Kinki, Chugoku, Shikoku, and Kyushu regions.

To determine the inundated area using the inundation model, low-lying land was divided into cells that indicated the inundated water level as a unit, based on topography.

The initial division included so many cells that intensive effort would have been required to create the datasets. To reduce the number of cells, despite a decrease in calculation accuracy, the following criteria were set:

[1] Remote islands < 100 km^2 were excluded from the calculation.
[2] Land area < 15 m above sea level was included.
[3] Cells > 1 km^2 with more than 2,000 persons/km^2 or cells > 5 km^2 were included.

Areas with cells satisfying these criteria are shown as the shaded areas in **Fig. 1**.

The final count included 535 cells with an area of 14,871 km^2 and a population of 39,239,000. The total area with an elevation < 15 m above sea level was 16,451 km^2 with a population of 39,991,000. The average coverage rate for the area was 90.4% and that for the population was 98.1% (**Table 1**).

3. INUNDATION MODEL AND DAMAGE ESTIMATION

(1) Topography

Topographic information on particular areas was necessary for calculating the inundation depth caused by storm surges. Digital elevation data in 50-m grid units were used. The data were obtained by vectorizing the contour lines of 1/25,000-scale maps published by the Geographical Survey Institute, Japan.

(2) Population

The area mesh populations from the 2000 Population Census was used. Since these data were available only in a 500-m mesh, each mesh value was divided by 100 and assigned to a 50-m mesh.

(3) Shore Protection

The maximum elevations and lengths of shore protection structures were gathered and surveyed for use in the calculations.

(4) Storm Surges

The 5-h duration, peak time 2.5 h after the surge rise and triangular storm surge time-series profiles were used for the storm surge wave profiles, based on the analysis by Kawai *et al.*[5] of storm surge duration in Tokyo Bay. Storm surge occurrence follows the statistical theory of extreme values[6],[7]. The probability distribution function of storm surge height was determined using the method outlined by Goda[8] for each block based on the storm surge observation point. The probability distribution function shapes used were the extreme value I-shape, extreme value II-shape, and Weibull distribution. The mean correlation coefficient obtained using Goda's fitting method was 0.987 with a standard deviation of 0.008.

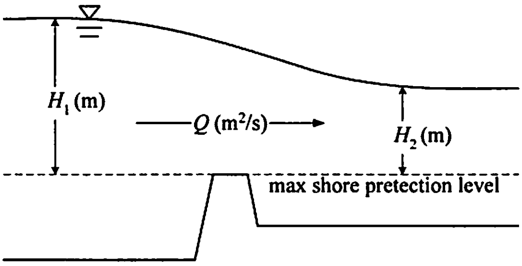

Fig. 2 Diagram of the overflow cross-section.

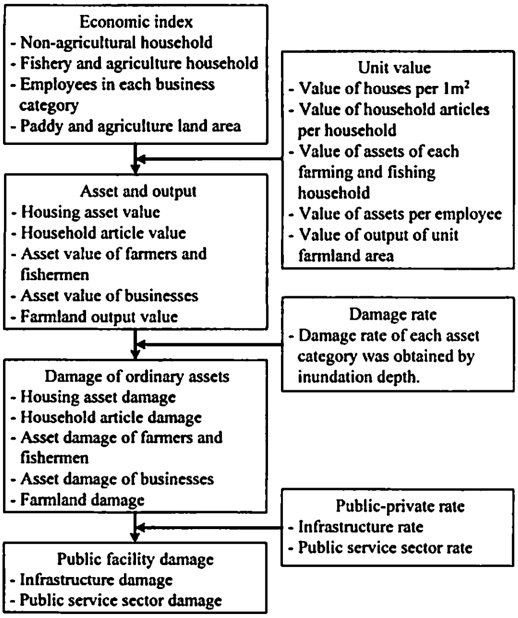

Fig. 3 The procedure for estimating inundation damage.

(5) Flooding

Since the 50-m mesh elevation digital map had a 1-m resolution for elevation data, the precision was insufficient for investigating inundation area changes caused by global warming. Therefore, the calculation was performed assuming that the elevation value was uniformly distributed within ±1 m for each mesh.

To determine the inundation depth of each mesh, a horizontal-surface flooding model was used. Inundation depth was changed by 10-cm increments, and the inundation volume of each cell was determined. Finally, the relationship between the inundation volume and height was formulated for the calculation.

(6) Overflow

Overflow occurred when the sea water level exceeded the maximum shore protection elevation. The flow rate Q (m²/s) per unit width was calculated using Honma's equations (1a, 1b)[9],[10]. A schematic of the definition of overflow is shown in **Fig. 2** where H_1 and H_2 are water levels above the maximum shore-protection elevation, g is gravity.

Complete overflow:

$$Q = 0.35H_1\sqrt{2gH_1},\ H_2 \leq 2H_1/3 \qquad (1a)$$

Submerged overflow:

$$Q = 0.91H_2\sqrt{2g(H_1 - H_2)},\ H_2 > 2H_1/3 \qquad (1b)$$

(7) Damage Estimation

The inundated area was determined by adding the inundated areas in each mesh. The inundated population was obtained by adding the populations of the inundated areas in each mesh.

Inundation damage was determined as follows. The numbers of non-agricultural households and of those engaged in fishery and agriculture were obtained from the 2000 Population Census[11]. The numbers of employees in each business category were obtained from the 2001 Establishment and Enterprise Census[12]. The business categories were based on the Japan Standard Industry Classification[13].

Rice paddy and agricultural land areas were obtained from the 1997 Digital National Land Information[14]. In addition, housing asset and article values, asset values of farming and fishing households, business establishment asset values, and farmland production values were obtained by multiplying the above data by the assessed values of houses per 1 m^2 in each prefecture, household articles per household, inventory assets of each farming and fishing household, assets of inventory per employee in each business category, and the output of unit farmland area in each prefecture, respectively.

The damage rate for each asset category was determined from the damage rate[15)] of each asset for inundation depth related to the calculated maximum inundation depth. Then, the ordinary asset damage was determined by multiplying the rate of damage by the quantity of assets.

The amount of infrastructure damage and damage to public services were determined by multiplying the infrastructure rate and percentage of public services by ordinary asset damage. Storm surge inundation damage was calculated by adding the ordinary asset damage to the amount of damage (**Fig.3**).

4. ESTIMATION METHOD

The inundated area and population and inundation damage caused by storm surges were estimated using the inundation model and damage estimation method with the following integration procedure:

[1] Estimate the storm surge inundation for each cell using the inundation model assuming a storm surge of a certain height occurs.
[2] Determine the inundated area and population and inundation damage of each mesh from the calculated maximum inundation depth. Then, calculate the inundated area and population and inundation damage of a cell by summing these values.
[3] Increase the storm surge height in 10-cm increments and calculate the inundated area and population until the occurrence probability reaches 1/10,000. The upper limit distribution of the storm surge height is shown in **Fig.4**.
[4] Average the results weighted by the storm surge height occurrence probability and estimate the annual expected inundated area and population and inundation damage values for each cell.
[5] Add the above values for each cell to estimate the annual expected inundated area and population and inundation damage values of the region along the Pacific Ocean.
[6] Repeat the above steps by changing the sea level increase and storm surge scale factors.

The increase in sea level used for the calculation ranged from 0–100 cm in 10-cm increments.

Regarding the increase in the number of strong typhoons, it was difficult to predict changes in the extreme value distribution profile. It was assumed that storm surge height increased at a constant rate and that the storm surge scale factor was used as an index to define the state of storm surges. The scale factor was set to 1 for the present state and changed by increments of 0.1, from 0.7–1.6.

The inundated area and population and inundation damage values were determined for all sea level increments and storm surge scale factors. The relationships between sea level increase and the storm surge scale factor and indicators of storm surge damage were plotted using the obtained data.

5. RESULTS AND DISCUSSION

Figures 5–7 show the inundated area, inundated population, and inundation damage, respectively, in the Pacific coastal region for various sea levels and storm surge scale factors determined using the inundation model. The figures include average data for large storm surges that occur rarely and do not cause damage annually. Since storm surges with very small occurrence probabilities are included in the calculation, estimated storm surge heights may or may not occur and the estimated damage indicators must be interpreted in the correct context.

The results indicate that when storm surge occurrence remains unchanged from the present and the sea level increases by 10 cm, the rate of increase in the inundated area and population tends to increase. Furthermore, the rate of inundation damage increases slightly with a 20-cm sea level increase. For both indicators, the trend lines have relatively smooth curves. As the storm surge scale factor increases, the trend lines straighten. When sea level remains constant and the storm surge scale factor increases,

Fig. 4 Upper limit of storm surge height.

the inundated area and population, and inundation damage increase linearly.

The inundation damage shown in **Fig. 8** is divided into two regions: west and east. The damage in the area from Kanto to Kinki is estimated to be 13 trillion yen, while that from Chugoku to Kyushu is 21 trillion yen. Although the Chugoku–Kyushu region has a smaller population and economy, damage there is greater than in the Kanto–Kinki region. This is because the Kanto–Kinki region has more shore-protection infrastructure than the Chugoku–Kyushu region. Furthermore, storm surges occur less frequently in the Kanto–Kinki region.

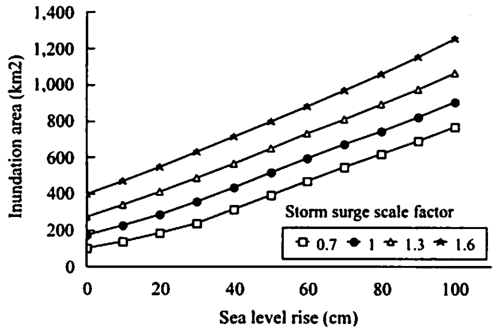

Fig. 5 Inundation area with sea level rise

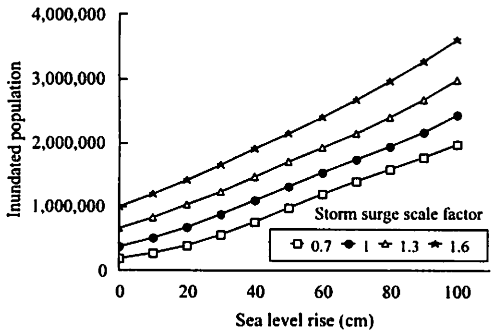

Fig. 6 Inundated population with sea level rise

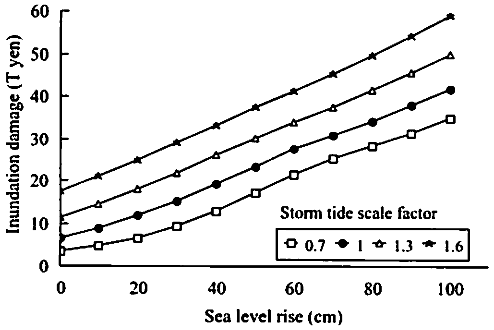

Fig. 7 Inundation damage versus sea level increase.

Therefore, as the sea level rises and the number of strong typhoons increases with global warming, inundation damage will gradually increase, starting in areas with low-height shore-protection structures. Strengthening these weaknesses at a rate consistent with global warming progression is an efficient way to protect against stronger storm surges.

The distribution of storm surge inundation damage in the Pacific coastal region was determined assuming a sea level increase of 60 cm, equivalent to the maximum sea level rise after 100 years forecast in the IPCC's Fourth Assessment Report, and a storm surge scale factor of 1.3, the second most severe condition in the graphs (**Fig. 8**). The shaded portions in the figure indicate the amount of damage exceeding one billion yen per cell.

The results suggest that Japan's three major bays, the Seto Inland Sea, and northwestern Kyushu face higher risks of storm surge inundation. Inlets and river mouths in other regions are also vulnerable to storm surges.

Areas that are not vulnerable to storm surges have shore-protection structures against high waves, tsunamis, and storm surges. Assuming that these structures function properly, the risk of storm surge inundation with increasing sea levels and storm surges due to global warming is almost negligible in these areas.

6. CONCLUSION

As sea levels rise due to global warming, inundation damage caused by stronger typhoons and storm surges will increase in coastal regions. This study estimated the inundated area and population and inundation damage along the Pacific coast of

Fig. 8 Inundation damage distribution caused by storm surges.

southern Japan. The results indicate that as sea level and storm surge height increase, the inundated area and population and inundation damage will also increase linearly. We must not argue that no preparation against storm surges is required until the hazard level reaches certain danger. A better approach would be to gradually prepare, following the progression of global warming, to avoid inundation damage and reduce the peak cost burden associated with these countermeasures. As meteorological models are improved and more precise information on storm surge height distribution becomes available, estimations of the increased rate of risk could also be improved.

The present results indicate that the areas vulnerable to storm surges are Japan's three major bays, the Seto Inland Sea, and the northwestern coast of Kyushu. Measures to protect against storm surges associated with global warming must be planned, including an effective and efficient combination of both short- and long-term measures. In areas that are vulnerable to storm surges, countermeasures against storm surges should be planned and systematically implemented. Further studies on preventing storm surge inundations are essential.

Results from studies on storm surge risk associated with global warming should also be consolidated, and the risk of inundation by storm surges should be estimated across Japan to support policy making on stabilizing greenhouse gas concentrations. Furthermore, for accurate estimation using the storm surge model, global climate models must be improved to better predict future typhoon strength and sea level increase.

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