

# A new index for evaluation of risk of complex disaster due to typhoons

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**Abstract** This study examines a new index to evaluate complex disaster risk in coastal zones involving typhoons. Typhoons generate not only strong winds but also storm surges and high waves. Therefore, complex disasters attributable to typhoon forces can be expected to occur in coastal zones. The durations for which the wind speed, storm tide, and wave height simultaneously exceed their respective design values were calculated as simultaneous excess duration (SED) to evaluate the risk of a complex disaster. To verify the utility of SED, numerical simulations were conducted for intensified typhoons under both present-day and global warming climates in Ise Bay, Japan, using an atmosphere–ocean–wave coupled model with a typhoon bogussing scheme. Results showed that the middle part of Ise Bay is more dangerous from the standpoint of SED than the inner part of Ise Bay, which has been regarded as the most dangerous area from the standpoint of extreme values of storm tide. These results suggest that SED is important as an index of risk of complex disaster, and the risk of typhoon disaster should be evaluated not only from extreme values of storm tide but also from SED.

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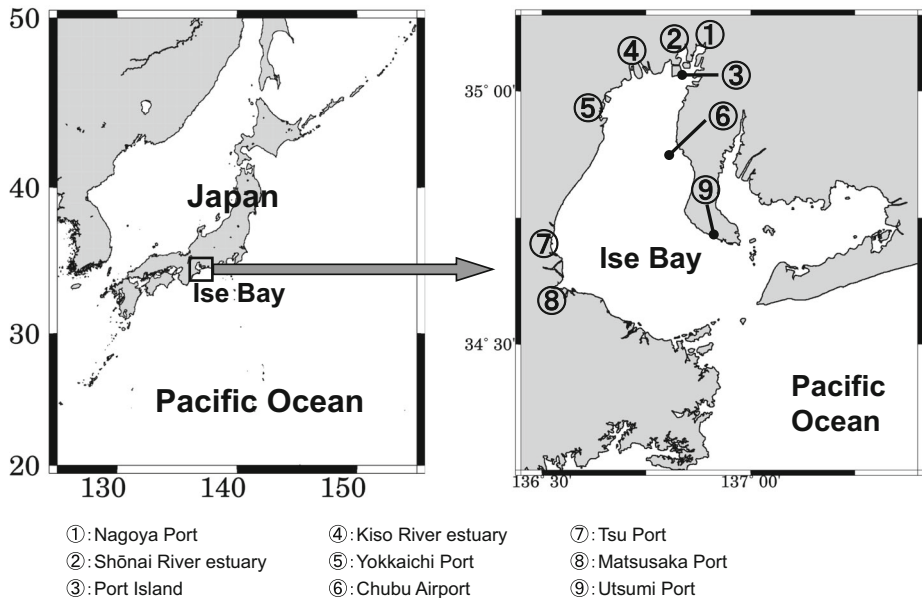
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**Keywords** Risk evaluation · Typhoon · Storm surge · High wave · Strong wind · Complex disaster

## 1 Introduction

Hurricane Katrina made landfall in the southeastern part of New Orleans on August 29, 2005. The hurricane created a storm surge of more than 9 m, which broke the levees of the 17th Street Canal, the London Avenue Canal, and the Industrial Canal. The storm surge caused severe and widespread inundation of New Orleans. One reason the levees failed was that the height of the levees needed to resist extreme values of storm tides, which were regarded as an important design consideration, but the strength of the levees needed to resist the pressure from a long duration storm surge, which was not considered (ASCE 2007). This fact indicates that a discussion of extreme values of storm tides alone was insufficient for countermeasures against typhoons in coastal zones.

Ise Bay (Fig. 1) has a history of experiencing the worst storm surge disaster in Japan, occurring after the Edo era (1868). Typhoon Vera (designated as the Ise Bay typhoon in Japan) struck Ise Bay in September 1959, generating the largest storm tides ever recorded in Japan. A storm tide of 3.5 m was observed at Nagoya Port, located in the innermost part of Ise Bay. Then, a high wave of about 2 m occurred simultaneously. The concurrence of the largest storm surge and the high wave destroyed the levees along the coast of Ise Bay and increased the inundation damage. Additionally, strong winds of over 30 m/s blew around Ise Bay. As a result, it was difficult for people to take refuge. More than 4000



**Fig. 1** Ise Bay in Japan and nine representative locations

people perished: Such concurrence of storm surges, high waves, and strong winds over the designed values caused the increase in damage and the disturbance of refugees.

Future typhoons are expected to be more intense under future climate conditions because of global warming (e.g., McDonald et al. 2005; Oouchi et al. 2006). Such intensified typhoons generate not only strong winds but also storm surges and high waves. If the wind speed, storm tide, and wave height caused by the intensified typhoon exceed their respective design values simultaneously, then complex disasters can be expected to occur in coastal zones. This is likely to cause a complex disaster similar to the severe and broad inundation of Hurricane Katrina and Typhoon Vera. Therefore, development of an evaluation method for risk of the complex disaster caused by typhoons is necessary to prepare effective countermeasures against the complex disaster and to hold damage below tolerable limits.

This study is aimed at proposing an evaluation method for the risk of the complex disaster in coastal zones caused by typhoons. First, the complex disaster in this study is defined as a disaster that occurs when the wind speed, storm tide, and wave height caused by the intensified typhoon exceed their respective tolerable limits simultaneously. Then, durations for which the wind speed, storm tide, and wave height simultaneously exceed their respective design values are calculated as the simultaneous excess duration (SED) to evaluate the risk of the complex disaster. SED is an index showing the risk of the complex disaster, and will be as important as the individual extreme values.

To verify the utility of SED, results of the evaluation of SED are demonstrated under both the present-day and the global warming climates in Ise Bay, Japan. An atmosphere–ocean–wave coupled model with a typhoon bogussing scheme is used to obtain data of the time history of the wind speed, storm tide, and wave height, although the model and its configuration are the same as those reported by Shimokawa et al. (2014). Finally, SEDs are calculated using the calculated data of the time history of the wind speed, storm tide, and wave height and are presented as an index showing the risk of the complex disaster in coastal zones.

The numerical model used for this study and the experimental methods are described in Sect. 2. The numerical results for the intensified typhoons under the present-day and global warming climates are stated, respectively, in Sect. 3. Based on these results, the utility of SED as the index of risk of the complex disaster is discussed in Sect. 4.

## 2 Numerical model and experimental methods

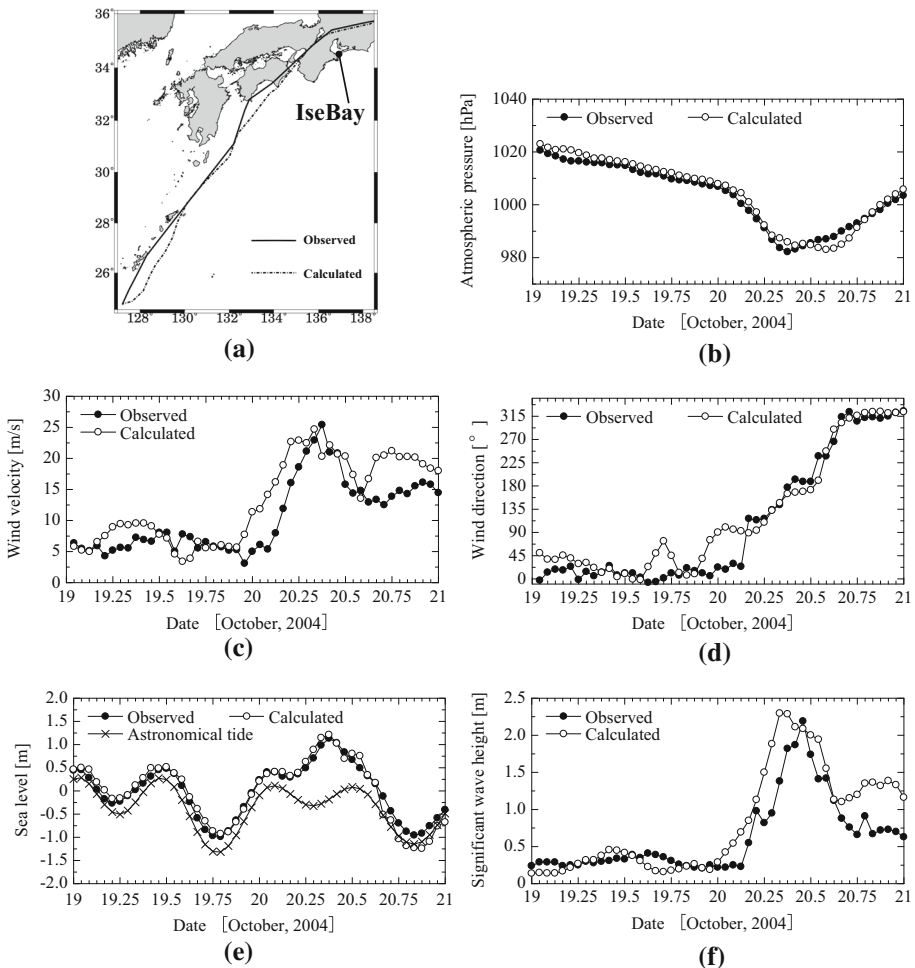
### 2.1 Numerical model

SED is calculable if the data of time history of the wind speed, storm tide, and wave height are obtained, irrespective of calculation models or field observations. In this study, the time history data are obtained using the atmosphere–ocean–wave coupled model with a typhoon bogussing scheme. The benefits of using the atmosphere–ocean–wave coupled model with the typhoon bogussing scheme in this study are explained below.

Conventional simulations for evaluations of the damage affected by typhoons under future climates have used parametric typhoon models (Mitsuta and Fujii 1987) such as those presented by Schloemer (1954) and others, or global climate models (GCM). However, the former parametric typhoon models are inadequate for the physical evaluation of the roughness effects of complicated coastlines and landforms and the three-dimensional

effects of the meteorological field on sea surface winds. Furthermore, for the prediction of typhoons under a future climate, parametric typhoon models cannot evaluate the intensity and tracks of the typhoons according to physical laws governing the atmosphere and ocean because best track data (observed data) of typhoons are nonexistent. For the latter global climate models, it is difficult to make the typhoon strike the targeted areas as expected because the models do not enable control of the typhoon track.

However, the atmosphere–ocean–wave coupled model with typhoon bogussing scheme used for this study comprises a meteorological model MM5 (Dudhia 1993), a coastal ocean current model with a multi-sigma coordinate system CCM (Murakami et al. 2008), and a wave model SWAN (Booij et al. 1996).



**Fig. 2** Comparisons of typhoon track, atmospheric pressure, wind velocity, wind direction, storm tide, and significant wave height at Ise Bay under Typhoon Tokage, 2004 between the calculated values and the observed data, as reported by Murakami and Kawasaki (2009). **a** Typhoon track, **b** atmospheric pressure, **c** Wind velocity, **d** wind direction, **e** storm tide, **f** significant wave height

Meso-scale Model 5 (MM5), a nonhydrostatic, fully compressible primitive equation model, was designed to simulate complex mesoscale meteorological phenomena of approximately a few to several hundred kilometers. It can therefore physically evaluate the roughness effects of a complicated coastline and landforms, three-dimensional effects of the meteorological field on the sea surface winds, and so on. The coastal ocean current model (CCM), our original ocean model, adopts a multi-sigma coordinate system, although it is a primitive ocean model. The multi-sigma coordinate system supports the accurate calculation of inflow rates of seawater from offshore, which greatly influences the storm surge occurring in the inner bays. A sophisticated third-generation time-dependent spectral wave model designed for the near shore to offshore zone, Simulating WAVes Nearshore (SWAN), can simulate wave generation and propagation attributable to local winds. Therefore, the coupled model can provide physically desirable solutions to complex hazard problems.

Verification of the model accuracy is extremely important in the studies that use the model. As an example, a verification of the atmosphere–ocean–wave coupled model for physical phenomena of Typhoon Tokage, 2004, which was conducted in our previous study (Murakami and Kawasaki 2009), is presented here. Typhoon Tokage struck Ise Bay, which is the research area in this study, and yielded various observed data. Figure 2 presents comparisons of the typhoon track, atmospheric pressure, wind velocity, wind direction, storm tide, and significant wave height at Ise Bay between the calculated values and the observed data. The results show that all the extreme values calculated using the coupled model agree well with those observed in Ise Bay. The durations of the storm tide, high waves, and strong wind are also important for the evaluation of SED. The coupled model enabled us to calculate the durations with high accuracy. Therefore, it is considered that the evaluation of SED using the atmosphere–ocean–wave coupled model is reliable.

The typhoon bogussing scheme described in Sect. 2.2 can initialize the three-dimensional well-matured typhoon structure for MM5 physically, as entirely consistent with the atmospheric dynamics. Moreover, this scheme can change the spatial distributions of the meteorological condition treated in the potential vorticity field and enable control of the typhoon track to make it strike the targeted area.

## 2.2 Typhoon bogussing scheme

Details of the typhoon bogussing scheme and its application were described by Shimokawa et al. (2014). The outline is described as follows.

To reproduce an atmospheric field with a numerical model, initial and boundary values including sea surface temperatures are needed. However, if the initial values do not include a bogus of the typhoon (i.e., they are a simple environment field obtained from observational and/or objective analysis data), the initial values in the model cannot develop into a typhoon (i.e., the model cannot reproduce the typhoon). Therefore, in general, an artificial initial vortex is embedded in the initial values as a bogus of the typhoon to allow the model to reproduce it. However, depending on the way the artificial initial vortex is embedded in the initial values, a large discontinuity between the internal structure of the typhoon and the environment field might result, which can create large errors in the reproduced results.

To evaluate the storm surge of an intensified typhoon for present-day and global warming climates, the typhoon's internal structure must be generated so that it is physically consistent (continuous) with the environment field. In addition to increasing the reliability of the evaluation, the number of calculated typhoons and applicable regions must be increased. The center position and the strength of the typhoon must be changed in

a manner that maintains physical consistency (continuity) with the environmental field. However, existing typhoon bogussing schemes (e.g., the method of the Japan Meteorological Agency, Ueno 1989; Ueno and Ohnogi 1991; Davidson et al. 1993) cannot alter the internal structure of the typhoon while maintaining physical consistency with the environmental field.

The typhoon bogussing scheme used for this study can do that, however, using a potential vorticity inversion method (Yoshino et al. 2008; Ishikawa et al. 2013). Potential vorticity, which is defined as the product of vorticity and stability, has two helpful principles. The first is the Lagrangian conservation principles for potential vorticity, which is approximately valid in adiabatic and inviscid atmospheric flows. The second is the invertibility principle for the potential vorticity distribution in which the dynamic fields, such as winds, temperatures, geopotential heights, static stabilities, and vertical velocities can be deduced diagnostically under suitable balance conditions and boundary conditions. A reader who requires more information should consult papers written by Rossby (1940), Hoskins et al. (1985), and Davis and Emanuel (1991).

Using the reversibility of the potential vorticity, the method can produce simultaneous physical quantities such as wind speed, temperature, and pressure (or height) under an adequate boundary condition from the single physical quantity of potential vorticity. The method can easily change the center position and strength of the typhoon and provide a physically consistent atmospheric field because the transformation of physical quantities is made from a single physical quantity: potential vorticity.

In this study, the typhoon bogussing scheme based on the potential vorticity described above (Yoshino et al. 2011) is used to provide the initial fields of the MM5. This scheme treats the meteorological field as a potential vorticity field and divides it into a mean field changing in a long period and a deviation field changing in a short period. Small-scale

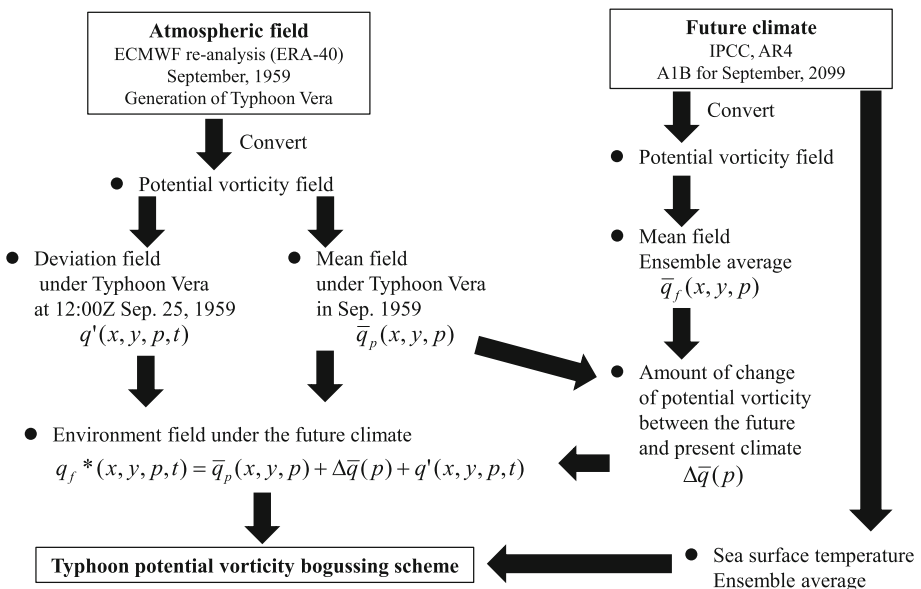


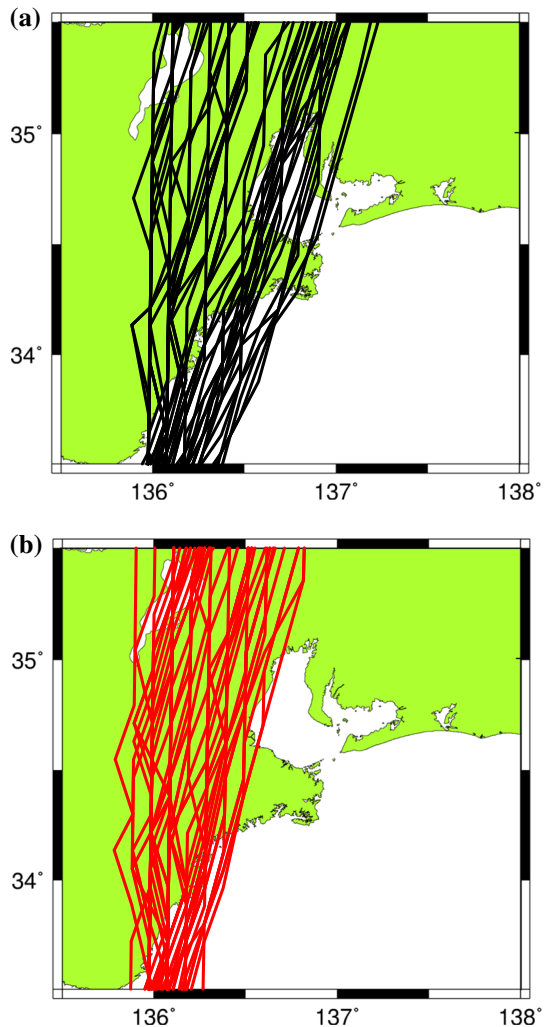
Fig. 3 Configuration of the environment field under the future climate

disturbances such as typhoons cannot be observed in monthly mean fields of the atmosphere. The influence of global warming is reflected not only in the central pressure and internal dynamic structure around the typhoon, but also in the typhoon environment by adding the temperature variation of global warming to the former mean field of the potential vorticity field. The concrete procedures of this scheme are described in the next section.

### 2.3 Experimental methods

In this study, the following cases are considered: (a) Ise Bay for the present-day climate and (b) Ise Bay for the global warming climate. These experimental methods are the same as those described by Shimokawa et al. (2014).

**Fig. 4** Tracks of the 50 potential typhoons under **a** the present-day climate and **b** global warming climate



## (a) Ise Bay for the present-day climate

The potential vorticity field based on ECMWF/ERA40 re-analysis data in September 1959 is divisible into a mean field and a deviation field. The 50 possible maximum typhoons are set in the initial field on section of 26.5°N, 131.35–135.70°E at 9-km intervals.

## (b) Ise Bay for the global warming climate

Figure 3 shows procedures for making the environment field under the future climate in this study. The climate in September of 2099 based on the IPCC, AR4, and A1B scenarios is assumed to have the future meteorological conditions. Separating the potential vorticity field based on ERA-40 data from September 1959 into the mean and deviation components and adding the predicted atmospheric and sea surface temperatures given by the IPCC, AR4, A1B for September 2099 to the average component, an environmental field is obtained. In the initialization method, not only a potential vorticity field but also a moisture field (mixing ratio field) is also adjusted by the IPCC, AR4, and A1B scenarios. The temperature variation of global warming in this study is defined as the difference in monthly mean temperatures between September 1959 and September 2099. The relative humidity is held constant with the present-climate values, but the mixing ratio is modified according

**Table 1** Model configuration

Coupled model	Time interval of data exchange	300 s
Meteorological model MM5	Calculation domain (two-way nesting)	Region 1: 23.6–39.6°N, 127.0–143.9°E Region 2: 33.9–35.2°N, 136.0–137.6°E
	Horizontal resolution	Region 1: 9 km Region 2: 3 km
	Number of horizontal grids	Region 1: 199 × 160 Region 2: 52 × 52
	Vertical levels	Region 1: 23 Region 2: 23
	Time step	Region 1: 30 s Region 2: 10 s
	Physical parameterizations	Planetary boundary layer: Blackadar scheme Cloud physics: Reisner graupel scheme
	Initial and boundary conditions	ECMWF re-analysis (ERA-40)
Ocean model (CCM)	Calculation domain	34.2–35.1°N, 136.5–137.4°E
	Horizontal resolution	450 m
	Number of horizontal grids	209 × 208
	Number of regions in multi-sigma	7
	Total number of layers	31
	Time step	2 s
Wave model (SWAN)	Calculation domain (one-way nesting)	Region 1: 28.2–35.2°N, 135.0–139.0°E Region 2: 33.2–35.1°N, 135.3–138.4°E Region 3: 34.2–35.1°N, 136.5–137.4°E
	Number of horizontal grids	Region 1: 300 × 523 Region 2: 300 × 192 Region 3: 209 × 208
	Time step	150 s



to the change of air temperature. The deviation field from the monthly mean is dominated by smaller-scale disturbances such as mid-latitude high- or low-pressure systems and the Pacific high-pressure system, which all play key roles in tropical cyclone movement. Monthly mean fields might contain cold wakes in our methods. However, the effect of cold wakes weakens because the sea surface temperature used in our study is the ensemble means of A1B scenarios (Fig. 3). Therefore, moving the positions of the deviation field and initial vortex forcibly makes the typhoon strike the targeted areas. Therefore, the results obtained in this study are reasonably satisfied with the theory of maximum potential intensity. The 50 possible maximum typhoons are set in the initial field on section of 26.5°N, 131.35–135.70°E at 9-km intervals.

In the use of the typhoon bogussing scheme, the initial typhoon position in each simulation is shifted slightly from the original position of Vera. The perturbed initial fields can create ensemble simulations portrayed in Fig. 4. The numerical results of the 50 intensified typhoons under the present-day and global warming climates are referred to, respectively, as Cases 1–50 and 51–100. These cases cover a broad area around Ise Bay (Fig. 4). Therefore, the numerical results include a range of possible paths for the intensified typhoon.

The data of time history of the wind speed, storm tide, and wave height are necessary for the evaluation of SED. Calculations of the data around Ise Bay under the 100 cases of typhoon using the coupled model are performed based on the configuration presented in Table 1. Moreover, design values for storm tide, wave height, and wind speed on representative points (Fig. 1) around Ise Bay needed for the evaluation of SED are presented in Table 2 (JMT and CDIT 2000).

### 3 Results and discussion

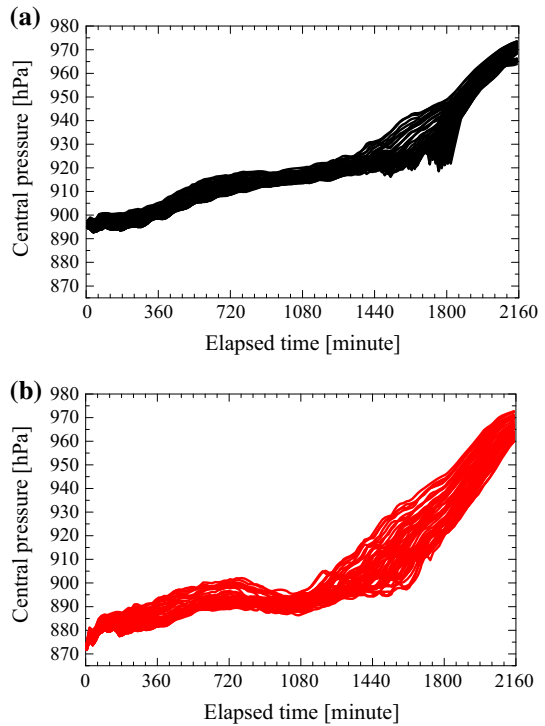
Figure 5a, b, respectively, portrays the time evolutions of center pressures for the 50 cases under the present-day and global warming climates. The central pressures at the landfall under the present-day and global warming climates are, respectively, from 920 to

**Table 2** Design values of storm tide, significant wave height, and wind speed at each point (JMT and CDIT 2000)

	Design storm tide (m)	Design wave height (m)	Design wind speed (m/s)
Nagoya Port	3.55	1.02	35.0
Syounai River estuary	3.55	1.02	35.0
Port Island	3.55	2.60	35.0
Kiso River estuary	3.55	2.90	35.0
Yokkaichi Port	3.00	2.80	35.0
Chubu International Airport	2.50	2.29	35.0
Tsu Port	2.14	2.80	35.0
Matusaka Port	2.14	2.80	35.0
Utsumi Port	2.54	2.90	35.0

Each point’s location is indicated in Fig. 1

**Fig. 5** Time evolutions of center pressures of the 50 potential typhoons under **a** the present-day climate and **b** global warming climate



930 hPa and from 895 to 905 hPa. These values are less than observational value of Typhoon Vera, 930 hPa. Table 3a, b shows the maximum values of sea-level departure, significant wave height, and wind speed under the present-day and global warming climates, respectively, and the cases obtained the values at the representative locations Nagoya Port, Kiso River estuary, Yokkaichi Port, Chubu International Airport, and Tsu Port (see Fig. 1).

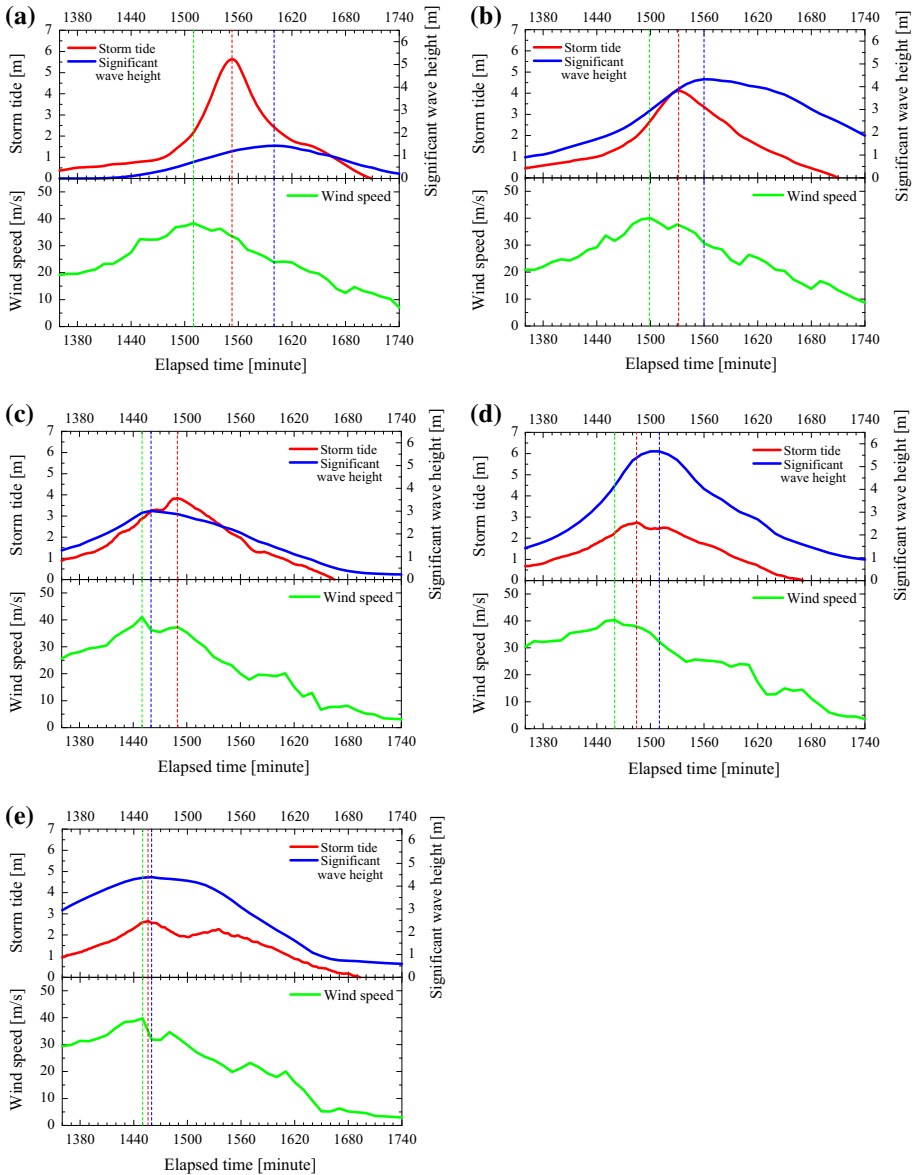
Figures 6 and 7, respectively, portray the time evolutions of storm tide, significant wave height, and wind speed for the cases shown in Table 3a, b. In both cases under the present-day and global warming climates, at Nagoya Port (Figs. 6a, 7a), the peaks of each component occur in the following sequence: wind speed, storm surge, and significant wave height. The time differences between the first peak (i.e., wind speed at Nagoya Port) and the last peak (i.e., significant wave height at Nagoya Port) under the present-day and global warming climates are, respectively, only 90 and 110 min. The time differences at the Kiso River estuary, Yokkaichi Port, Chubu International Airport, and Tsu Port (Fig. 6b–e) under the present-day and global warming climates are, respectively, 60, 40, 50, and 20 min, and 80, 39, 80, and 20 min. These results suggest that when the intensified typhoons hit Ise Bay, the peaks of storm tide, significant wave height, and wind speed can all be concentrated within a few hours and thereby cause a complex disaster.

Figures 8 and 9 present the durations for storm tide, significant wave height, and wind speed simulated under the present-day and global warming climates, which exceed the design values at each location of excess duration (ED) and their SED. The longest EDs

**Table 3** Maximum values of the storm tide, significant wave height, and wind speed under (a) the present-day climate and (b) global warming climate, and the cases yielding those values at the representative locations: Nagoya Port, Kiso River estuary, Yokkaichi Port, Chubu International Airport, and Tsu Port (see Fig. 1)

	Storm tide	Significant wave height	Wind speed
(a) Present-day climate			
Nagoya Port	Case 27 5.6 m	Case 48 1.5 m	Case 37 40.2 m/s
Kiso River estuary	Case 27 4.1 m	Case 39 4.4 m	Case 35 42.8 m/s
Yokkaichi Port	Case 33 3.8 m	Case 34 3.1 m	Case 32 41.5 m/s
Chubu International Airport	Case 33 2.7 m	Case 29 5.8 m	Case 27 41.2 m/s
Tsu Port	Case 30 2.7 m	Case 68 4.4 m	Case 27 41.5 m/s
(b) Global warming climate			
Nagoya Port	Case 70 6.9 m	Case 68 1.7 m	Case 77 45.2 m/s
Kiso River estuary	Case 73 5.1 m	Case 94 4.5 m	Case 75 50.1 m/s
Yokkaichi Port	Case 74 5.0 m	Case 81 3.5 m	Case 74 50.7 m/s
Chubu International Airport	Case 66 3.5 m	Case 70 6.1 m	Case 73 49.5 m/s
Tsu Port	Case 73 3.4 m	Case 92 4.5 m	Case 70 47.7 m/s

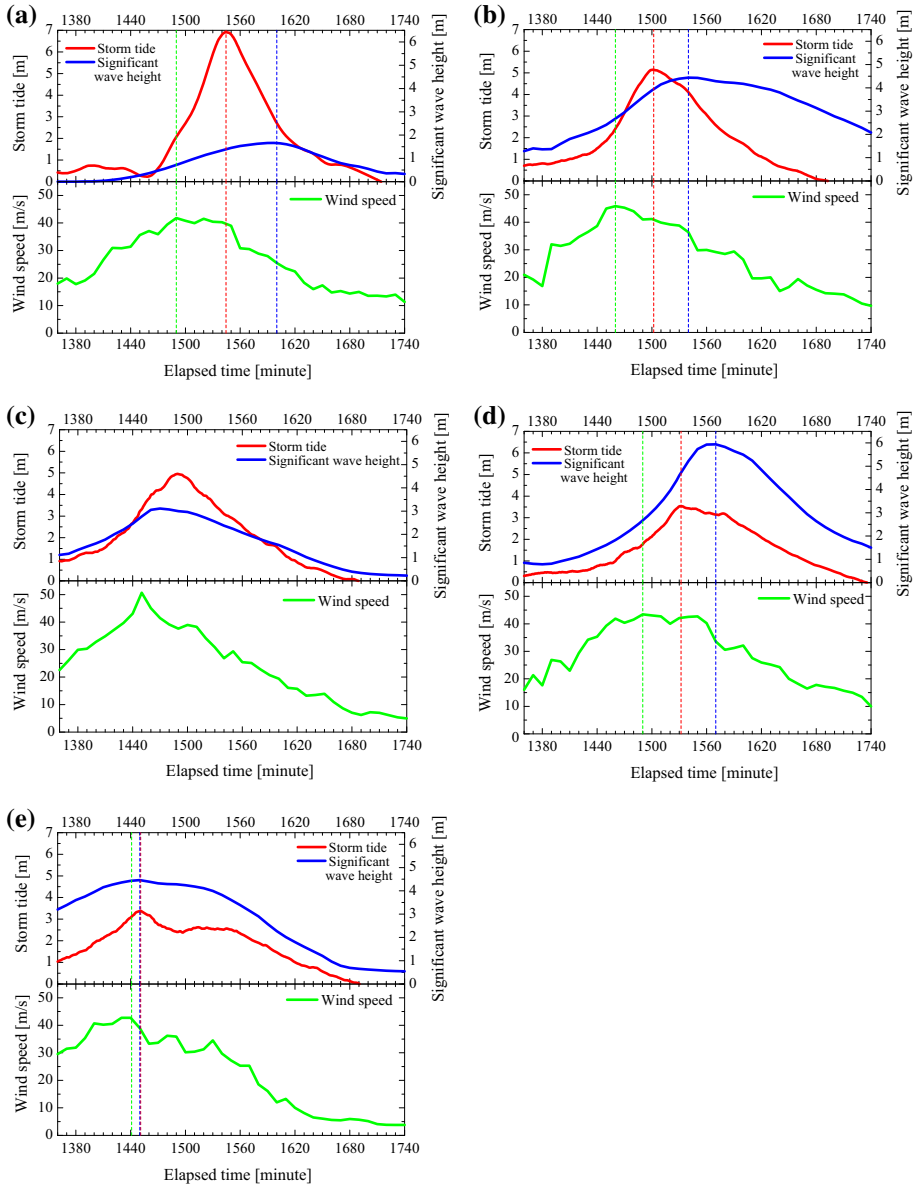
of storm tide under the present-day and global warming climates appear at Tsu Port and are 78 and 170 min, respectively, which are longer than those at Nagoya Port (i.e., 53 and 84 min, respectively), where the extreme storm tide values are at a maximum (i.e., 5.6 and 6.9 m, respectively) in Ise Bay (Table 3a, b): The extreme values of storm tide at Tsu Port under the present-day and global warming climates (i.e., 2.7 and 2.9 m, respectively) are smaller than those at Nagoya Port, but the EDs of storm tide at Tsu Port are longer than those at Nagoya Port. The longest EDs of significant wave height appear at Tsu Port (Figs. 8b, 9b). The longest EDs of wind speed appear at Chubu International Airport (Figs. 8c, 9c). Results show that the longest SEDs under the present-day and global warming climates appear at Tsu Port. They are, respectively, 58 and 111 min (Figs. 8d, 9d). In addition, the average SEDs at Tsu Port under the present-day and global warming climates (i.e., 10 and 72 min, respectively) are the largest in Ise Bay: the values of ED and SED at Tsu Port are considerably larger than those at Nagoya Port. Therefore, in both cases under the present-day and global warming climates, the risk of complex disaster at Tsu Port is regarded as being greater than that at Nagoya Port. In addition, the longest and average SEDs at the Kiso River estuary, Yokkaichi Port, and Chubu International Airport are longer than those at Nagoya Port. This result suggests that the middle part of Ise Bay is more dangerous from the standpoint of SED than the inner part of Ise Bay, which has been regarded as the most dangerous area from the standpoint of extreme storm tide values.



**Fig. 6** Time evolutions of storm tide, significant wave height, and wind speed under the present-day climate at **a** Nagoya Port (Case 27), **b** Kiso River estuary (Case 27), **c** Yokkaichi Port (Case 33), **d** Chubu International Airport (Case 33), and **e** Tsu Port (Case 30). These cases correspond to cases in which the maximum storm tide was recorded (Table 3a)

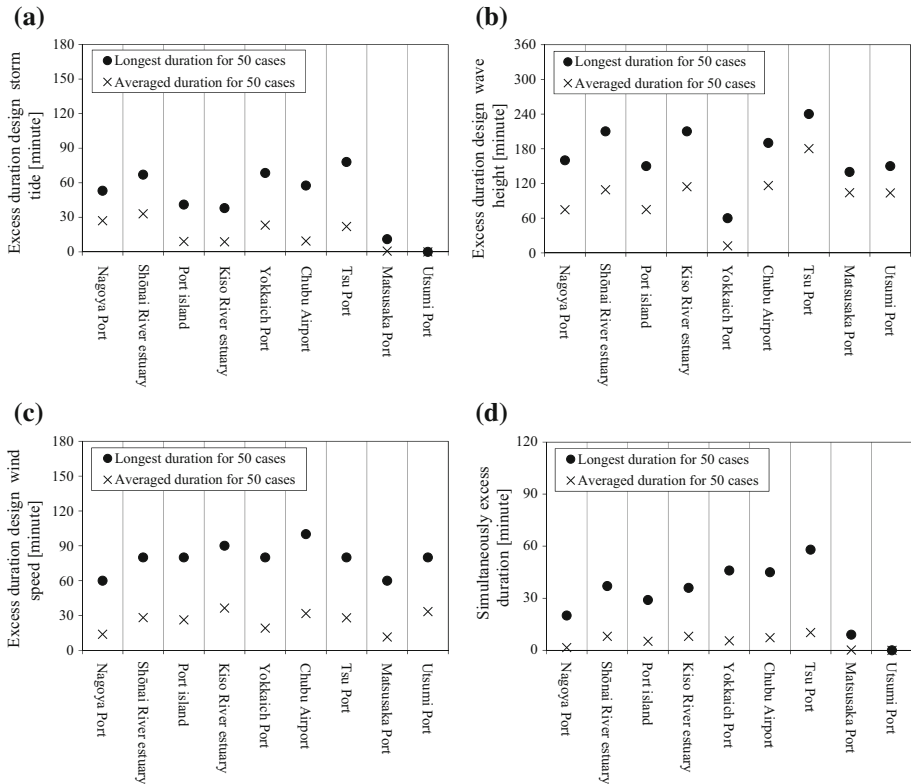
## 4 Summary and discussion

When the storm tide, significant wave height, and wind speed under the typhoon are regarded as a combined force, then the duration that each value exceeds the simultaneous design value will be as important as the individual extreme values. To verify the validity of



**Fig. 7** Time evolutions of storm tide, significant wave height, and wind speed under global warming climate at **a** Nagoya Port (Case 70), **b** Kiso River estuary (Case 73), **c** Yokkaichi Port (Case 74), **d** Chubu International Airport (Case 66), and **e** Tsu Port (Case 73). These cases are correspondent to cases in which the maximum storm tide was recorded (Table 3b)

SED as an index of risk of complex disaster, we conducted numerical simulations for intensified typhoons under present-day and global warming climates in Ise Bay, Japan, using an atmosphere–ocean–wave coupled model with a typhoon bogussing scheme and calculated the SED for storm tide, significant wave height, and wind speed. The results

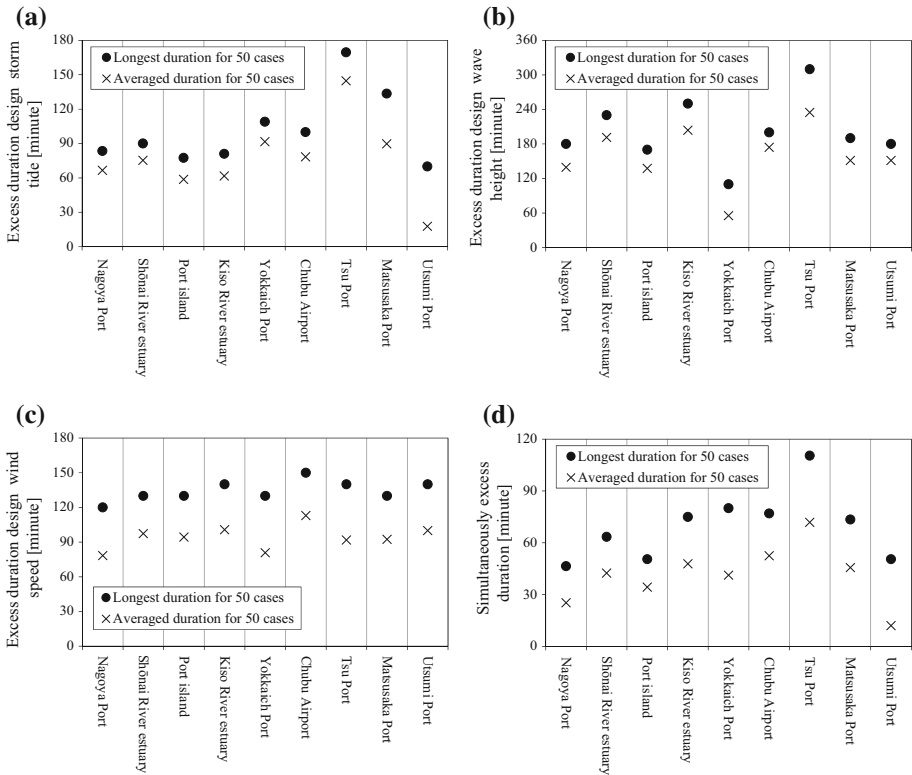


**Fig. 8** Durations for **a** storm tide, **b** significant wave height, **c** wind speed simulated under the present-day climate, which exceed the design values at each location, and **d** their simultaneously excess duration. *Black circles* and *times symbols*, respectively, denote the longest and averaged durations among the 50 cases

demonstrated that the middle part of Ise Bay is more dangerous from the standpoint of SED than the inner part of Ise Bay, which has been regarded as the most dangerous area from the standpoint of extreme values of storm tide. This fact is extremely important for countermeasures against typhoon in Ise Bay. The results are the same for both the present-day and global warming climates, although the SEDs under the global warming climate are longer than those under the present-day climate. The results suggest that SED is important as an index of risk of complex disaster. The risk of typhoon disaster should be evaluated not only from extreme value of storm tides, but also from SED.

In this study, SED was calculated using the results of simulations of the atmosphere–ocean–wave coupled model with typhoon bogussing scheme, and its utility was demonstrated. If results of field observation, parametric typhoon models, global climate models, and so on give data of the time history of the wind speed, storm tide, and wave height, then the calculation of SED can be conducted using these results instead of the results of the atmosphere–ocean–wave coupled model with typhoon bogussing scheme. Therefore, the evaluation of SED is applicable in various situations related to countermeasures against typhoons in coastal zones.

However, to ensure the validity of SED as an index of risk of complex disaster case studies, data from other bays and other typhoons must be accumulated and analyzed. In



**Fig. 9** Durations for **a** storm tide, **b** significant wave height, **c** wind speed simulated under the present-day climate, which exceed the design values at each location, and **d** their simultaneously excess duration. *Black circles and times symbols*, respectively, denote the longest and averaged durations among the 50 cases

addition, estimation of the inundation area by storm surges caused by the intensified typhoons will be important as an index of risk of a complex disaster. In the exact estimation, the effect of a high wave on inundation must be evaluated. Although Kawasaki et al. (2012) evaluated it as half of the significant wave height as an initial attempt, continual discussion of the evaluation method of the effect of a high wave on inundation will be necessary.

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