CLIMATE CHANGE ADAPTATION IN TOKYO BAY: THE CASE FOR A STORM SURGE BARRIER

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Increases in typhoon intensity and sea level rise could pose significant challenges to coastal defences around Tokyo Bay. In order to analyse the extent of future problems the authors determined the increase storm surge that could result from an increase in typhoon intensity and sea level rise to this area around the turn of the 21st century. Results show how the various settlements around Tokyo Bay are at considerable risk of storm surges and sea level rise in the future. If defences are breached the potential direct economic consequences could be significant, potentially in excess of 100 trillion yen, with the indirect costs likely to be even greater. As a result it is likely that sea defences will have to be strengthened around Tokyo Bay in the future, which could cost in the order of 370bn yen to defend against a 1 in 100 year storm by the year 2100. Alternatively, a storm surge barrier could be built, which would be more expensive (possibly in the range of 700-800bn yen), though it could increase the protection level and would be able to cope with 1 in 200 or 500 year events, amongst other benefits.

Keywords: adaptation, typhoons, Tokyo Bay, storm surge; sea level rise; typhoons; coastal defences, flood risk

INTRODUCTION

Climate change and sea level rise are expected to pose considerable challenges to low-lying coastal areas in the course of the 21st century. Such effects could lead to the flooding of low-lying deltas and atolls (such as the Mekong delta for example, see Nguyen et al., 2014, Nobuoka and Murakami, 2011, Yamamoto and Esteban, 2014), unless significant adaptation measures are undertaken. The present work will focus on trying to quantify the increase in flood risk and economic damage that could be expected around Tokyo Bay if the coastal defences that protect several major cities in the area were overcome. “Greater Tokyo”, with a population of more than 35 million people is the largest urban area in the planet (Japan Statistics Bureau, 2010), and includes not only Tokyo but also other cities such as Yokohama and Kawasaki.

As a country Japan is attacked every year by a number of tropical cyclones, some of which have caused widespread damage. Tropical cyclones need high surface sea temperatures to form, as they use the heat from the evaporation of sea water to maintain or increase their strength. Aside from wind damage, these weather systems also generate powerful waves and storm surges, which can inundate coastal areas and lead to widespread devastation. As tropical cyclones feed on ocean heat, it appears logical that global warming as a consequence of increasing concentrations of greenhouse gases in the atmosphere could lead to an increase in their future intensity (Knutson et al., 2010). The 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 5AR) highlighted how

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during the course of the 20th century the oceans have continued to warm up, and it is expected that this trend will continue in the 21st century (see also Knutson and Tuleya, 2004, Elsner et al., 2008, Landsea et al., 2006, Webster and Holland, 2005). In particular, Knutson et al (2010) summarised the most important work on tropical cyclone simulations, which appears to suggest that the intensity of tropical cyclones could increase by between 2 and 11% by 2100. The intensification of typhoons could have severe consequences for many coastal areas in Japan, such as the possibility of higher storm surges, more frequent damage to breakwaters due to high waves (Takagi et al., 2011), greater downtime to ports (Esteban et al., 2009) and other effects on the economy in general (Esteban and Longarte-Galnares, 2010). The problems of higher storm surges could be compounded by those of sea level rise. During the 20th century global average sea level rose by around 1.7mm on average per year, though this appears to have intensified to 3mm per year by the end of the century (IPCC 4AR). According to the IPCC AR5, global sea levels are likely to rise in the range of 26 to 82 cm by 2100. So-called "semi-empirical methods" (see IPCC 5AR), such as those by Vermeer and Rahmstorf (2009), indicate that for the future global temperatures scenarios given in the IPCC 4AR the projected sea level rise by 2100 could be even higher, in the 0.75 to 1.9m range.

Although the cities that are located around Tokyo Bay appear to well protected (by an extensive network of coastal levees and storm gates) the combination of sea level rise and an increase in typhoon intensity will eventually require the strengthening of these defences. In the present work the authors argue that rather than upgrading these defences, it could also make sense to build a storm surge barrier at the entrance of Tokyo bay, in order to establish a safety system composed of multiple layers. Also, the authors will argue that there is a possibility that defences in Tokyo could be currently under-designed, and given the large protected values it would be worthwhile to move to a higher design standard (such as designing against a 1 in 200 or 500 year storm). To do so the authors will first attempt to analyse likely water levels during the passage of a typhoon by the year 2100 and estimate the expected economic damage this could bring about. Finally, the cost of upgrading the defences or building a storm surge barrier will be analysed in view of other potential benefits and problems that a barrier could bring to the area.

PHILOSOPHY OF THE DESIGN OF COASTAL DEFENCES AROUND TOKYO BAY

For the case of Tokyo Bay sea defences have been designed against the largest historical typhoon that has taken place in the central southern Honshu coastline, which could be equivalent to a once-in-100-years event. Thus, dyke design was not necessarily based on a thorough statistical analysis because of the shortage of available data (e.g. typhoon track, pressure, wind speed) at the time of the design. Instead, numerical simulations are typically performed for a number of possible typhoon tracks, assuming their intensities following some historical events during the last century (Miyazaki, 2003).

One of the most important storms to hit Japan during the 20th century was the 1959 Typhoon Isewan (Vera), which caused a 3.5m storm surge in Ise Bay in Japan (Kawai et al., 2006). Following this event the Japanese Government determined that defences around Japan should be designed to cope against such a typhoon (i.e. it was designated as the "standard typhoon" against which defences should be built), and undertook extensive efforts to construct coastal defences (Kawai et al., 2006). Thus, as a result, the design water level for storm surge defences is determined by one of the two following criteria (Kawai et al., 2006): 1. The sum of the mean spring high tide level and the maximum storm surge recorded at a tide station or simulated assuming this "standard typhoon" or 2. The highest tidal level recorded at a tide station.

According to such philosophy, the first criteria has been adopted for major bay areas with a large population, such as Tokyo, Ise and Osaka Bays, while the second criteria is used for the central region of the Seto Inland Sea (Kawai et al., 2006). However, it is important to note that design tidal levels are still established in a deterministic way and there are still a number of problems to ascertain the return period of storm surges, including a comparative lack of historical data (Kawai et al., 2006).

METHODOLOGY

The following section will outline the methodology followed by the authors to obtain maximum water levels in the year 2100, which results from a combination of storm surge, sea level rise and maximum tide. The objective of such analysis is to find out what would be the equivalent of a typhoon with a return period of 1 in 100 years by the turn of the 21st century.

Choice of design typhoon for Tokyo Bay: Taisho 1917 typhoon

Despite defences in Tokyo Bay being designed against the equivalent of the Isewan 1959 typhoon, and in order to be conservative, the current work instead adopted the typhoon of October 1917 (6th year of the Taisho period Typhoon), which was the worst typhoon to affect Tokyo Bay in the last 100 years. This event caused widespread damage, flooding an area of over 200 km^2 and leaving over 1300 people dead or missing. The typhoon did not pass directly above Tokyo Bay but slightly to the west of it. The lowest pressure recorded during the passage of the typhoon was 952.7hPa, according to Miyazaki (1970), eventually producing a maximum storm surge of +2.1m (corresponding to a T.P. (Tokyo Pail) level of +3.0m).

Storm Surge Simulation Model

In order to simulate the storm surge height due to the passage of a typhoon a 2-level numerical simulation model was set up (see Fig. 1). Such a 2-level model was introduced by Tsuchiya et al (1981) and has been used by many researchers in the past (see also Shibayama et al., 1990). The governing equations models of the model are the mass conservation equation and the momentum conservation equation, with the governing equations for the storm surge expressed by Eqs. (1)-(5)

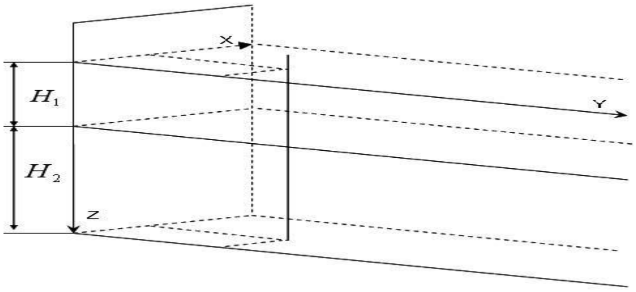

Figure 1. A 2-level storm surge model diagrammatic representation

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(M_1 + M_2) + \frac{\partial}{\partial y}(N_1 + N_2) = 0 \tag{1}$$

$$\frac{\partial M_1}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M_1{}^2}{H_1}\right) + \frac{\partial}{\partial y}\left(\frac{M_1 N_1}{H_1}\right) + gH_1\frac{\partial \eta}{\partial x} + fN_1 + \frac{H_1}{\rho_w}\frac{\partial P}{\partial x} - \frac{\tau_{sx}}{\rho_w} - A_h\left(\frac{\partial^2 M_1}{\partial x^2} + \frac{\partial^2 M_1}{\partial y^2}\right) + \frac{\tau_{ix}}{\rho_w} + (uw)_i = 0 \tag{2}$$

$$\frac{\partial N_1}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M_1 N_1}{H_1}\right) + \frac{\partial}{\partial y}\left(\frac{N_1{}^2}{H_1}\right) + gH_1\frac{\partial \eta}{\partial y} + fM_1 + \frac{H_1}{\rho_w}\frac{\partial P}{\partial y} - \frac{\tau_{sy}}{\rho_w} - A_h\left(\frac{\partial^2 N_1}{\partial x^2} + \frac{\partial^2 N_1}{\partial y^2}\right) + \frac{\tau_{iy}}{\rho_w} + (uw)_i = 0 \tag{3}$$

$$\frac{\partial M_2}{\partial t}+\frac{\partial}{\partial x}\left(\frac{{M_2}^2}{H_2}\right)+\frac{\partial}{\partial y}\left(\frac{M_2N_2}{H_2}\right)+gH_2\frac{\partial\eta}{\partial x}+fN_2+\frac{H_2}{\rho_w}\frac{\partial P}{\partial x}$$
$$-\frac{\tau_{sx}}{\rho_w}-A_h\left(\frac{\partial^2 M_2}{\partial x^2}+\frac{\partial^2 M_2}{\partial y^2}\right)+\frac{\tau_{ix}}{\rho_w}+(uw)_i=0 \qquad (4)$$

$$\frac{\partial N_2}{\partial t}+\frac{\partial}{\partial x}\left(\frac{M_2N_2}{H_2}\right)+\frac{\partial}{\partial y}\left(\frac{{N_2}^2}{H_2}\right)+gH_2\frac{\partial\eta}{\partial y}+fM_2+\frac{H_2}{\rho_w}\frac{\partial P}{\partial y}$$
$$-\frac{\tau_{sy}}{\rho_w}-A_h\left(\frac{\partial^2 N_2}{\partial x^2}+\frac{\partial^2 N_2}{\partial y^2}\right)+\frac{\tau_{iy}}{\rho_w}+(uw)_i=0 \qquad (5)$$

Where η is water surface profile above still water level, h is the still water level, $H_1=\eta+h_i$, $H_2=h+h_i$, g is acceleration of gravity, x, y are horizontal coordinates, t is time, M and N are x, y component of momentum flux, τ_s is water surface shear stress due to wind, τ_b is sea bottom shear stress, τ_i is shear stress between upper layer and lower layer, ρ_w is sea water density, and n is Manning's friction factor. Subscript 1 is used for the upper layer and 2 for lower layer. The pressure term is governed by Myers's formula (1954):

$$P=P_0-\Delta P\exp\left(-\frac{r_{\max}}{r}\right) \qquad (6)$$

where P is pressure at a point that has distance r from centre of typhoon, P_0 is lowest pressure at the centre of typhoon, ΔP is the different in pressure between the centre of typhoon and the normal air pressure, and r_{max} is the radius of maximum wind speed.

The authors also verified by themselves that the observed storm surge levels during the passage of the Taisho (1917) typhoon matched those simulated at different locations along Tokyo Bay using such a 2-level model. The suction effect due to wind blow is the most important factor in this simulation, particularly in shallow waters such as Tokyo Bay. However, it is reasonable to state that its effect can be limited to the sea surface layer because the shear stress caused by wind can be negligible at sufficiently deep locations. The governing equations of the model are the mass conservation and the momentum conservation equations, and the pressure of the typhoon is governed by Myers's formula (1954). For a more detailed description of the model see Hoshino et al., (2011).

The simulation uses a nesting approach, with a grid of around 3km for the large domain and 900m for the inner side of Tokyo Bay. The typhoon path was approximated as a straight line because of the lack of reliable information on the typhoon track in 1917 (see Figure 2). It is interesting to note that the eye of the storm did not go through the centre of Tokyo Bay, but rather to the west of it. To ascertain that this is indeed the worst case scenario for a 1 in 100 year storm the authors performed numerous simulations altering the course of the typhoon, all of which yielded storm surge results lower that those given by the course shown in Figure 2. Figure 3 shows the location of the different points of interest for which storm surge levels were simulated along the bay.

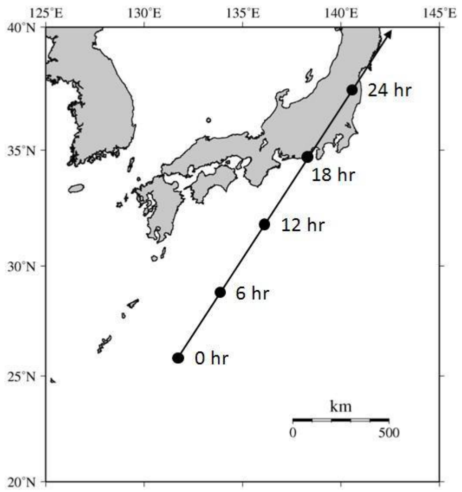

Figure 2. Simulated typhoon course

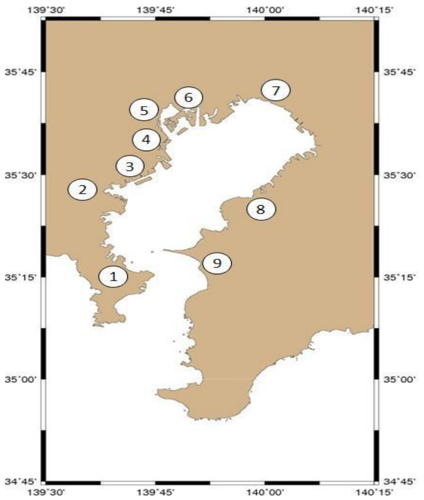

Figure 3. Location of points of interest

Methodology to modify typhoons in Tokyo bay to take into account climate change by 2100

To understand how future increases in tropical cyclone intensity will affect storm surge it is necessary to obtain the future probability distribution functions of the central pressure of these events in the target region. Thepresent work applied the research of Yasuda et al. (2010a), who provide the present and future expected distribution of typhoon intensity for storms around Tokyo Bay in the year 2100 (See Figure 3). SSTs were used as an external forcing of the AGCM as a bottom boundary condition. The observed SST from the UK Met Office Hadley Centre (HadlSST) were used for the present climate conditions, and the ensemble mean SSTs from CMIP3 multi-model projections of SRES A1b were employed for the future climate experiments. According to the probability distribution functions indicated by Yasuda et al. (2010a) it is possible to obtain that a 1 in 100 year storm in Tokyo Bay (i.e. the storm in the year 2100 than would be equivalent to the Taisho typhoon) would have a minimum central pressure of 933.9hPa instead of the historically recorded minimum value of 952.7hPa (see Hoshino et al., 2011)

One of the main problems of the model employed relates to the determination of the radius of maximum wind speeds r_{max}, which is necessary for the correct resolution of the Myers formula (1954). To do so, the method of Yasuda et al. (2010b) was used, where the radius is not given a deterministic value but rather follows a probabilistic curve. As a consequence of utilizing such a stochastic value for r_{max} it was necessary to run the simulation a number of times to obtain the storm surge for each r_{max} probability range, and finally the storm surge results are also expressed in terms of a probability distribution function.

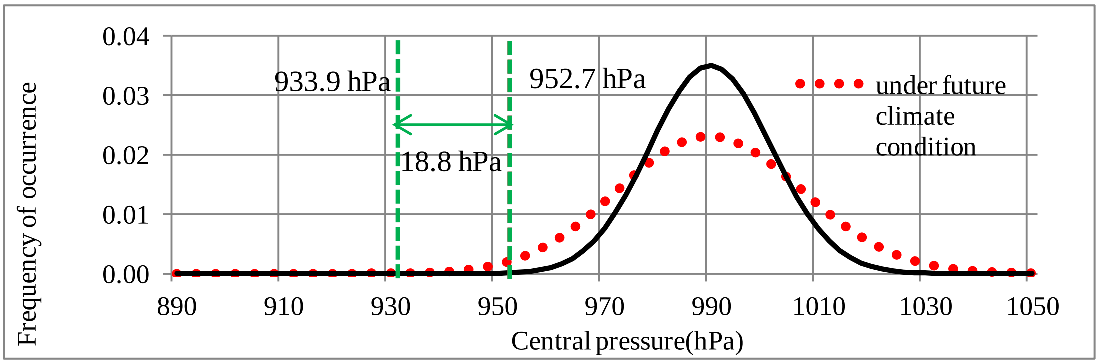

Figure 3. Present and future probability distribution of typhoon intensity at Tokyo Bay according to Yasuda et al. (2010a). The central pressure of a 1/100 year storm now and in the year 2100 are also shown

Sea level rise scenarios

After computing the storm surge at each given location, the effect of sea level rise was added to compute the final level of the water that could be expected for a given event. Due to current uncertainty regarding future greenhouse gas emissions and how the planet will respond to these, three sea level rise scenarios were used in the present research:

- The first scenario does not consider any sea level rise, in order to isolate the contribution of increases in typhoon intensity alone to the flooding risk in Tokyo Bay.
- The next scenario represents a sea level rise of 0.59cn, similar to the higher range scenario presented in the IPCC 4AR.
- Finally, the most extreme scenario took into account the sea level rise of the semi-empirical model of Vermeer and Rahmstorf (2009).

Calculation of probability of sea defences being overcome

To predict the possible water levels during a storm surge in the year 2100 it is necessary to consider the central pressure, radius of maximum wind speed of the typhoon and sea level rise, as mentioned in the previous section. However, as the methodology of Yasuda et al. (2010) is probabilistic, this also results in a probabilistic answer, where the storm surge for a given central pressure takes a range of possible values. However, in the present work the most important value is not the range of expected values, but the probability that the defences at each point would be overtopped, given in Table 1 for the three sea level rise scenarios considered. Overtopping is defined as the water levels (a combination of high tide, storm surge and the sea level rise scenarios, but not the waves) becoming higher than the top of the coastal levees. The overtopping probability depends not only on the storm surge height, but the range of values of maximum wind speeds of the typhoon, according to Yasuda et al. (2010b). To calculate such probability the authors considered the height of the defences at various locations throughout Tokyo Bay (according to data from the Chiba, Tokyo, Kanagawa Prefectural Governments, 2004), and calculated the probability of overtopping as sea levels gradually increase. It should be noted at this point that the authors are considering that the overtopping of the defences by the storm surge along will result in several breaches taken place along the defences (due to the relative fragility of some of these levees), and large scale inundation would come about as a result. However, it is clear that this is an over-simplification, and that detailed geotechnical and structural calculations should be carried out to ascertain whether the overtopping of the levees would lead to catastrophic failures. Other elements in the system, such as the storm surge gates, would also have to be analysed in more detail.

Table 1.Probability (%) that storm surge height becomes higher than case A or B of defences.

Level of Sea level rise	0 cm	28 cm	59 cm	190 cm
Yokosuka	0	0	64	100
Yokohama	0	0	0	100
Kawasaki	0	0	0	100
Samezu	0	0	0	100
Shibaura	0	0	0	100
Toyosu	0	0	0	100
Funabashi	0	0	0	81
Sodegaura	0	0	0	100
Futtsu	00	0	64	100

ECONOMIC DAMAGE OF FLOODING

Once the probabilities of inundation at each location are known, it is necessary to establish what would be the damage caused if present day sea defences were overtopped. For the present work the authors approximated these using elevation maps of Tokyo Bay, and thus represent a worst case scenario, were the present-day dykes would suffer large-scale failure during overtopping and allow water to freely flow into the city. Generally speaking, it is not clear that this overtopping of the dykes would lead to their complete failure, though current Japanese dykes to not appear to resist overtopping well, as was manifested during the *2011 Great East Japan Earthquake and Tsunami* (Jayaratne et al.,2014, Mikami et al., 2012). However, this appears logical given the precedent of New Orleans, where several floodwalls and other defences failed due to overtopping. Nevertheless, future work should concentrate on inundation simulations to more accurately predict the consequences of the defences being overcome.

The maximum inundation values are considered to take place at maximum high tide (+2.1m A.P.) and take into account the mean expected value of storm surge and the sea level rise for each scenario. These values are expressed at Tokyo Pail (T.P.) elevations (T.P.=A.P. -1.134m). Due to the comparative small population density in Chiba, the economic analysis will be restricted to Tokyo and Kanagawa prefectures

The calculation of the possible economic damage to an area is quite complex, involving a number of different mechanisms and types of damage. The inundation damage to offices, houses and other infrastructure should all be independently calculated, and depend on the inundation height in each location. To do so, the authors applied the methodology of the Ministry of Agriculture, Forestry and Fisheries (2012). The total household property value is estimated from the average value (in yen/m^2) of the ward. Then, the percentage of inundated area in the ward can be obtained from 5m elevation maps for each ward, providing the house property value affected for a given inundation height. Finally, the property value that would be damaged as a consequence of the inundation can be calculated by using stage damage functions.

By adding up all the damage to all areas inundated in Tokyo city and Kanagawa prefecture it is possible to calculate the total damage to each prefecture for a given water level, as shown in Figure 4. In this sense it is important to note that even at present some areas in Tokyo are lower than the highest tide levels, and if the dykes protecting them should break Tokyo would suffer damage even for a 0m water level in the Bay.

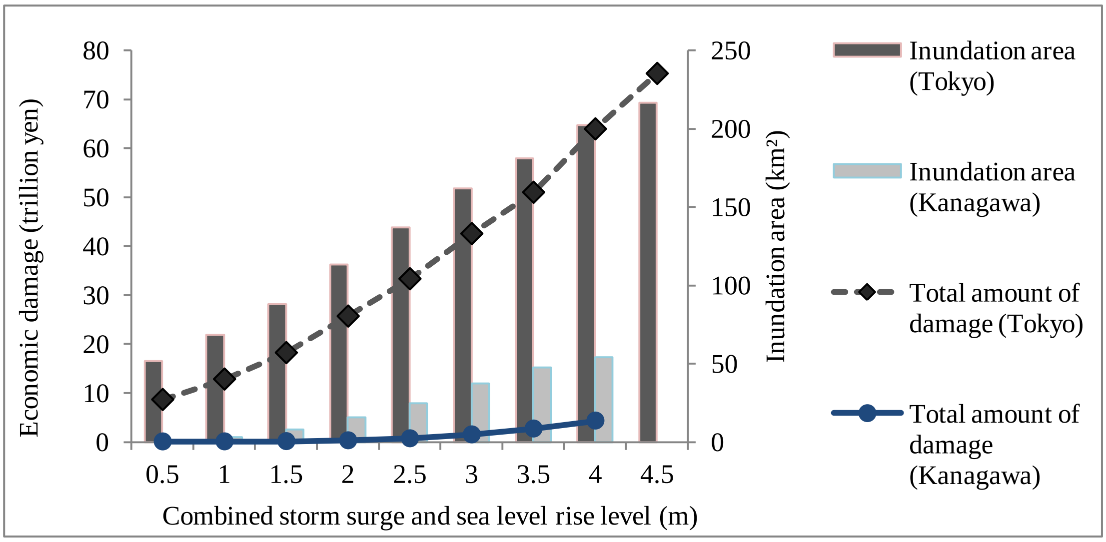

Figure 4. Total economic damage in Tokyo and Kanagawa for different inundation levels

CLIMATE CHANGE AND SEA LEVEL RISE ADAPTATION COSTS IN TOKYO BAY

The combined effect of an increase in typhoon intensity and sea level rise could pose significant challenges to coastal defences in the Tokyo area. Current construction policy of Tokyo Metropolitan Government specifies that coastal defences around Tokyo Metroplitan area should be constructed to a level of +3.5-5.9m T.P., though some old structures have been designed to a lower level. To keep the risk of a 1 in 100 year storm by the year 2100 similar to that at present it would be eventually necessary to undertake significant adaptation measures around Tokyo Bay. Such adaptation measures could include either raising existing defences, or the construction of a storm surge barrier at the entrance of Tokyo Bay.

Cost of Raising Existing Defences

Generally speaking these would include higher dykes, which would mean elevating and reinforcing current structures or building new ones, and raising the elevation of the areas outside of these dykes (generally corresponding to port areas). In the following section the cost of adapting against a 1.9m sea level rise scenario will be summarised, which would include work on over 57km of levees in Tokyo and Kanagawa Prefectures alone (see Esteban et al., 2014 and Hoshino, 2013).

The total cost of reinforcing sea dykes is directly proportional to the length of the dykes. Using maps from the local governments of Kanagawa Prefecture, Tokyo Metropolitan Government and Chiba Prefecture the total length of the dykes that would require reinforcement could be calculated (Hoshino, 2013). The total port area outside the dykes that would require elevation, according to maps from the Geospacial Information Authority of Japan, is shown in Fig. 10 for the case of Tokyo.

The cost of raising parapets (low wall) in Tokyo and Kawasaki is estimated at 34,942 yen/m^3 for the additional concrete that would be placed on top of the existing dykes. The cost of building new coastal dykes is estimated at 35,000 yen/m^3 for the material, together with the construction of a 10m sheet pile of 0.25 million yen/m. The cost of the required new anti-earthquake measures were derived from the dyke protection works of Naka-river at Katsushika (around 0.44bn yen per 100m section, from figures from the Tokyo Metropolitan Government, 2011). Unit costs for the elevation of port areas around the bay were derived from the Economic Research Foundation of Japan (2010). However, it should be noted that the cost of demolishing and rebuilding present port structures was not taken into account, as it was assumed that many of these structures have comparatively limited useful lives, and would be demolished and rebuilt several times before the year 2100. The current analysis is thus probably conservative, as it does not include the strengthening of other protection features, such as storm surge gates at the entrance of rivers, which are assumed to remain useful.

Table 2 summarises the cost of either building new dykes or reinforcing existing ones. It is interesting to note how the difference between either of these is not significant, as most of the adaptation costs in a high-seismicity area such as Tokyo come from the seismic counter-measures required. Thus, if it were possible to adapt the old dykes by just raising them, the cost total cost would amount to 117.5 and 257.1 bn yen in Tokyo and Kanagawa prefectures, respectively. However, if new dykes were required, the total cost would only be slightly higher, at 389.3bn yen (compared to 374.6 bn), see Table 2.

Table 2 Total cost of adapting old dykes or building new ones, for Tokyo and Kanagawa regions, for a 1.9m sea level rise scenario.

	Length of dykes (km)	Adapting old dykes (bn yen)	Building new dykes (bn yen)
Tokyo	22	117.5	123.0
Kanagawa	34.9	257.1	266.3

Preliminary Analysis of Freeboard of a Storm Surge Barrier

Another possible adaptation measure for Tokyo Bay would be the construction of a storm surge barrier at the entrance of the bay (Esteban et al., 2014). Such barriers have already been constructed at a number of locations around the world, including the London, the Netherlands and New Orleans (Mooyaart et al., 2014).

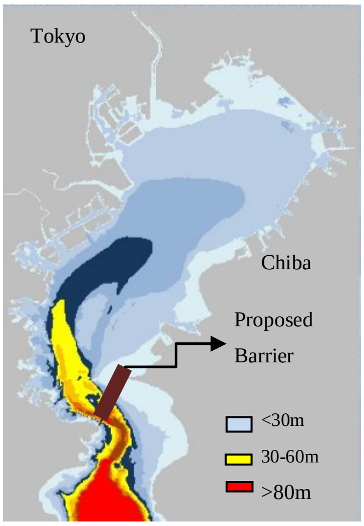

Figure 5. Proposed location of storm surge barrier, together with bathymetry of Tokyo Bay.

It is possible to envisage such a barrier to be located further inside the bay, to take advantage of shallower bathymetries. The location shown in Fig. 5 would represent a barrier of around 7km depth, with the deepest section located at depths of around 80m. Ruiz-Fuentes (2014) carried out a conceptual design analysis of placing the prospective barrier at different locations, and arrived at the conclusion that the location proposed is actually the cheapest of all possible barriers that can be considered (around 700-800bn yen, or 7-8bn US$).

A preliminary analysis of the required freeboard of the storm surge barrier was also carried out, using the same methodology outlined in earlier sections of this chapter. As a result of climate change the storm surge at the barrier by the year 2100 for a 1 in 100 year storm could be in excess of 1.6m, around 0.4m higher than what could be expected for a similar return period if the barrier was built nowadays. When combined with a 1.9m sea level rise and high tide (+2.1m) this could require a barrier over +5.6m T.P. high, assuming that it can be overtopped (see Table 3). Otherwise, wave data from NOWPHAS measured at Hamakanaya wave buoy indicate that the significant wave height in the area is approximately $H_{1/3}$=7.3m, though the location of this buoy is not exactly the same as where the barrier would be located, and more detailed simulations would be needed.

Table 3. Design level of Storm Surge Barrier

Component	**Height**	**Notes**
Storm surge (Pressure and wind set-up)	+1.62 m	Considering climate change by 2100
Spring maximum tide level	+2.1 m	
Sea level rise	+1.9 m	According to Vermeer and Ramhstorf (2009)

DISCUSSION

When contemplating whether to improve coastal dykes or build a storm surge barrier it is important to consider not only how much each type of measure could cost, but the protection that they would offer, and how easy it would be to upgrade such defences in the future. In this sense, it is important to remember that sea level rise and climate change will continue after the year 2100 which would require constant upgrades to coastal defences. Thus, cost might not be the only argument determining whether to build a storm surge barrier or strengthen coastal defences.

Essentially, upgrading current defences would be far cheaper than building a storm surge barrier, as preserving the current level of protection (against a 1 in 100 year storm) would be about half the cost of building a storm surge barrier. However, the protection given by such a barrier is much higher, and for it to protect against a 1 in 500 year storm would only cost marginally more than protecting against a 1 in 100 year storm (Ruiz-Fuentes, 2014). Also, it is important to consider how for the case of upgrading the defences, work would be concentrated only in one point (the barrier), rather than having to execute work throughout the entire perimeter of Tokyo Bay. Furthermore, this barrier extends protection to the port areas currently outside the dykes, which could suffer damage in the event of a storm surge that was not as high as a 1 in 100 year storm. Preserving current dykes also creates a system of multi-layered defence, where even if the storm surge barrier failed there would still be an extra layer of defence offering some protection. Finally, the construction of a barrier can also offer significant co-benefits as a bridge or railway link. However, the barrier could reduce water quality inside the bay, as it would inevitably interfere with water exchanges between the bay and the ocean. Although Tokyo Bay does not constitute a major fishing ground, some fishing does exist and could face opposition from fisherman and other stakeholders, and careful consideration should be given to such issues. Also, the presence of a barrier would affect navigation, and would require more careful planning and control around the entrance of the Bay.

CONCLUSIONS

An increase in typhoon intensity and sea level rise are likely to pose significant challenges to coastal defences around Tokyo Bay, the seat of the Japanese government and also a major economic, industrial and commercial centre. To attempt to understand such risks the authors determined the storm surge that could result from an increase in typhoon intensity around Tokyo Bay by the year 2100. This was then combined with a variety of sea level rise scenarios to obtain potential water levels for a 1 in 100 year design storm, based on the Taisho (1917) typhoon.

The results show that the various settlements around Tokyo Bay are likely to be severely affected by the consequences of storm surges and sea level rise in the future. Particularly, the risks at Yokosuka, Yokohama, Kawasaki, and Futtsu are high, even when the maximum computed storm surges are at Shibaura and Funabashi. However, the greatest risks are in the low-lying areas in the Koto delta and other wards in Tokyo, which is significant due to its population density and the economic activities concentrated in the area. If these defences are breached the potential direct economic consequences are massive, potentially in excess of 100 trillion yen (around 20% of the current GDP of Japan), assuming no inflation or economic growth between now and the year 2100. The indirect consequences of such an event could be far greater, in terms of the recovery processes, loss of business time and other indirect costs, as seen by the effects of hurricanes Katrina and Sandy in the United States.

As a result of this it is likely that sea defences would have to be strengthened around Tokyo Bay in the future to maintain the current level of protection. Alternatively, a storm surge barrier could be built, which would cost in the range of 700-800bn yen, though such a structure could raise the protection level as it would be able to cope with a 1 in 500 year storm or even higher if designed well. However, the barrier could have a number of negative impacts on water quality in the bay and hinder somewhat navigation, though these could be partly compensated by the multi-layer protection it would offer to all cities within the bay and by serving as a transport link. Also, it would be easier to upgrade the barrier (rather than each individual dyke around the bay), something that would be inevitable in the future, as sea level rise and climate change is unlikely to end in the year 2100 but continue into the 22nd and 23rd centuries. Given such a scenario it is clear that further study on flood risk reduction strategies (including a barrier) are warranted for the case of Tokyo Bay.

REFERENCES

Chiba, Tokyo, Kanagawa (2004): Tokyo Bay Basic Plan on Coastal Management. 千葉県・東京都・神奈川県（2004

Economic Research Foundation of Japan (2010), *Monthly quantity survey information for construction material.*

Esteban, M., Webersik, C., Shibayama, T., 2009. Methodology for the Estimation of the Increase in Time Loss Due to Future Increase in Tropical Cyclone Intensity in Japan, *Journal of Climatic Change*, Volume 102, Numbers 3-4,pp. 555-578

Esteban M. and Longarte-Galnares, G. 2010., Evaluation of the Productivity Decrease Risk due to a Future Increase in Tropical Cyclone Intensity in Japan, *Journal of Risk Analysis*, pages 1789–1802

Esteban, M., Mikami, T. Shibayama, T., Takagi, H. , Jonkman, S.N. and Ledden, M.V. (2014) Climate change adaptation in Tokyo Bay: The case for a storm surge barrier, *Proc. 34th International Conference on Coastal Engineering (ICCE)*, 15th -20th June 2014, Seoul, Korea

Hoshino, S., Esteban, M., Mikami, T., Takabatake, T. and Shibayama, T., 2011 Effect of Sea Level Rise and Increase in Typhoon Intensity on Coastal Structures in Tokyo Bay. *Proc. Of Coastal Structures Conference*, Yokohama 6th-8th Sept 2011.

Hoshino, S. 2013. Estimation of storm surge and proposal of the coastal protection method in Tokyo Bay. *MSc Thesis*, Waseda University

Japan Statistics Bureau, 2010. http: //www.e-stat.go.jp/SG1/estat/XlsdlE.do?sinfid=000008640423 Accessed 15 Sept 2012

Jayaratne, R. , Abimbola, A., Mikami, T. Matsuba, S., Esteban, M. and Shibayama, T. (2014) Predictive model for scour depth of coastal structure failures due to tsunamis, *Proc. 34th International Conference on Coastal Engineering (ICCE),* 15th -20th June 2014, Seoul, Korea

Kawai, H, Hashimoto, N. and Matsuura K., 2006. Improvement of Stochastic Typhoon Model for the Purpose of Simulating Typhoons and Storm Surges under Global Warming, *Proceedings of the 30th International Conference on Coastal Engineering (ICCE2006)*, Vol.2, pp.1838-1850.

Kawai, H., Hashimoto, N., Matsuura, K., 2008. Estimation of Extreme Storm Water Level in Japanese Bays by using Stochastic Typhoon Model and Tide Observation Data. *Proc. 18th (2008) International Offshore and Polar Engineering Conference*, Vancouver, BC, Canada, July 6-11, 2008.

Knutson, T., McBride, J., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J., Srivastava, A., & Sugi, M., 2010. Tropical cyclones and climate change. *Nature Geoscience*, 3 (3), 157-163

Masamori, M., 2003.Study of storm surge. *Seizando-shoten Publishing*. pp30-33.

Mooyaart, L.F., Jonkman, S.N., de Vries, P., Toorn, A.V.D. and Ledden, M.V. (2014) Design aspects and costs of storm surge barriers. *Proc. of 33nd Int. Conf. on Coastal Engineering (ICCE 2014),* Seoul, Korea.

Mikami, T., Shibayama, T., Esteban, M. and Matsumaru, R., 2012. Field Survey of the 2011 Tohoku Earthquake and Tsunami in Miyagi and Fukushima Prefectures. *Coastal Engineering Journal (CEJ)*, Vol. 54, No. 1, pp. 1-26

Miyazaki, M., 1970. Tsunami Storm Surge and coastal Disasters. Ed. By Wadachi, K., Kyouritsu Shuppan (in Japanese)

Miyazaki, M. (2003) Study on Storm Surge, Seizando Publishing, ISBN4-425-51181-6, 134p.(in Japanese)

Mousavi, M. E., Irish, J. L., Frey, A. E., Olivera, F., and Edge, B. L. (2011). Global warming and hurricanes: the potential impact of hurricane intensification and sea level on coastal flooding. *Climatic Change* 104: 575-597.

Myers, V.A., 1954. Characteristics of United States Hurricanes Pertinent to Levee Design for Lake Okeechobee, Florida. *Hydro-Meteorological Report of U.S Weather Bureau*, 32, pp.1-106.

Nagai, T. 2002. Long term statistics report on nations ocean wave information network for ports and harbours (NOWPHAS 1970-1999*). Technical Note of the Port and Airport Research Institute*, No.1035**,** 388p.

Nobuoka, H. and Murakami, S., 2011. Vulnerability of coastal zones in the 21st century. In: Climate Change and Global Sustainability: A Holistic Approach. *In: Sumi, A., Mimura, N. and Masui, T (eds).* UNU Press. ISBN: 978-92-808-1181-0, 325pages

Nguyen, D. T., Takagi, H., and Esteban, M. (2013) Coastal Disasters and Climate Change in Vietnam: Engineering and Planning Perspectives, *Edited Book on Elsevier Insights*, Elsevier

Ohira, K., Shibayama, T., Esteban, M., Mikami, T., Takabatake, T. and Kokado, M., 2012 Comprehensive Numerical Simulation of Waves Caused by Typhoon Using a Meteorology-Wave-Storm Surge-Tide Coupled Model. *Proc. of 32nd Int. Conf. on Coastal Engineering (ICCE 2012),* Santander, Spain.

Ruiz-Fuentes, M.J., 2014.. Storm Surge Barrier Tokyo Bay – Analysis on a System Level and Conceptual Design. *MSc Thesis*, Delft University of Technology

Shibayama, T. Okayasu, A. and Toki, M., 1990. A numerical calculation of storm surge in Tokyo Bay by using Two-level model. *Annual Journal of Civil Engineering in the Ocean*, JSCE.6.pp77-82

Takagi, H., Kashihara, H., Esteban, M. and Shibayama, T., 2011. Assessment of Future Stability of Breakwaters under Climate Change, *Coastal Engineering Journal*, Vol. 53, No. 1

Tokyo Metropolitan Government, 2011. Bidding information, http://bidfind.openbeat.org/, Accessed 15 Jan 2013

Tokyo Metropolitan Government, 2012. http://www.metro.tokyo.jp/ENGLISH/PROFILE/overview03.htm. Accessed 15 Sept 2012

Tsuchiya, Y., Yamashita, T. and Oka, Y.(1981) Storm surge hind-casting by using 2 level model, *Proc. Of 28th Japanese Conf. on Coastal Eng.,* 54-58.

Pricewaterhouse Coopers, 2009. http://www.pwc.com/ Accessed 15 Sept 2012

Vermeer M and Rahmstorf S *PNAS* 2009;106:21527-21532

Yasuda, T. Mase, H. and Mori. N, 2010a. Projection of future typhoons landing on Japan based on a stochastic typhoon model utilizing AGCM projections, *Hydrological Research Letters*, 4. 65-69.

Yasuda, T. Hayashi, Mori, N. and Mase, H., 2010b. A Stochastic Typhoon Model Applicable to Storm Surge and Wave Simulations for Climate Change, *Proceedings of JSCE*, Vol. 66, No. 1, 1241-1245.

Yamamoto, L. and Esteban, M. (2014) Atoll Island States and International Law – Influence of Climate Change on Sovereignty and Human Rights, *Springer*, ISBN 978-3-642-38186-7