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Cost of Adaptation to Rising Coastal Water Levels

for the People's Republic of China, Japan, and the Republic of Korea

Robert Nicholls, Susan Hanson, and Jochen Hickel

Asian Development Bank

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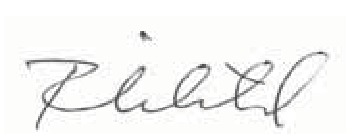
Foreword

Anticipating rising sea levels as a result of climate change and estimating possible adaptation costs is an important undertaking for coastal areas of Northeast Asia, a region that—for this study—consists of areas of the People's Republic of China, Japan, and the Republic of Korea. The coastal areas of the Northeast Asia region account for about 180 million people living in low-elevation coastal areas (within 10 meters of sea level), and where roughly one-fifth of global trade—largely by sea—is being conducted. Ignoring adaptation and neglecting possible climate change impact would not only directly affect the livelihood of millions of people, but could lead to severe disruptions in production and trade that would result in much higher than the estimated adaptation costs, potentially having impacts across the world.

As this study indicates, adaptation to sea-level rise is costly but manageable; up to $1.9 billion per year in the Republic of Korea, $2.3 billion in Japan, and $2.6 billion in the People's Republic of China from 2010 to 2050. Note that these are just the incremental costs of adapting to the effects of climate change on sea levels and should not be confused with the total cost of coastal management, which addresses a much wider range of issues than sea-level rise, hence, cost will be significantly higher. Adaptation to sea-level rise will need to be integrated with this broader coastal management agenda to successfully promote public safety and continued grow in these coastal regions.

This study is part of the technical assistance "Economics of Climate Change and Low Carbon Growth Strategies in Northeast Asia" financed by the Asian Development Bank (ADB) and the Korea International Cooperation Agency. Jörn Brömmelhörster from ADB's East Asia Department (EARD) led the technical assistance and coordinated this study with the assistance of Maria Luisa Panlilio and under the guidance of Edgar A. Cua, Deputy Director General, EARD. We are grateful for the collaboration with distinguished experts—Robert J. Nicholls and Susan Hanson from the University of Southampton in the United Kingdom, and Jochen Hinkel from the Potsdam Institute for Climate Impact Research in Germany.

We are indebted to the DINAS-COAST consortium, which developed the Dynamic Interactive Vulnerability Assessment (DIVA) model that was used for this study. Further, we want to thank Kotaro Kawamata, formerly an ADB staff and now with the Ministry of the Environment of Japan for providing additional data for ports in Japan; and Gordon Hughes of the University of Edinburgh, United Kingdom, who provided the population and gross domestic product projections for this study.



Robert Wihtol
Director General
East Asia Department
Asian Development Bank

Abbreviations

cm	–	centimeters
DIVA	–	Dynamic Interactive Vulnerability Assessment
EACC	–	Economics of Adaptation to Climate Change
GDP	–	gross domestic product
IPCC	–	Inter-Governmental Panel on Climate Change
km^2	–	square kilometer
LECZ	–	Low Elevation Coastal Zone
OECD	–	Organisation for Economic Co-operation and Development
PPP	–	purchasing power parity
PRC	–	People's Republic of China
SRES	–	Special Report on Emissions Scenarios
TEU	–	twenty-foot equivalent unit
UNFCCC	–	United Nations Framework Convention on Climate Change

Executive Summary

This report explores the potential costs for coastal adaptation from 2010 until 2050 in East Asia due to climate-induced sea-level rise and possibly more intense tropical cyclones. It builds on the assessment in "Economics of Adaptation to Climate Change (EACC)" by the World Bank (Nicholls et al. 2010) in looking at the adaptation costs of three important coastal countries: the People's Republic of China (PRC), Japan, and the Republic of Korea. The results are estimates of possible adaptation needs, which illustrate the possible magnitude of adapting to the future impacts of climate change on coastal areas in these countries.

The analysis uses the framework of the Dynamic Interactive Vulnerability Assessment (DIVA) model to explore the costs of three main protection responses to the impacts of climate change. These responses are

- sea-dike construction and upgrades with associated maintenance costs for sea-flood impacts,
- beach nourishment for beach erosion impacts, and
- raising of port areas to maintain their effective operation.

There is a long history of hard protection and land claim in the region using dikes, so future extension and upgrade of dikes and other defenses for sea-level rise is a response consistent with history. The analysis also considers a range of impacts and costs, including dryland and wetland loss, associated forced migration, and sea-flood costs with and without upgraded protection. The adaptation methods are applied using a standard methodology using criteria that select optimum or quasi-optimum rule-based adaptation strategies. Using the DIVA approach, *actual* damages associated with sea-level rise (and storm intensification) will be much lower than the *potential* damages ignoring protection.

A range of scenarios broadly consistent with an A2 scenario of the Special Report on Emission Scenarios (A2 SRES) are considered, following the EACC study. Four scenarios of global sea-level rise are considered, comprising a (i) no-rise in global temperature (a reference case of no climate change), (ii) low, (iii) middle, and (iv) high change scenarios covering climate-induced rise in sea level of between 0 and 38 centimeters (cm) by 2050 following the same assumptions as the EACC study. As a sensitivity analysis, a fifth scenario of an increase in the intensity of tropical storms is also considered, combined with a high sea-level rise scenario. These scenarios represent interesting, useful, and plausible scenarios to adopt for the exercise of adaptation planning under uncertainty. Impacts are evaluated based on one socioeconomic scenario describing population and gross domestic product (GDP) change developed specifically for this study. These are an improvement on those used in the EACC study. Following best engineering practice for sea dikes, sea-level rise is anticipated in terms of additional height for 50 years into the future based on extrapolating the rate of sea-level rise at the time of the adaptation decision. For other adaptation measures, there is no anticipation of future conditions, again reflecting best engineering practice.

Assuming no adaptation measures were undertaken, the impacts by 2050 are significant, especially under the high scenario with increased cyclones. It is unlikely that coastal societies could tolerate such losses and an adaptation response based on protection seems plausible, as already explained. From 2010 to 2050, the average annual adaptation costs are estimated to be up to $1.9 billion per year in the Republic of Korea, $2.3 billion in Japan, and $2.6 billion in the People's Republic of China (PRC). These costs are dominated by sea dikes—the capital costs of upgrade are largest

(54%–73% of national average annual costs), but as the stock of dikes grows, maintenance costs also grow (21%–31% of national costs). In contrast, the costs of nourishment are relatively minor in the region (less than 6% of national average annual costs). Unlike in the EACC study, the costs of port upgrade are significant in the PRC and Japan, and less so in the Republic of Korea (up to 15%, 10%, and 4% of national average annual costs, respectively). This reflects the importance of ports and imports and/or exports in the region. For all three countries, the costs are minimum estimates as the national port data is incomplete; in the case of Japan, adding new national data roughly doubled the annual adaptation costs for this country.

Other important uncertainties include the unit costs of defenses—higher unit defense costs in urban areas, reflecting land prices, could substantially raise dike cost estimates and the cost of upgrading all the defenses and/or drainage systems in coastal lowlands where water levels will rise with sea level, also called the backwater effect. These are just the incremental costs of adapting to climate change; the total cost of coastal management would be significantly higher. The maintenance of preexisting dikes, which are assumed to exist in this analysis, could be substantial and is estimated as $2.3 billion per year for the PRC, $1.6 billion for Japan, and $2.3 billion for the Republic of Korea. Non-climate processes, such as the other human drivers of coastal change, may also be significant, including human-induced subsidence (due to groundwater withdrawal), dam construction, and sediment starvation at the coast. Hence, this study shows the need for an integrated management of coastal hazards and change in general, with climate change being one component among a range of drivers.

1. Introduction

The coast contains high and growing concentrations of people and economic activity (Dasgupta et al. 2009a; MCGranahan et al. 2007; Small and Nicholls 2003; Sachs et al. 2001) and there is a significant and expanding exposure to coastal hazards associated with climate variability, such as storms, and non-climate events, such as tsunamis (Kron 2008). For example, about 120 million people are, on average, estimated to be exposed every year to tropical cyclone hazard (UNDP 2004). Asset loss as a consequence of extreme events is also significant, driven largely by the increase in asset exposure, especially in wealthy and rapidly growing countries (Pielke Jr. et al. 2008). Therefore, human-induced climate change and sea-level rise are of major concern as they increase coastal risks as shown in the assessments of the Inter-Governmental Panel on Climate Change (IPCC) (Nicholls et al. 2007b; McLean et al. 2001; Bijlsma et al. 1996).

Asia dominates population exposure in coastal areas and with rising living standards, asset exposure becomes increasingly significant in absolute and global terms. The People's Republic of China (PRC), Japan, and the Republic of Korea alone are estimated to account for 28% of the global population in the Low Elevation Coastal Zone (LECZ)[1] (CIESIN 2012). A significant proportion of national populations are also located in these areas (Table 1). For example, 24% of the Japanese population lives on the 7% of the total land area, which is in the LECZ.

With large export-based economies, coastal production areas and associated ports and harbors are vital to current and future prosperity. In the three countries considered here, 23 coastal cities with a population of over a million people are associated with ports—14 port cities in the PRC, 6 port cities in Japan, and 3 port cities in the Republic of Korea (Nicholls et al. 2008a). In 2005, for these 23 coastal cities alone, around 12 million people and $864 billion of assets are estimated to be exposed to the 1-in-100 year flood event. Using high-end scenarios of possible changes to both extreme water levels and population/gross domestic product (GDP) in these cities by the 2070s, this exposure could increase to 37 million people and $13 trillion of assets. Increases in expected damages are more difficult to evaluate, but would be expected to be higher by one or two orders of magnitude, assuming no adaptation measures were undertaken. This highlights the

Table 1 **Coastal Zone Populations in the People's Republic of China, Japan, and the Republic of Korea**

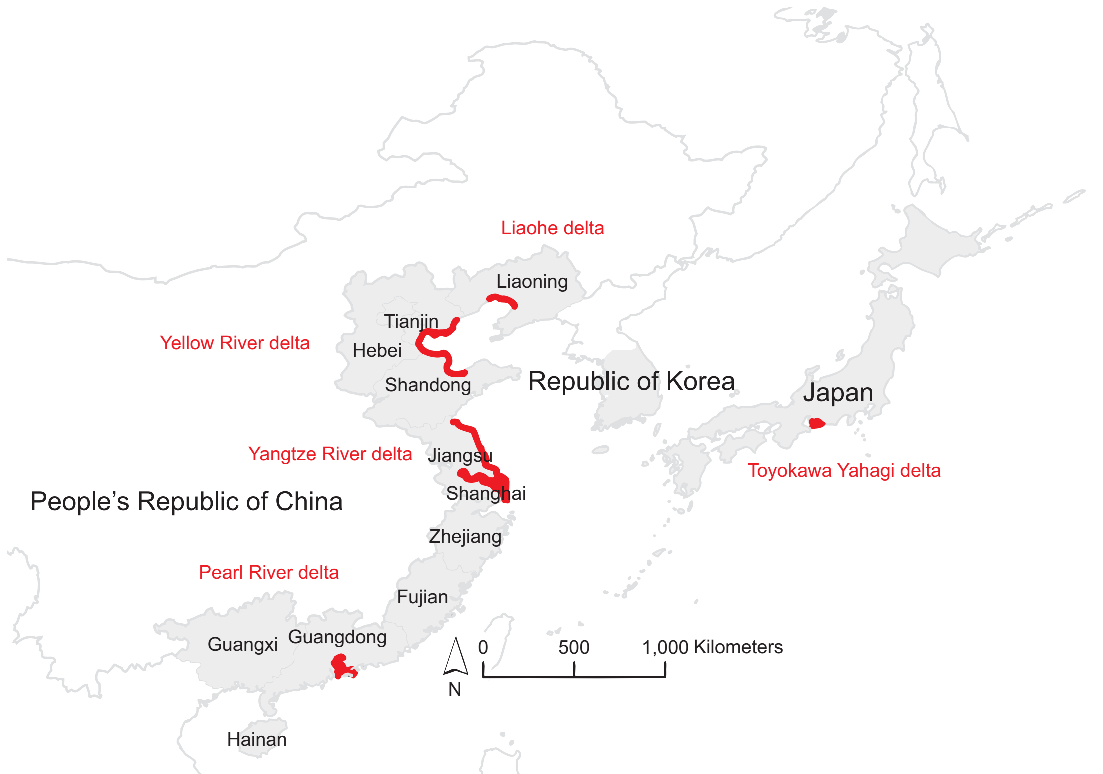
	Country		Low Elevation Coastal Zone (LECZ)		
Country	Population (2000)	Total area (km^2) (Circa 1995)	Population (2000)	Number of Urban Areas > 1 million people	Area (km^2) (Circa 1995)
People's Republic of China	1,262,333,728	9,198,069	143,879,600	26	182,041
Japan	126,578,071	372,634	30,477,106	11	26,802
Republic of Korea	46,739,744	98,977	2,878,453	4	4,959

km^2 = square kilometer.

Source: CIESIN (2012).

[1] LECZ is an area below 10-meter elevation.

Figure 1 **Areas Included in the Study with the Location of Major Deltas**



Note: The People's Republic of China consists of provinces, municipalities, and autonomous regions.

Source: Authors.

possible consequences of climate change and the need to establish an adaptation process to be implemented over the coming decades.

Adaptation has been a feature of assessments of sea-level rise since the 1980s (e.g., Barth and Titus 1984). Over time, a wider range of options have been considered as the need for adaptation has increased (Linham and Nicholls 2010; Klein et al. 2001). However, the costs of the required adaptation and the residual impacts are often not evaluated in economic terms. A fundamental result from integrated assessment models is that protection selected based on benefit–cost approaches greatly reduces the impacts of sea-level rise, at least for people and assets, and the residual damage is lower by as much as two orders of magnitude than the potential impacts[2] (Nicholls and Tol 2006). This suggests that protection will be widely applied around the world's coasts, especially for cities and other developed areas. Building on their long tradition of protection, this is expected to be the case in the PRC, Japan, and the Republic of Korea.

The global costs of protecting developed coasts against sea-level rise were first estimated by Delft Hydraulics for the IPCC (IPCC CZMS 1990a), later improved by Hoozemans et al. (1993) followed by Fankhauser (1995), Tol (2007), and Sugiyama et al. (2008). In 2007, the United Nations Framework Convention on Climate Change (UNFCCC) conducted an assessment of the possible adaptation investment needs for sea-level rise from 2010 to 2030 (Parry et al. 2009; Nicholls 2007). This

[2] Assuming no adaptation whatsoever were undertaken.

compared the response of the A1B and B1 SRES[3] IPCC sea-level rise scenarios (Meehl et al. 2007), assuming protection were applied using dike construction and beach nourishment. The UNFCCC estimates additional investment costs of $4 billion–$11 billion/year in 2030, assuming a 50-year planning horizon, and that there is no adaptation deficit.[4] Due to accelerating sea-level rise, annual investment costs would be expected to increase beyond 2030.

Parry et al. (2009) reviewed the UNFCC assessment of coastal adaptation costs and found that they appeared reasonable within the assumptions made. However, they noted that (i) only a limited range of sea-level scenarios were considered, (ii) the adaptation approach might change and protection costs could increase if impacts on coastal ecosystems were considered, and (iii) other aspects of climate change such as more intense storms were not considered. Hence, the costs should be seen as a minimum estimate. The importance of the adaptation deficit was also emphasized, with less-developed countries such as Africa being of most concern (Hinkel et al. 2012). In the PRC, Japan, and the Republic of Korea, extensive defenses already exist so the adaptation deficit is less of an issue in this assessment. The World Bank's investigation into the Economics of Global Adaptation to Climate Change (Nicholls et al. 2010) addressed some of these points.[5] It considered adaptation costs up to 2050 and post-2007 literature on sea-level rise scenarios, embracing a rise of between 40 centimeters (cm) and 126 cm by 2100. It also considered the possibility of more intense tropical storms. Lastly, it added dike maintenance and port upgrade to the adaptation costs. Hence, the Economics of Adaptation to Climate Change (EACC) investment cost estimates are significantly higher than the UNFCCC costs, ranging from $26 billion to $89 billion per year in the 2040s, depending upon the sea-level rise scenario being considered. Excluding high-income countries, the annual investment costs were $13 billion to $45 billion per year in the 2040s. Most of these investments would be sea dike construction and upgrade, and their maintenance costs would rise significantly with time. Beach nourishment costs are also significant and would also increase with time. Port upgrade costs were minor (1%–2%) relative to costs at a global level (excluding high-income countries). The important implications of the adaptation deficit were also emphasized.

Building on the EACC study, the Asian Development Bank (ADB) has commissioned a study of the costs of adaptation for these East Asian countries—the PRC, Japan, the Republic of Korea, and Mongolia. Using a similar methodology to the EACC, this study describes the coastal adaptation component, which examines adaptation costs to 2050 under a range of plausible scenarios of sea-level rise, and as a sensitivity analysis, one scenario of increased intensity of tropical storms. Mongolia does not have a coastline and was, therefore, not considered. Possible impacts, adaptation options, and associated costs are reported at the national level for Japan and the Republic of Korea, and at the coastal province level for the PRC (comprising 11 provinces).

Climate Change Effects at the Coast

Table 2 summarizes the possible impacts of climate change at the coast. Of these impacts, rising mean sea levels and larger surges are directly related to the incidence of flooding as components of extreme water levels. Rising sea levels due to global warming have received most attention to date; thermal expansion and melting and/or disintegration of the small glaciers and large ice sheets of Greenland and Antarctica due to rising temperatures being the underlying cause. During the

[3] A1B and B2 are future socioeconomic storylines used to generate future global temperature and then sea level projections (Nakicenovic et al. 2000).

[4] The adaptation deficit reflects poor adaptation to the current climate, before climate change is even considered (Parry et al. 2009; Burton 2004).

[5] http://climatechange.worldbank.org/content/economics-adaptation-climate-change-study-homepage

Table 2 **Main Drivers for Coastal Systems, Trends Due to Climate Change, and Main Physical and Ecosystem Effects**

Driver (Trend)	Main Physical and Ecosystem Effects on Coastal Systems
CO_2 concentration (↑)	Increased CO_2 fertilization. Decreased seawater pH (or "ocean acidification") negatively impacting coral reefs and other pH-sensitive organisms.
Sea surface temperature (SST) (↑, R)	Increased stratification and/or changed circulation. Reduced incidence of sea ice at higher latitudes. Increased coral bleaching and mortality. Poleward species migration. Increased algal blooms.
Sea level (↑, R)	Inundation, flood, and storm damage. Erosion. Saltwater intrusion. Rising water tables and/or impeded drainage. Wetland loss (and change).
Storm	
Intensity (↑, R)	Increased extreme water levels and wave heights. Increased episodic erosion, storm damage, inundation, and defense failure.
Frequency (?, R) Track (?, R)	Altered surges and storm waves and risk of storm damage and flooding.
Wave climate (?, R)	Altered wave conditions, including swell. Altered patterns of erosion and accretion. Reorientation of beach.
Runoff (R)	Altered flood risk in coastal lowlands. Altered water quality and/or salinity. Altered fluvial sediment supply. Altered circulation and nutrient supply.

CO_2 = carbon dioxide.

Notes: Trend: ↑ = increase; ? = uncertain; R = regional variability.

Source: Adapted from Nicholls et al. (2007b).

20th century, global-mean sea levels rose by an estimated 17 cm–19 cm (Church and White 2011; Jevrejeva et al. 2008; Bindoff et al. 2007). This was primarily due to thermal expansion and the melting of the small land-based glaciers. Human-induced global warming is expected to cause a significant acceleration in global sea-level rise through the 21st century due to continued thermal expansion and the melting of land-based ice.

There is some debate about the potential magnitude of these changes with the possible contribution of Greenland and Antarctica ice sheets. The IPCC Fourth Assessment Report (AR4) (Meehl et al.

2007) estimated rises by up to 59 cm.[6] However, the AR4 report is clear that the upper bound of sea-level rise remains uncertain and unquantified due to the uncertainty about the response of the large ice sheets (IPCC 2007). More recent studies (Nicholls et al. 2011b) have emphasized a range of rises with the upper limit exceeding the quantified AR4 range (Grinsted et al. 2010; Vermeer and Rahmstorf 2009; Rahmstorf 2007). Hence, it is clear that at present, a rise of 1 meter (m) or more through the 21st century cannot be excluded and needs to be evaluated in impact and adaptation assessments (Lowe et al. 2009). More locally, relative sea level is composed of climate-induced changes in sea level combined with vertical land movement (Nicholls 2010). Uplift and subsidence processes include tectonics and glacial-isostatic adjustment, and human-induced processes, such as subsidence due to fluid withdrawal and drainage of coastal soils susceptible to subsidence and oxidation. Hence, relative sea-level rise varies from place to place—it is higher than the global-mean rise in areas that are subsiding, which includes many populated deltas, many of which are in Asia (Syvitski et al. 2009; Ericson et al. 2006). Subsidence can greatly exacerbate sea-level rise as observed in many subsiding deltas and coastal cities and could be as important as climate change in many Asian cities built on deltas (Hanson et al. 2011; Fuchs 2010; World Bank 2010). In contrast, an uplift process counters sea-level rise to some degree, but has a much smaller effect over the long term within the region of study.

Until recently, no study has addressed the impacts of changing storms, in part due to the lack of credible scenarios. Hanson et al. (2011) did consider more intense tropical and extra-tropical storms as one factor in the potential increase in exposure of coastal cities to coastal flooding.[7] The effect was significant and comparable in magnitude to changes due to (i) climate-induced sea-level rise, and (ii) human-induced subsidence, but much smaller than (iii) socioeconomic changes. Dasgupta et al. (2009b) also investigated the impacts of more severe tropical storms and sea-level rise and found that severe impacts are likely to be limited to a relatively small number of countries and a cluster of large cities at the low end of the international income distribution. In the EACC study, Nicholls et al. (2010) conducted a sensitivity analysis of adaptation costs based on an arbitrary increase in the intensity of tropical storms. While this increased adaptation costs, in aggregate terms, the effect was not large, although at regional scales it may be more important. The coasts of the PRC, Japan, and the Republic of Korea all experience tropical storms, which are termed typhoons in this region, and hence, more intense tropical storms are of concern.

Coastal Adaptation

Coastal areas have a long and established tradition of adaptation. While there has often been a focus on protection, the available adaptation measures can be placed in a wider context as one of three generic approaches (Linham and Nicholls 2010; Klein et al. 2001; Bijlsma et al. 1996; IPCC CZMS 1990b):

- (Planned) Retreat—The impacts of sea-level rise are allowed to occur and human impacts are minimized by reducing human use of the coastal zone via land use planning, development control, and set-back zones, among others.
- Accommodation—The impacts of sea-level rise are allowed to occur and human impacts are minimized by adapting human use of the coastal zone to the hazard via increasing flood resilience (e.g., raising homes on pilings or flood proofing), risk-based hazard insurance, and others.

[6] This rises to 76 cm globally if observed increases in ice sheet discharge are scaled up by temperature rise and is included.
[7] Following the regions identified by Meehl et al. (2007).

- Protection—The impacts of sea-level rise are controlled by soft or hard engineering (e.g., nourished beaches and dunes or seawalls), reducing human impacts in the zone that would be impacted without protection.

Note that a residual risk always remains despite a given protection as there are always a population of events, however small, that can exceed the defense standard; hence, complete protection cannot be achieved. Managing residual risk is a key element of a protection strategy that has often been overlooked in earlier applications. The cost of maintaining protection infrastructure is also an important issue (Nicholls et al. 2010), as also considered in this report. Aspects of the three generic approaches may be combined in a portfolio of adaptation measures. This could include information measures, such as flood forecast and warning systems.

Broad-scale policy assessments that are available consider a choice of "protect" versus "retreat" to examine the economics of sea-level rise, while "accommodation" has not been considered as extensively as yet.[8] Protection at the global scale has generally been assessed based on one of two distinct approaches, as follows:

(i) Arbitrary protection of all "developed areas,"[9] such as the Inter-Governmental Panel on Climate Change Coastal Zone Management Subgroup (IPCC CZMS) (IPCC CZMS 1990a), the Global Vulnerability Assessment (Hoozemans et al. 1993), and the Fast Track Analyses (Nicholls 2004).
(ii) Employ an optimization approach where "economically worthwhile areas" are defended, such as Fankhauser (1995), Tol (2007), Sugiyama et al. (2008) and Anthoff et al. (2010). This is normally based on comparing avoided damage and protection costs.

In both cases, the costs of the required protection and the residual impacts in areas can be determined.

It should be noted that the success or failure of protection is controversial and the contrasting views on this aspect of adaptation explain much of the differences between estimates of actual, as opposed to potential impacts of sea-level rise (Nicholls and Tol 2006). Pessimists expect protection to either be unavailable or to fail, and hence, potential impacts translate into actual impacts and the world likely faces tens of millions or more of environmental refugees due to sea-level rise alone (Dasgupta et al., 2009a; Myers 2002). In contrast, optimists expect widespread protection for sea-level rise and expect actual impacts to be much less than potential impacts. Both views tend to be caricatures of real responses, but this debate does stress that worst-case impacts of sea-level rise could happen but should not simply be accepted, hence, the importance of understanding adaptation and its costs. One relevant conclusion is the importance of continued economic growth to support investments in adaptation options; protection is much harder to justify under a scenario of no economic growth (Anthoff et al. 2010). This shows that coastal adaptation is strongly linked to wider development goals and related issues. It has been argued that assistance for adaptation measures is critical in the developing world in the coming few decades while these countries develop their capacity to adapt (Patt et al. 2010).

In the PRC, Japan, and the Republic of Korea, there is a strong historic reliance on protection and extensive systems of dikes and other defenses are found today (Li et al. 2004). Hence, an

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[8] "Accommodation" is currently observed at lower population densities in areas that are not economic to protect, such as much of the United States coast and Bangladesh, where flood warnings and shelters have greatly reduced the death toll during the landfall of major tropical cyclones.

[9] Usually based on an arbitrary definition, such as all areas with a population exceeding 10 persons/km^2 are protected.

adaptation analysis based on defense upgrades seems realistic, and this is the methodology that was followed here.

Adaptation Cost Assessments

While there is significant interest in elaborating coastal adaptation measures and understanding their costs (Bosello et al. 2007; Klein et al. 2001; UNFCCC 1999), it is difficult to ascertain investments in coastal adaptation as there is never a single "Ministry for Coastal Adaptation" with published accounts in any country (Nicholls 2007). Moreover, adaptation is rarely, if ever, focused purely on climate change and sea-level rise; coastal adaptation addresses all hazards. This is illustrated by the changing approaches to managing coastal flooding and erosion in the Netherlands (Deltacommissie 2008; Van Koningsveld et al. 2008), which has more recently moved from hard to softer protection based on large-scale beach nourishment with sea-dredged sand, with approximately 12 million cubic meters (m^3) being used in 2008.[10] There is also growing interest in ensuring human safety while minimizing environmental impacts and making adaptation multifunctional. This suggests, for example, moving from fixed to mobile surge barriers to allow water and biotic exchanges, and utilizing defense structures for multiple purposes (e. g., recreation, power generation, and others).

In terms of the unit costs of adaptation, most of the experience that is available concerns traditional hard engineering approaches and protection and their costs. Unit costs, therefore, are based on bottom–up estimates drawing on a long history of coastal management and engineering experience that mainly assumes protection via dikes (for flood management) and nourishment (to preserve beaches). The costs of these measures were documented globally using a series of country cost factors by IPCC CZMS (1990a) and Hoozemans et al. (1993), based on the global experience of Delft Hydraulics.[11] These cost estimates are grounded in extensive coastal engineering experience and developed here for application in this study (see pp. 8–16). There is much less understanding of retreat and accommodation costs because of the limited experience in these measures, hence, the greater difficulty of costing them.

The recent UNFCCC (Nicholls 2007) and EACC (Nicholls et al. 2010) cost assessments used the DIVA model and database that focused on dike construction and upgrade, and beach nourishment. The dike costs are derived from Hoozemans et al. (1993), while the nourishment costs are derived from the experience of Deltares, among others, in beach nourishment projects around the world. In the EACC study, cost estimates of the dike maintenance and port upgrade are also included. Residual damages are estimated in terms of land values, flood damage, and the costs of relocating people.

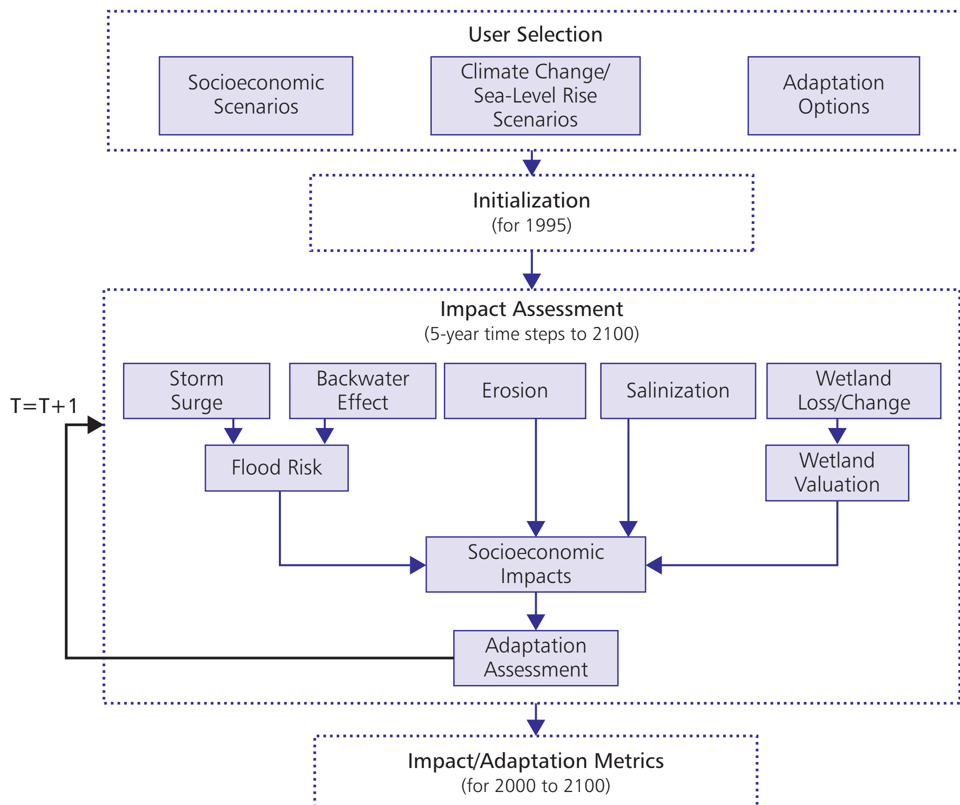
[10] See Ecomare at www.ecomare.nl/en/ecomare-encyclopedie/man-and-the-environment/mineral-exploitation/extraction-seabed-products/sand-extraction/

[11] Delft Hydraulics is now part of Deltares, the Dutch Institute for Delta Technology. www.deltares.nl

2. Methodology

This study is focused on the human impacts of climate change. The methodology is based on the Dynamic Interactive Vulnerability Assessment (DIVA) model as applied in the Economics of Adaptation to Climate Change (EACC) study (Nicholls et al. 2010). DIVA is an integrated model that estimates impacts and costs for given climate and socioeconomic scenarios and explicit adaptation options (Figure 2). An offline assessment of the costs of upgrading existing port areas outside DIVA is also made. The port analysis used the same scenarios as DIVA, hence, all cost estimates are consistent.

Figure 2 Schematic of Module Linkages in the Dynamic Interactive Vulnerability Assessment Model



Note: Adaptation decisions are implemented at the next time step, which are at 5-year intervals.

Sources: Hinkel and Klein (2009); Nicholls et al. (2007a).

The Dynamic Interactive Vulnerability Assessment Model

The DIVA model is an integrated model of coastal systems that assesses biophysical and socioeconomic impacts of sea-level change and development driven by socioeconomic and climatic scenarios (Hinkel and Klein 2009). For this study, version 3.4.0 of DIVA was used, together with the STRM

DIVA database 19. The DIVA database was developed specifically for the DIVA model (Vafeidis et al. 2008; McFadden et al. 2007). It comprises a one-dimensional global database that divides the world's coasts (excluding Antarctica) into 12,148 linear segments[12] and associates about 100 pieces of data with each segment concerning the physical, ecological, and socioeconomic characteristics of the coast.[13] The segments have a variable length, with an average length of 70 kilometers (km). Hence, the spatial resolution is two orders of magnitude higher than any other integrated assessment models that can conduct coastal analysis. As an example, the Framework for Uncertainty, Negotiation and Distribution (FUND)[14] model operates at national scales, so resolves approximately 200 coastal units (Nicholls and Tol 2006). While some data in DIVA are stored in other forms, such as data associated with rivers, lagoons and/or basins, administrative units, countries, and on a raster grid (Vafeidis et al. 2008), the segment is the fundamental spatial unit of DIVA. Most calculations operate at the segment scale and this defines the fundamental resolution of the model.

DIVA is driven by scenarios (plausible futures) of climate and socioeconomic change. The climate scenarios describe temperature and consequent sea-level change while socioeconomic scenarios describe land use, coastal population change, and gross domestic product (GDP) growth. Self-consistent scenarios, which evolve over time to 2050, are utilized in this study. In addition, an important aspect of the model is the consideration of explicit adaptation options. Following the discussion in earlier sections, DIVA focuses on protection costs, which can be costed globally; and DIVA considers (i) beach nourishment in response to beach erosion, and (ii) dike upgrade and maintenance in response to coastal flooding. Calculated impacts, therefore, do not only depend on the selected climatic and socioeconomic scenarios, but also on the selected adaptation strategy. The base year for the DIVA model is 1995 with potential impacts and costs being calculated at 5-year intervals (until 2100). It is important to note that there are different time frames for adaptation within DIVA as applied here: beach nourishment is based on the actual sea-level change while dike upgrade and/or maintenance anticipates sea-level change into the future (i.e., it represents proactive adaptation). Here, dike upgrade anticipates sea-level rise over a 50-year timescale. This reflects current engineering practice where nourishment is essentially a reactive approach to observed erosion with instantaneous benefits, while flood defenses have a longer design life with long-term benefits and need to anticipate some change to provide an appropriate standard of service over this life.

Climate and Socioeconomic Scenarios

The main scenarios considered in this report are climate-induced sea-level change, vertical land movement (uplift and subsidence), possible changes in tropical storms (as a sensitivity analysis), population change, and an increase in GDP. They are similar to the EACC scenarios used in the World Bank analysis of adaptation costs and follow a trajectory consistent with an A2 world in the Special Report on Emissions Scenarios (SRES) (Nakićenović et al. 2000; Nicholls et al. 2010). In the baseline, climate is constant (i.e., maintained at 1995 levels), but non-climate changes do occur, most notably population and GDP growth, and also relative sea-level rise due to uplift and subsidence only. The impacts and adaptation costs are then estimated for a range of climate change scenarios as explained in the following subsections.

[12] The number of segments per country in DIVA are as follows: the People's Republic of China, 226 segments; Japan, 159 segments; and the Republic of Korea, 28 segments.

[13] The data includes population, elevation and bathymetry, geomorphic type, landform type, tidal range, wetland characteristics, administrative boundaries, world heritage sites, extreme sea levels, uplift and/or subsidence, land use, GDP per capita, tourist arrivals and/or departures, rivers, tidal basins, and wave climate (Vafeidis et al. 2008).

[14] The climate FUND model is available at http://www.fund-model.org/

Relative Sea-Level Scenarios

The DIVA model calculates relative sea-level rise by combining rates of climate-induced sea-level change with rates of uplift and subsidence to produce rates of sea-level change for each individual coastal segment (Vafeidis et al. 2008).

Rates of vertical land movement are a combination of glacial-isostatic adjustment according to the geophysical model of Peltier (2000a and 2000b), and where appropriate, deltaic subsidence. Five major deltas in the region are considered in this analysis (Figure 1). Three of these deltas use subsidence estimates by Ericson et al. (2006), which include present human-induced effects at the scale of the delta—Yellow River, Yangtze River, and Pearl River all in the People's Republic of China (PRC)—and these rates are assumed to continue to 2050. In addition, a uniform subsidence rate of 2 millimeters (mm) per year is assumed for the Liaohe delta in the PRC and for the Toyokawa–Yahagi delta in Japan, as no other estimates are available. Local human-induced subsidence at sub-delta scales (for example, due to ground fluid abstraction or drainage) is not considered as there is no basis to predict future changes and this cannot be meaningfully included here. Based on historic subsidence in large coastal cities built on deltas in the region, namely Shanghai, Tianjin, Osaka, and Tokyo (Nicholls 2011; Yoshikoshi et al. 2009; Han et al. 1995; Wang et al. 1995; Endo 1992) this has the potential to be significant and could lead to additional impacts and adaptation costs not evaluated here.

The climate-induced sea-level change scenarios published by the Inter-Governmental Panel on Climate Change (IPCC) AR4 Report (Meehl et al. 2007) have been widely contested since they were published. Many papers have indicated the potential for larger rises than those included in the AR4 range (as reviewed by Nicholls et al. 2011b) and this has been considered in some national sea-level scenarios (Lowe et al. 2009). To acknowledge this debate, the EACC study developed four sea-level scenarios (Nicholls et al. 2010), which are also used here:

- No-change scenario—No climate change, so changes in relative sea levels result from vertical land movements only (a reference case).
- Low scenario—Based on the midpoint of the IPCC AR4 A2 range in 2090–2099 (Meehl et al. 2007).
- Mid scenario—Based on the Rahmstorf (2007) A2 trajectory.
- High scenario—Based on the "maximum" trajectory of Rahmstorf (2007).

These scenarios give a climate-induced global-mean rise in sea level of 16–38 centimeters (cm) by 2050 (Table 3).

Tropical Cyclone Intensity

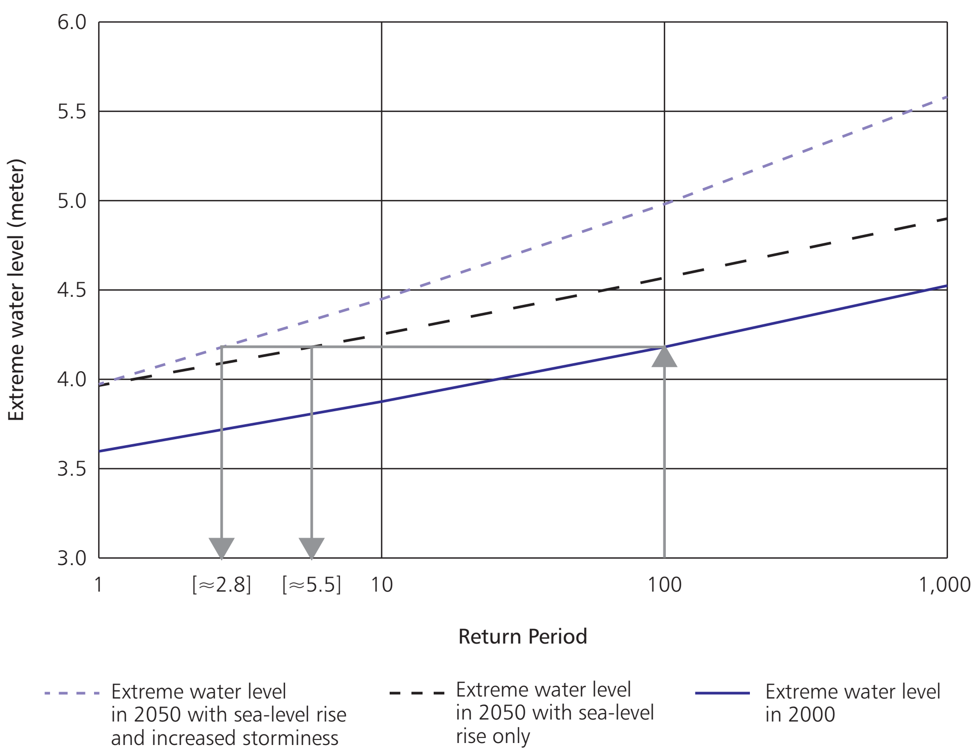
An intensification of tropical cyclones (or storms) in those areas of the world that currently experience such storms is of widespread concern (Meehl et al. 2007; Nicholls et al. 2007b). As there is no scientific consensus as to whether storms will or will not intensify, in this study, increased storminess is included in terms of a uniform increase of extreme water levels where tropical cyclones affect coasts in addition to mean sea-level rise with the largest changes for the most extreme events. Therefore, extreme water level events with return periods of 1-in-10 year, 1-in-100 year, and 1-in-1,000 year increase linearly by 5%, 10%, and 15%, respectively, by 2050 compared to 2000, following the assumptions in the EACC study (Figure 3). This method means that the lower the probability of the event, the greater the increase in extreme water level. This differs from the effect of sea-level rise on extreme water levels, which is uniform across return periods.

Table 3 **Climate-Induced Global-Mean Sea-Level Rise Scenarios**
(in centimeters above 1990 levels)

	Scenario			
Year	No Change	Low	Medium	High
2010	0.0	+4.0	+6.6	+7.1
2020	0.0	+6.5	+10.7	+12.3
2030	0.0	+9.2	+15.5	+18.9
2040	0.0	+12.2	+21.4	+27.1
2050	0.0	+15.6	+28.5	+37.8

Source: Nicholls et al. (2010).

Figure 3 **Change in the Distribution of Extreme Water Levels in Shanghai**
(DIVA segment 2366)[a]



[a] The change takes into account an increase in mean sea level (high scenario) and increase in tropical storm intensity (high with cyclones scenario).

Source: Authors.

In effect, this is a guided sensitivity analysis, which gives an indication of the impact and costs of this change by influencing dike costs and residual flood damage. Note that the impacts of increased wind speeds are not considered here; the only impact considered is the higher water levels.

Population and Gross Domestic Product Scenarios

Many existing studies assume the current level of coastal development when estimating impact and adaptation costs for both the near and medium term. However, growing wealth and population is driving increased coastal development at the global scale, as already noted earlier. In turn, this will change the impact of climate change on countries' economies, the type and extent of adaptation required, and their capacity to adapt. Population and GDP scenarios were, therefore, developed for each country by Prof. Gordon Hughes of the University of Edinburgh. These improve on the earlier EACC scenarios and use the best available data in 2011; projections of growth rates and population composition are consistent with the growth rates, age composition, and urbanization rates in the UN Population Division's 2010 Medium Fertility scenario and the 2009 *World Urbanization Prospects* (UNDP 2011 and 2010). Here, the scenarios were analyzed at the national level for Japan and the Republic of Korea, and province level for the PRC. The scenarios show a decline in population over time in all three countries considered (Table 4), although there are exceptions at the province level in the PRC, most notable in Guangdong. This reflects migration to these provinces. Human exposure to sea-level rise and marine events in general, therefore, commonly declines over time, with exceptions. However, GDP per capita grows substantially over the same period, especially in the PRC. By 2050, Shanghai's GDP per capita is the highest in the region, overtaking both Japan and the Republic of Korea. Full details of the population and GDP scenarios can be found in Appendix 1.

Table 4 **National Population and Gross Domestic Product for the People's Republic of China, Japan, and the Republic of Korea, 2010 and 2050**

	Population (millions)		**GDP** ($ billion)	
	2010	**2050**	**2010**	**2050**
People's Republic of China	1,388.7	1,296.5	8,382.6	47,722.2
Japan	127.2	102.4	3,877.0	5,062.9
Republic of Korea	48.0	47.0	1,151.7	2,320.9

GDP = gross domestic product.

Source: Authors.

Scenario Combinations

The scenario combinations that are considered are summarized in Table 5. The "No change" scenario allows for the exploration of the evolving baseline of no climate change, and includes only vertical land movement and socioeconomic change. If the incremental costs of sea-level rise and climate change alone are required, then the costs for the "No change" scenario need to be removed.

It is important to note that these scenarios are not an attempt to represent the most likely outcomes. Rather they represent plausible, interesting, and useful futures to explore in an exercise of understanding adaptation planning and investment needs in the coastal zones of these countries under uncertainty.

Table 5 **Scenario Combinations Used in this Study**

Scenario	Sea-Level Scenario	Vertical Land Movement	Increased Storminess of Cyclones	Population and GDP Growth
No change	No change	Yes	No	Yes
Low	Low	Yes	No	Yes
Medium	Medium	Yes	No	Yes
High	High	Yes	No	Yes
High (with cyclones)	High	Yes	Yes	Yes

GDP = gross domestic product.

Source: Authors.

Impact Calculations

The following impacts are considered in this study:

- Coastal wetland loss (in km^2/year),
- Dryland loss due to erosion or submergence (in km^2/year), and
- Forced migration due to erosion or submergence (in thousands/year).

To estimate these impacts, wetland loss, beach erosion, and sea flooding need to be assessed for the relevant scenarios.

DIVA calculates coastal wetland loss by considering the effect of three interacting drivers, which are (i) sea-level rise (scaled by tidal range), (ii) sediment supply, and (iii) accommodation space (McFadden et al. 2007). Rather than model-detailed processes, wetland change is described using a behavior-orientated model akin to the Bruun Rule and ASMITA[15] model for erosion described below. For the wetlands in each segment, a series of scores are estimated for each driver as a function of the different scenarios. This includes the presence or absence of dikes that hinder the onshore migration of wetlands, where they exist, leading to coastal squeeze. Each wetland-type loss was calibrated against available results from the landscape modeling literature (McFadden et al. Forthcoming).

For long-term coastal erosion due to sea-level rise, both the impacts of direct and indirect effects are assessed (Nicholls et al. 2011a; Hinkel et al. (Forthcoming).[16] The direct effect of sea-level rise on coastal erosion is estimated using the Bruun Rule (Zhang et al. 2004). While the Bruun Rule ignores processes, such as long-shore drift, it is considered appropriate here as the average retreat for a coastal segment is being calculated. Erosion is only calculated for sandy coasts. The length of sandy beaches was taken directly from the DIVA database for the PRC, with improved data for Japan based on Uda (2010), and improved data for the Republic of Korea using expert judgment. Sea-level rise also affects coastal erosion indirectly as tidal basins become sediment sinks under rising sea level, trapping sediments from the nearby open coast into tidal basins (Stive 2004). This indirect erosion is also calculated where appropriate using a simplified version of the ASMITA model (Van Goor et al. 2003; Stive et al. 1998). This analysis considers five tidal basins in Japan and three

[15] Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast (ASMITA).

[16] No sediment addition or removal from outside the coastal segment is considered. In this analysis, the available sediment is redistributed.

tidal basins in the PRC. For a more detailed account of the erosion impact methods, see Nicholls et al. (2011a) and Hinkel et al. (Forthcoming).

Inundation and flooding of the coastal zone caused by mean sea-level rise and associated storm surges is assessed for sea floods. Due to the difficulties of predicting changes in storm surge characteristics due to climate change (Von Storch and Woth 2008) and following 20th century observations (Menendez and Woodworth 2010), extreme sea-level events produced by a combination of storm surges and astronomical tides were raised uniformly across all return periods by mean sea-level rise over the 20th century. In addition, due to the possibility of more intense tropical cyclones, the High (with cyclones) scenario increases the water levels of rare events more than those of frequent events, as explained in the section on Tropical Cyclone Intensity (p. 10). Figure 3 illustrates the High and High (with cyclones) scenarios using this method for Shanghai in 2050.

The DIVA model assumes the construction and upgrade of dikes as the adaptation option for inundation and flooding, drawing on the experience of Deltares, including its application in the global analysis of Hoozemans et al. (1993). This includes defining the base state in 1995. Since there is no empirical data on actual dike heights available at a global level, a demand for safety is computed, and the required safety level is assumed to be provided by dikes (Tol and Yohe 2007; Tol 2006). This function was derived econometrically based on observed protection levels in Europe (Tol 2006). This function increases with per capita income and population density, reflecting that as societies grow richer and population density increases, the demand for safety rises and higher dikes are built. Hence, baseline dike standards represent a scenario rather than an observation, and calculations are not based on a benefit–cost analysis. This analysis also assumes that there is no adaptation deficit.

The dikes are provided as follows: where there is very low population density ($<$ 1 person/km^2) there are no dikes. Above this population threshold, an increasing proportion of the demand for safety is provided. Half of the demand for safety is applied at a population density of 20 persons/km^2, and 90% at a population density of 200 persons/km^2. This is similar to providing isolated dikes around individual settlements at lower population densities and more continuous dikes at higher population densities. Based on the selected dikes, land elevations, relative sea level, including more extreme sea levels if appropriate, the frequency of flooding is estimated over time. This is further converted into flooded people and economic flood damages based on population density and GDP. Flood damages still occur where dikes are in place (representing residual flood risk) as the potential for some flooding still exists. For a more detailed presentation of the flooding model, see Tol (2006).

If sandy beaches and flood plain occur in the same coastal segment, then both erosion and flood impacts occur. Further nourishment and dike construction and/or upgrade can both be applied as adaptation measures in the same segment.

DIVA translates all these physical changes into social and economic consequences. Social consequences are expressed in terms of various indicators. The indicator "forced migration" gives the number of people that have to migrate away from the areas of dryland, which have been permanently lost due to erosion and submersion. To determine the number of people displaced by flooding, a flood frequency threshold is required; in this analysis it is assumed that all land areas subject to flooding more than once per year are abandoned by people.

The economic consequences are expressed in terms of damage and adaptation costs (see discussion on Cost Calculations, p. 15). The cost of (dry) land loss is estimated based on land-use scenarios and the assumption that only agricultural land is lost. Agricultural land has the lowest value and it is assumed that if land used for other purposes (e.g., industry or housing) is lost then those usages would move and displace agricultural land. The value of agricultural land is a function of income density. If all the agricultural land has been lost, then the losses are being underestimated and the land loss values calculated are minimum estimates. The cost of extreme flood events is calculated as the expected value of damages to assets (buildings and infrastructure) based on a damage function logistic in flood depth. The costs of migration are calculated based on an estimate of the loss of GDP per capita. For a more detailed account of the valuation of impacts, see Tol (2006).

Cost Calculations

The costs evaluated in this study are shown in Table 6. All these results are developed with the global DIVA model of impacts and adaptation to sea-level rise.

With no adaptation undertaken, potential impacts are assessed in a traditional impact analysis manner. For example, existing dikes (as estimated by DIVA for 1995) are maintained, but not raised, so flood risk rises with time as relative sea level rises. With adaptation undertaken, dikes are progressively raised, based on the demand function for safety already described.[17] The incremental costs of dike construction are then determined. Both rising sea levels and rising wealth (and hence, lower risk tolerance) lead to higher dikes. Explicit in these calculations is the assumption that all existing dikes can be raised incrementally. The unit costs for dikes are provided by Hoozemans et al. (1993) who developed a national set of dike costs of $3 million per km per meter height rise for the PRC, $2.7 million for Japan, and $8.4 million for the Republic of Korea.

For this analysis, the demand function for safety was modified to also include the design life of dike and flood defense infrastructures in general. This reflects the fact that it is prudent for a society or country to anticipate future sea-level rise so that the desired level of protection is realized over the lifetime of the defense infrastructure (Nicholls et al. 2010). A 50-year design life is assumed in the analysis, which means that for each segment and in each 5-year time step, sea-level rise is anticipated 50 years ahead by extrapolating the rate of local sea-level rise linearly into the future.[18] In other words, the "observations" available from 2045 to 2050, for example, drive the decision in 2050 to upgrade dikes to a level that would satisfy the society's demand for safety in 2100. If sea-level rise accelerates, the raised dikes would have a shorter life than 50 years.

The adaptation analysis also develops a stock of dikes that require maintenance and operation; avoiding these costs leads to deterioration and an increasing likelihood of failure. Nicholls et al.

Table 6 **Impacts and Adaptation Responses within the Dynamic Interactive Vulnerability Assessment as Costed in this Study**

Sea-Level Rise Effect	Impact Costs	Adaptation Response Costs
(Long-term) Beach erosion	Land loss Forced migration	Beach/shore nourishment
Increased flooding due to storm surges	Expected annual flood damage	Sea dikes, including maintenance
Submergence	Land loss Forced migration	Sea dikes, including maintenance

Source: Authors.

[17] In the PRC, Japan, and the Republic of Korea, dike-raising is the only option as all flood-prone coasts are assumed to be defended today due to their high population density.

[18] This assumption differs from the EACC study where acceleration in sea level is considered and, hence, bigger dikes were built at greater cost (Nicholls et al. 2011a).

(2010) found that these costs are approximately 1% of capital stock per year for sea dikes and this factor is applied in DIVA (see Appendix 2 for more details). Note that as the stock of dikes grows over time, maintenance and operation costs grow in importance. The costs reported here only reflect the maintenance cost of the dikes built since 2010, i.e., they are the incremental maintenance and operation costs only.

DIVA includes beach and/or shore nourishment to replace eroded sand as an adaptation option for coastal erosion. The unit costs of nourishment depend on the likely availability of sand, rising with scarcity. In beach nourishment, the sand is placed directly on the intertidal beach, while in shore nourishment the sand is placed below low tide in the active zone where the sand will progressively feed onshore due to wave action, following current Dutch practice (Van Koningsveld et al. 2008). Shore nourishment is cheaper than beach nourishment, but the benefits are not felt immediately. The maximum costs of beach nourishment are \$14.9 per cubic meter (m^3) while for shore nourishment, they are \$11.6/m^3 (at 2005 prices). Nourishment follows a cost–benefit analysis that balances costs and benefits (in terms of avoided damages to land, residents, and tourism) of protection (Nicholls et al. 2011a). Beach nourishment is the preferred adaptation option, but only if the tourism revenue is sufficient to justify the additional costs. Otherwise, (the lower cost) shore nourishment or no nourishment is followed. Tourism revenues are derived from the Hamburg Tourism Model (HTM Version 1), an econometric model of tourism flows that includes the effects of changes in population, GDP, and climate (Hamilton et al. 2005a and 2005b). For a more detailed account of the adaptation methods for erosion, see Nicholls et al. (2011a) and Hinkel et al. (Forthcoming).

Port Upgrade Costs

The volume of seaborne trade tripled globally over 30 years (UNCTAD 2008) and despite the contraction in trade since 2008 (UNCTAD 2010), ports will need to adapt their infrastructure to changes in sea levels to maintain their future role in the global supply chain. This part of the investigation aims to estimate the costs associated with port adaptation to sea-level rise—with adaptation here to mean the raising of existing port ground level to maintain relative elevation to mean sea level (IPCC CZMS 1990a). This maintains the port operational areas at an appropriate elevation relative to the local tidal regime. Based on discussions with port operators and as evidenced by the recent raising of port areas in parts of Japan following significant subsidence of up to 1 meter during the 2011 Tōhoku earthquake, this is a reasonable approach.

The estimated costs do not include explicit cost and/or benefit considerations; it is assumed that these strategic and valuable areas will need to be maintained to 2050 (and beyond). Only cost estimates associated with maintaining current port areas in response to relative sea-level rise projected to 2050 are included. The expansion of port areas is likely to be significant, but is not considered here. Rather, any new development is assumed to be designed for future changes in sea level to 2050 (or these can be seen as minimum costs).

Ports were selected from Lloyds List's Ports of the World (Lloyds List 2009). Any port that reported tidal data, including those located on rivers, was included in the analysis. The IPCC CZMS (1990a) methodology estimated the global costs of protection against a 1-meter rise in sea level. As primary data on port areas were limited, a methodology based on statistics of the tonnage moved was developed to estimate area of the port, which would require raising. The unit cost estimates (in US dollars) are based on those used in the IPCC CZMS (1990a) report and are resolved at the country level (updated to 2005). They represent a one-time raising of the port; the costs are annualized over the 40-year duration of the assessment. Full details of the methodology and data sources can be found in Appendix 2, section on Port Upgrade. Note that costs of damage to port areas are not evaluated.

3. Results

This chapter outlines the results of the analyses at the country level for the People's Republic of China (PRC), Japan, and the Republic of Korea, and provides the results at the coastal province level for the PRC (Figure 1). The monetary results are all reported in 2005 United States dollars with no discounting.

In general terms, the damage costs associated with flooding, land loss, and forced migration (due to both erosion and submergence) are large, especially if the higher sea-level rise scenarios are realized. However, this damage is reduced substantially by protection measures, such as sea dikes and beach nourishment. Therefore, understanding the feasibility of adaptation in these countries is fundamental. Further, the PRC has substantially higher damages than the other two countries, largely reflecting the higher number of people within the coastal zone, the longer length of coast, the lower defense standards, and the presence of extensive subsiding coastal deltaic lowlands (Figure 1). In these deltas, subsidence enhances the rates of relative sea-level rise, as noted in the section on Relative Sea-Level Scenarios (see p. 10).

Damage Indicators

The nonmonetary damage indicators used in this study are land (both dryland and wetland) loss and forced migration.

Land Loss

All three countries experience dryland loss (due to a combination of submergence and erosion) and wetland loss under all scenarios, with and without adaptation. Dryland losses are reduced by protection (Table 7), while for wetland losses, no adaptation is considered and losses are essentially independent of adaptation choices (Table 8). Average annual loss rates increase with the sea-level scenario resulting in substantial losses by 2050. In absolute terms, dryland loss is greatest in the PRC and smallest in the Republic of Korea, assuming no adaptation is undertaken. This reflects the situation that the Republic of Korea lacks sandy beaches and submergence is not expected to be

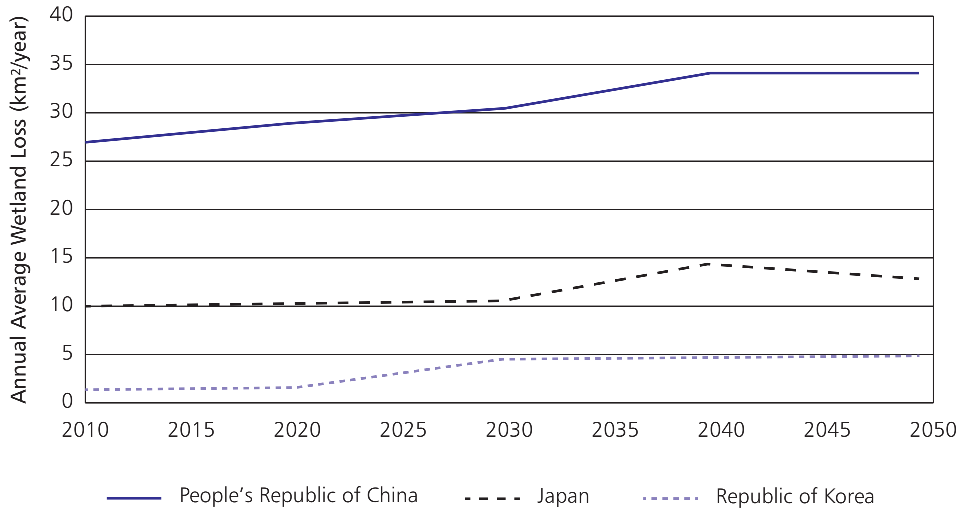
Table 7 **Average Annual Rates of Dryland and Wetland Losses for the People's Republic of China under All Scenarios, 2010–2050** (km^2/year)

	With Adaptation			Without Adaptation		
	Dryland			Dryland		
Scenario	Erosion	Submergence	Wetland	Erosion	Submergence	Wetland
High (with cyclones)	1.13	0.01	36.32	2.54	63.10	36.32
High	1.13	0.01	36.32	2.54	63.10	36.32
Medium	0.92	0.01	30.79	2.23	26.84	30.79
Low	0.74	0.00	25.91	1.82	0.00	25.91
No change	0.53	0.00	5.48	1.33	0.00	5.48

km^2 = square kilometer.

Source: Authors.

Figure 4 **Average Annual Rates of Wetland Loss Over Time under the Medium Scenario**



km^2 = square kilometer.

Source: Authors.

Table 8 **Coastal Wetland Areas Over Time, by Country, for All Scenarios** (km^2)

Scenario	Country	Time 2010	2020	2030	2040	2050
High (with cyclones)	People's Republic of China	5,806.45	5,520.57	5,192.32	4,796.63	4,309.20
	Japan	1,640.38	1,532.19	1,376.37	1,228.16	1,072.82
	Republic of Korea	827.45	785.67	741.46	695.28	647.52
High	People's Republic of China	5,806.45	5,520.57	5,192.32	4,796.63	4,309.20
	Japan	1,640.38	1,532.19	1,376.37	1,228.16	1,072.82
	Republic of Korea	827.45	785.67	741.46	695.28	647.52
Medium	People's Republic of China	5,806.55	5,522.14	5,221.60	4,897.78	4,556.12
	Japan	1,640.85	1,539.50	1,431.98	1,308.51	1,175.58
	Republic of Korea	827.45	811.47	765.79	718.02	668.63
Low	People's Republic of China	5,915.43	5,667.62	5,403.95	5,129.90	4,842.70
	Japan	1,674.88	1,572.26	1,469.86	1,373.06	1,283.10
	Republic of Korea	827.47	811.51	793.22	772.58	749.55
No change	People's Republic of China	6,126.93	6,081.50	6,028.81	5,968.47	5,900.33
	Japan	1,788.89	1,788.00	1,787.05	1,786.06	1,785.02
	Republic of Korea	847.34	847.34	847.34	847.34	847.34

km^2 = square kilometer.

Source: Authors.

significant as low-lying areas are limited. With adaptation measures, Japan has the largest land losses, indicating that in many areas prone to erosion, nourishment is not applied.

All three countries show a decline in wetland areas under all scenarios with the PRC having the highest rates of loss over the 40-year period under all scenarios (Figure 4 and Table 8). This largely reflects that the PRC has the largest stock of wetlands, which are often located in large subsiding deltas. In relative terms, the largest losses are in Japan, except under the "No change" scenario.

Within the PRC, Shandong, Jiangsu, and Guangdong provinces have the highest average annual rates of wetland decline across all the scenarios including no sea-level rise, as these provinces are subject to subsidence. As already noted, wetland area loss is not affected by the adaptation options considered here, and wetland loss is not costed in this study. However, these losses do have costs due to the loss of ecosystem services and there are implications for future management options. For instance, the buffering function of existing wetland areas on flood waters and waves reduces the need for engineered management. This effect is not evaluated here. There are also reasons other than sea-level rise for coastal wetland loss. For example, land reclamation has been significant in all three countries up to the present[19] and this may be expected to continue in the next few decades. On the other hand, there is a growing aspiration to conserve wetland areas across all countries and this may influence coastal management approaches in all three countries over the next 40 years

Table 9 **Cumulative Forced Migration and Associated Costs of Migration, 2010–2050**

		With Adaptation				No Adaptation			
		Number of People ('000)		Cost ($ million)		Number of People ('000)		Cost ($ million)	
Scenario	Country	E	S	E	S	E	S	E	S
High (with cyclones)	People's Republic of China	26	0	2,137	0	80	974	14,207	138,554
	Japan	36	0	4,071	0	62	2	7,625	219
	Republic of Korea	3	0	286	0	4	0	496	58
High	People's Republic of China	26	0	2,137	0	80	974	14,207	138,554
	Japan	36	0	4,071	0	62	2	7,625	219
	Republic of Korea	3	0	286	0	4	0	496	58
Medium	People's Republic of China	21	0	1,503	0	69	424	10,936	75,157
	Japan	30	0	3,438	0	54	0	6,651	0
	Republic of Korea	2	0	195	0	3	0	347	0
Low	People's Republic of China	17	0	881	0	55	0	7,185	0
	Japan	23	0	2,644	0	43	0	5,369	0
	Republic of Korea	1	0	85	0	2	0	166	0
No change	People's Republic of China	14	0	536	0	40	0	3,583	0
	Japan	16	0	1,930	0	32	0	4,066	0
	Republic of Korea	0	0	0	0	0	0	0	0

E = due to erosion, S = due to submergence.

Source: Authors.

[19] See http://en.wikipedia.org/wiki/Land_reclamation

(Nicholls et al. 2011c; Nicholls et al. 2008b). Hence, coastal wetland losses are driven by much more than sea-level rise and this wider context of change must be considered.

Land loss due to erosion has economic consequences, both due to a loss of productive land and forced migration of the resident population. The annual rates of these losses vary between "with adaptation" and "without adaptation" scenarios and result in significant total losses by 2050 in each country (Table 9). Under the "No change" scenario, some land loss still occur due to relative sea-level rise arising from subsidence.

Within the PRC, the highest rates of land loss due to erosion are found in Guangxi Province under all scenarios (Table 10). Adaptation (representing beach and/or shore nourishment) reduces the average annual rate of erosion and the largest effect can be found in the provinces of Guangdong and Guangxi (e.g., from 0.86 km^2/year to 0.36 km^2/year under the "Medium" scenario in Guangxi).

Forced Migration

Forced migration occurs when land is no longer habitable whether due to erosion or permanent submergence (Table 10). Assuming no adaptation was undertaken, the highest number of people forced to move are in the PRC where it is estimated that up to 1 million people could be displaced over the next 40 years for the "High" scenario, largely due to submergence. The higher defense standards in Japan and the Republic of Korea mean that there is no forced migration due to submergence, even "without adaptation." Erosion results in smaller numbers of displaced people—up to 80,000 for the PRC, 62,000 for Japan, and 4,000 for the Republic of Korea over the next 40 years for the "High" scenario, assuming no adaptations were undertaken. These numbers are

Table 10 **Average Annual Rates of Dryland Loss and Forced Migration Due to Submergence and Erosion for the Medium Scenario, 2010–2050**

	With Adaptation				No Adaptation			
	Land Loss (km^2/year)		Forced Migration ('000/year)		Land Loss (km^2/year)		Forced Migration ('000/year)	
Location	Submergence	Erosion	Submergence	Erosion	Submergence	Erosion	Submergence	Erosion
Japan	0.08	2.79	0.00	0.75	0.08	3.32	0.00	1.35
Republic of Korea	0.00	0.15	0.00	0.04	0.00	0.15	0.00	0.08
People's Republic of China	0.01	0.92	0.00	0.53	26.84	2.23	10.60	1.73
People's Republic of China, by Coastal Province/Autonomous Region/Municipality								
Fujian	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Guangdong	0.00	0.22	0.00	0.25	1.84	0.67	2.20	0.87
Guangxi	0.00	0.36	0.00	0.13	0.00	0.86	0.00	0.27
Hainan	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hebei	0.00	0.15	0.00	0.07	0.00	0.21	0.00	0.12
Jiangsu	0.00	0.01	0.00	0.01	0.00	0.04	0.00	0.04
Liaoning	0.00	0.03	0.00	0.01	24.99	0.04	8.40	0.01
Shandong	0.00	0.13	0.00	0.04	0.00	0.22	0.00	0.08
Shanghai	0.01	0.01	0.00	0.02	0.01	0.09	0.00	0.17
Tianjin	0.00	0.00	0.00	0.01	0.00	0.06	0.00	0.09
Zhejiang	0.00	0.01	0.00	0.01	0.00	0.04	0.00	0.07

km^2 = square kilometer.

Source: Authors.

substantially reduced by adaptation measures, particularly in the PRC where these figures are reduced by 66% due to protection in the form of nourishment.

Note that tropical cyclones have no effect on forced migration as inundation associated with these storms is temporary and populations are able to return to impacted areas after the event.

Damage Costs

Tables 11 and 12 report the damage costs of "with adaptation" and "without adaptation" across land loss (erosion only), forced migration, and flood damage. Table 11 presents the "medium" scenario, while Table 12 presents all the scenarios. The results show a number of points, as follows:

- The PRC in general experiences the highest damages, especially without adaptation being undertaken;
- Flooding generally produces the largest damages, again especially without adaptation measures;
- Forced migration has large costs without adaptation measures, but with adaptation these costs are significantly reduced, with all costs being due to erosion;
- Adaptation greatly reduces the damage, most especially flood damage; and
- Consideration of more intense cyclones increases flood damages, especially in the PRC.

Table 11 **Average Annual Damage Costs under the Medium Scenario With and Without Adaptation, 2010–2050** ($ million/year)

	With Adaptation			Without Adaptation		
Location	Land loss	Forced Migration	Flood	Land Loss	Forced Migration	Flood
Japan	1.53	85.96	0.00	2.13	166.28	488.95
Republic of Korea	0.13	4.87	0.00	0.15	8.69	609.64
People's Republic of China	0.65	37.57	16.45	2.91	2,152.33	33,522.80
People's Republic of China, by Coastal Province/Autonomous Region/Municipality						
Fujian	0.00	0.00	1.03	0.00	0.00	415.43
Guangdong	0.30	14.42	0.70	1.39	518.05	2,463.26
Guangxi	0.12	1.55	3.51	0.35	5.79	20.80
Hainan	0.00	0.00	0.47	0.00	0.05	11.41
Hebei	0.06	3.62	2.47	0.12	7.57	323.10
Jiangsu	0.01	0.89	3.44	0.09	7.52	13,200.71
Liaoning	0.02	0.82	4.77	0.02	1,461.04	755.84
Shandong	0.06	3.14	0.06	0.17	8.70	681.09
Shanghai	0.05	9.94	0.00	0.54	106.07	8,578.61
Tianjin	0.01	1.80	0.00	0.11	24.37	5,710.74
Zhejiang	0.02	1.38	0.00	0.12	13.17	1,361.80

Note: Land loss costs apply to erosion only.

Source: Authors.

Table 12 **Average Annual Damage Costs at National Level for All Scenarios With and Without Adaptation, 2010–2050** ($ million/year)

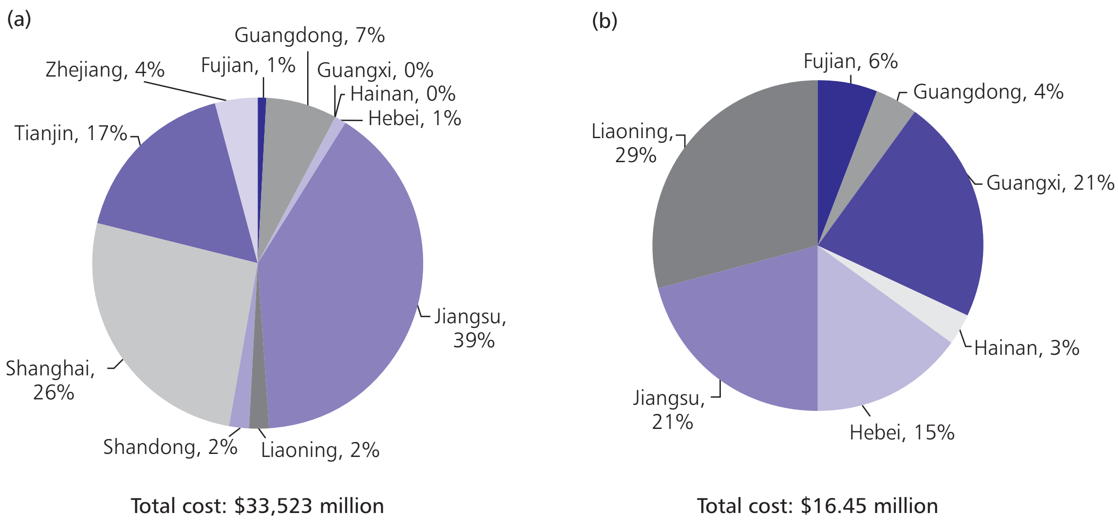
Scenario	Country	With Adaptation			Without Adaptation		
		Land Loss	Forced Migration	Flood Damage	Land Loss	Forced Migration	Flood Damage
High (with cyclones)	People's Republic of China	0.82	53.43	83.31	3.50	3,819.03	48,943.86
	Japan	1.83	101.78	0.00	2.50	196.10	922.40
	Republic of Korea	0.19	7.15	25.80	0.22	13.84	1,091.46
High	People's Republic of China	0.82	53.43	13.91	3.50	3,819.03	37,768.60
	Japan	1.83	101.78	0.00	2.50	196.10	601.31
	Republic of Korea	0.19	7.15	0.00	0.22	13.84	680.95
Medium	People's Republic of China	0.65	37.57	16.45	2.91	2,152.33	33,522.80
	Japan	1.53	85.96	0.00	2.13	166.28	488.95
	Republic of Korea	0.13	4.87	0.00	0.15	8.69	609.64
Low	People's Republic of China	0.49	22.03	109.22	2.21	179.62	29,150.65
	Japan	1.15	66.10	0.00	1.66	134.21	310.04
	Republic of Korea	0.07	2.13	3.94	0.08	4.14	494.87
No change	People's Republic of China	0.32	13.40	480.33	1.43	89.58	23,245.33
	Japan	0.71	48.26	12.27	1.11	101.65	30.61
	Republic of Korea	0.00	0.00	140.70	0.00	0.00	439.63

Note: Land loss costs apply to erosion only.

Source: Authors.

Among the provinces of the PRC, Guangdong, Tianjin, and especially Shanghai and Jiangsu, are most impacted under a "medium" scenario if no adaptation measures are undertaken (Figure 5). With adaptation measures, the impacts are greatly reduced with the projected sea-flood costs for some provinces expected to be minimal.

Figure 5 **Distribution of Average Annual Sea-Flood Costs (a) Without Adaptation and (b) With Adaptation for the Coastal Province/Autonomous Region/Municipality of the People's Republic of China under the Medium Sea-Level Scenario, 2010–2050**



Note: Some provinces are expected to have minimal sea-flood costs with the projected levels of protection and, therefore, do not appear in (b).

Source: Authors.

Future Adaptation Costs

Sea Dikes and Beach Nourishment

By 2050, at the national level for the three countries considered, cumulative adaptation costs under the climate-affected scenarios range from $81,893 million (low) to $298,001 million (high, with cyclones). The average annual rates are shown in Table 13.

For the coastal provinces of the PRC, average annual adaptation costs are highest in the province of Guangdong (Figure 6), but all provinces incur significant adaptation costs. The province of Tianjin has the lowest adaptation costs.

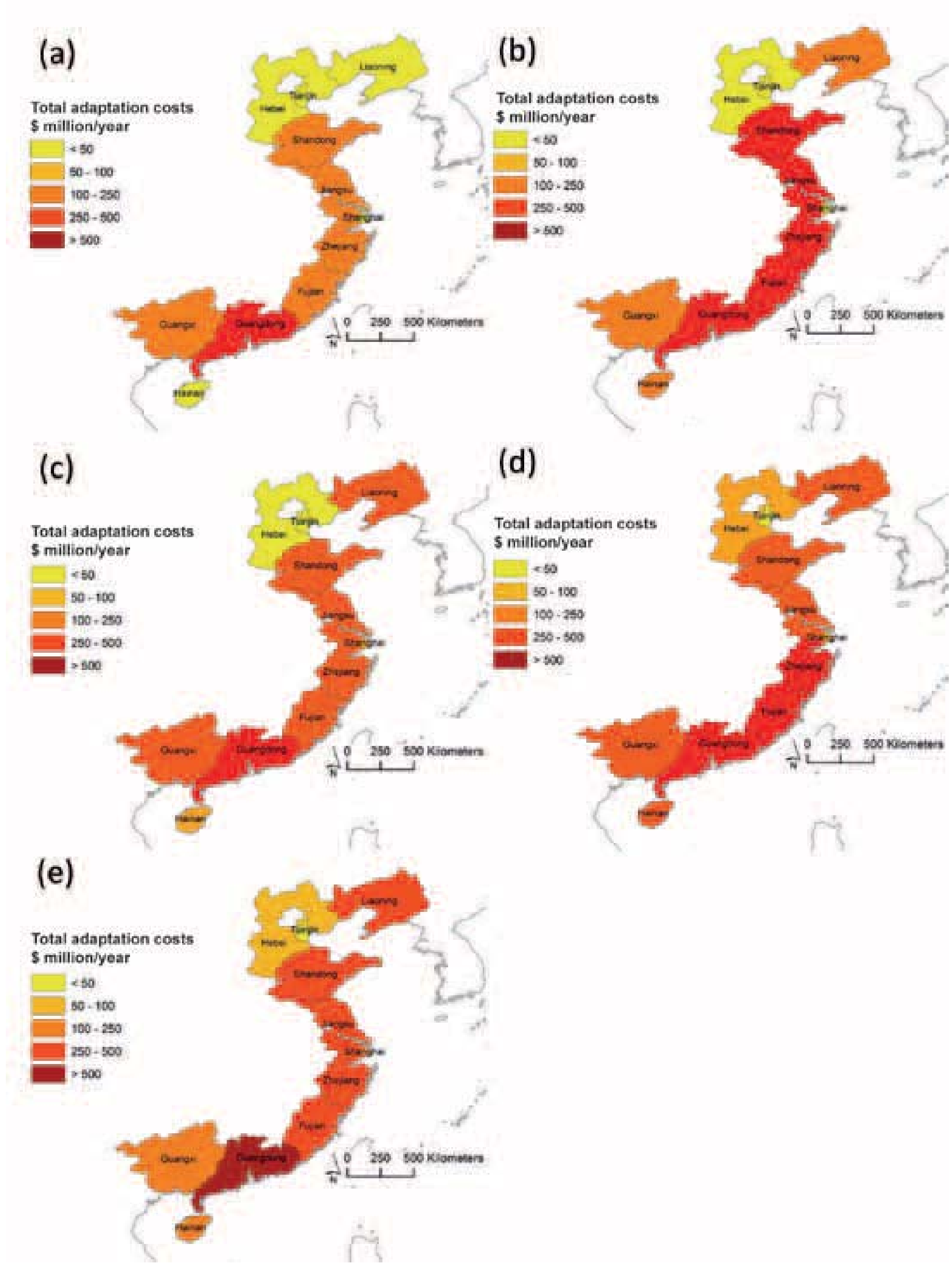
Table 13 **Average Annual Adaptation Costs under All Scenarios, 2010–2050** ($ million/year)

	Scenario				
Location	No Change	Low	Medium	High	High (with Cyclones)
Japan	100.55	542.17	1,059.36	1,591.21	2,234.65
Republic of Korea	119.21	407.13	734.81	1,074.19	2,021.47
People's Republic of China	627.01	1,048.11	1,527.69	2,008.89	3,012.20

Notes: Costs are beach nourishment, sea dike upgrade, and incremental sea dike maintenance costs post-2010. Port upgrade costs are not included.

Source: Authors.

Figure 6 Average Annual Total Adaptation Costs for the Coastal Province/Autonomous Region/Municipality of the People's Republic of China under (a) No Change, (b) Low, (c) Medium, (d) High, and (e) High with Cyclones Scenarios, 2010–2050



Notes: Total adaptation includes beach nourishment, sea-dike upgrade, and incremental sea-dike maintenance costs post-2010. Port upgrade costs are not included.

Source: Authors.

The estimated adaptation costs under a scenario of "No change" reflect improved dikes driven both by rising wealth and non-climate-induced relative sea-level rise, and to a lesser extent, by beach nourishment due to non-climate-induced relative sea-level rise (Table 14). In part, this indicates that the demand for safety function (Tol 2006; Tol and Yohe 2007) increases due to growing wealth and/or population density without a rise in sea levels. This is consistent with observed changing attitudes to risk during the 20th century where living standards rose substantially. High adaptation costs under the "No change" scenario are noted in the PRC provinces containing deltas, such as Guangdong Pearl River delta, Jiangsu/Zhejiang Yangtze River delta, and Shandong Yellow River delta (Table 14). The estimated costs of a "No change" scenario should not be confused with the costs of all coastal management, which are unknown, but expected to be much higher, as discussed further on p. 34.

Under all scenarios with climate change, the adaptation costs are dominated by the capital cost for sea dikes, although its contribution to total costs decreases over time (Figure 7). The capital costs of dikes are significant, in part reflecting the 50-year planning horizon for dike upgrade considered in this study. Incremental maintenance costs increase over time as the stock of new and/or upgraded sea dikes increases. The costs of beach nourishment are minor in comparison, and in the Republic of Korea, they are almost negligible.

As noted earlier, there are still residual damage costs even when adaptation is undertaken (Table 14), but these costs are greatly reduced with adaptation for all climate change scenarios.

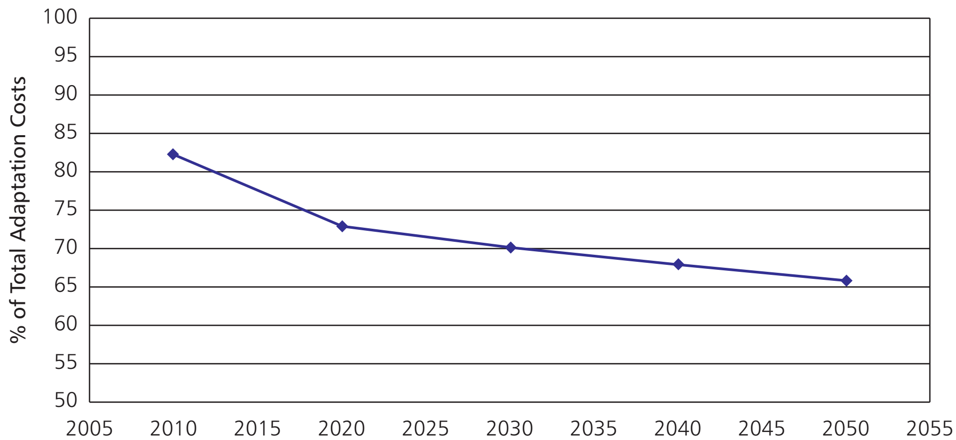
Table 14 **Average Annual Costs of Adaptation for Coastal Protection and Residual Damage Costs (Land Loss and Flood Damages) under the Medium Sea-Level Rise Scenario, 2010–2050** ($ million/year)

Location	Residual Damages	Beach Nourishment Costs[a]	Sea Dike Costs		Total Adaptation Costs[a+b+c]
			Capital[b]	Maintenance[c]	
Japan	1.53	56.42	709.77	293.16	1,059.36
Republic of Korea	0.13	0.71	516.50	217.60	734.81
People's Republic of China	17.10	145.98	963.53	418.19	1,527.69
People's Republic of China, by Coastal Province/Autonomous Region/Municipality					
Fujian	1.03	0.00	129.39	54.02	183.41
Guangdong	0.99	52.05	202.98	89.68	344.70
Guangxi	3.63	63.33	36.64	14.98	114.95
Hainan	0.47	0.46	68.13	27.11	95.71
Hebei	2.53	4.13	27.92	12.97	45.03
Jiangsu	3.45	2.94	121.04	54.78	178.77
Liaoning	4.79	0.90	96.17	40.62	137.68
Shandong	0.13	6.49	115.74	51.12	173.35
Shanghai	0.05	8.64	28.53	14.01	51.18
Tianjin	0.01	3.29	8.88	4.27	16.44
Zhejiang	0.02	3.75	128.10	54.63	186.48

Note: Land loss costs apply to erosion only.

Source: Authors.

Figure 7 **Change in the Percentage of Total Adaptation Costs to Capital Dike Costs for Fujian, People's Republic of China under the Medium Scenario**



Source: Authors.

At the province level in the PRC, adaptation costs are highest in the province of Guangdong, which consistently has the second highest expenditure on beach nourishment and the highest dike costs, amounting to an average adaptation cost of $435 million/year for the medium scenario (Table 14).

When comparing adaptation costs across scenarios, it is interesting to examine the influence of the "High (with cyclones)" scenario (Table 15). This raises extreme water levels compared to the "High" scenario and, hence, triggers dike-raising action to maintain safety. The resulting cost increase for adaptation in these three countries is significant. Compared to the "High" scenario, dike capital costs increase by 90% for the Republic of Korea, 42% for Japan, and 57% for the PRC. The PRC registers the largest absolute increase in dike capital costs. Dike maintenance costs are increased to a similar degree, and hence, the overall effect on adaptation costs is large (Table 16). This is an important message for policy makers and planners in the national planning of adaptation options.

Port Upgrade

The basic data was derived from the Lloyds List *Ports of the World 2009* directory (Lloyds List 2009). This contains information on 235 ports located in the three countries covered by this study, of which 81 ports have traffic data and were analyzed for upgrade costs (Table 17). Full details of the port upgrade methodology are included in Appendix 2, p. 42.

Nationally, the PRC has the largest annual costs, with the Republic of Korea having the smallest annual costs, reflecting the relatively small port area that was estimated and lower unit costs. Compared to adaptation costs due to dikes and nourishment, port upgrade costs are minor in the Republic of Korea (up to 3% of total costs), but are much more significant in the PRC (up to 20% of total adaptation costs). They are more important in relative terms than the earlier EACC results where they were less than 2% of national investment costs (Nicholls et al. 2010), probably reflecting the importance of trade to these export-oriented countries. Hence, the costs reported here represent a substantial ongoing investment by the government and/or private companies responsible for maintaining future port activity levels.

Table 15 **Average Annual Adaptation Costs at National Level for All Scenarios** ($ million/year)

Scenario	Country	With Adaptation				
		Residual Damages	Beach Nourishment	Dikes Capital	Dikes Maintenance	Total
High (with cyclones)	People's Republic of China	84.13	154.77	2,116.31	741.12	3,096.34
	Japan	1.83	61.91	1,618.00	554.75	2,236.48
	Republic of Korea	25.99	1.00	1,504.69	515.78	2,047.45
High	People's Republic of China	14.74	154.77	1,346.95	507.17	2,023.63
	Japan	1.83	61.91	1,136.98	392.32	1,593.03
	Republic of Korea	0.19	1.00	791.73	281.46	1,074.38
Medium	People's Republic of China	17.10	145.98	963.53	418.19	1,544.79
	Japan	1.53	56.42	709.77	293.16	1,060.89
	Republic of Korea	0.13	0.71	516.50	217.60	734.94
Low	People's Republic of China	109.71	122.03	630.55	295.52	1,157.81
	Japan	1.15	48.78	337.55	155.85	543.32
	Republic of Korea	4.01	0.36	277.25	129.51	411.14
No change	People's Republic of China	480.65	94.75	364.48	167.78	1,107.66
	Japan	12.98	40.20	44.70	15.65	113.53
	Republic of Korea	140.69	0.00	83.49	35.71	259.89

Source: Authors.

Table 16 **Increase in Annual Adaptation Costs Due to Tropical Cyclones** ($ million/year)

Scenario	Combined Adaptation Costs (Beach nourishment, dike building, and maintenance)		
	Japan	Republic of Korea	People's Republic of China
High (with cyclones)	2,234.65	2,021.47	3,012.20
High	1,591.21	1,074.19	2,008.89
Percentage increase due to cyclones	40.00	88.00	50.00

Source: Authors.

In the PRC, the municipalities of Shanghai and Tianjin, and the province of Jiangsu are the most sensitive to relative sea-level change (Figure 8 and Table 17). The municipality of Tianjin, despite only having one port, has consistently high costs due to both the large amount of trade the port handles and its location in the subsiding Yellow river delta. However, fewer than half of the ports listed in the PRC had traffic data available for the analysis.

Table 17 **Average Annual Cost to Upgrade Port Areas for All Scenarios Based on Data from 2009 Lloyds List, 2010–2050** ($ million/year)

Location	Coastal Ports		Scenario			
	Total Number	Included in Analysis[a]	No Change	Low	Medium	High
Japan	131	30	0.00	0.14	37.60	95.19
Republic of Korea	17	12	0.00	1.00	20.05	34.93
People's Republic of China	87	39	158.97	219.07	283.88	341.90
People's Republic of China, by Coastal Province						
Fujian	7	3	0.00	0.00	3.19	7.65
Guangdong	21	9	1.30	4.36	8.91	13.98
Guangxi	3	3	0.00	0.00	0.07	0.48
Hainan	6	3	0.00	0.00	0.97	2.29
Hebei	3	1	0.00	0.00	0.00	0.00
Jiangsu	13	10	40.26	55.17	67.51	76.40
Liaoning	6	2	22.94	26.82	32.76	40.07
Shandong	11	3	0.00	0.00	2.44	7.52
Shanghai	5	1	34.66	61.09	82.95	98.70
Tianjin	1	1	59.08	70.17	79.34	85.95
Zhejiang	10	2	0.00	0.00	3.67	6.36

[a] With reported traffic in Lloyds List (2009).

Source: Authors.

As discussed earlier, many ports in the PRC will experience relative sea-level rise under the "No change" scenario. These ports are located in the deltaic areas that subside and these provinces show the highest adaptation costs in 2050 across the climate scenarios. Being associated with large cities (e.g., Shanghai, Tianjin, Guangzhou), the adaptation costs for the ports are likely to be further exacerbated if human-induced subsidence was considered, but this factor has not been included in this analysis due to the large uncertainties.

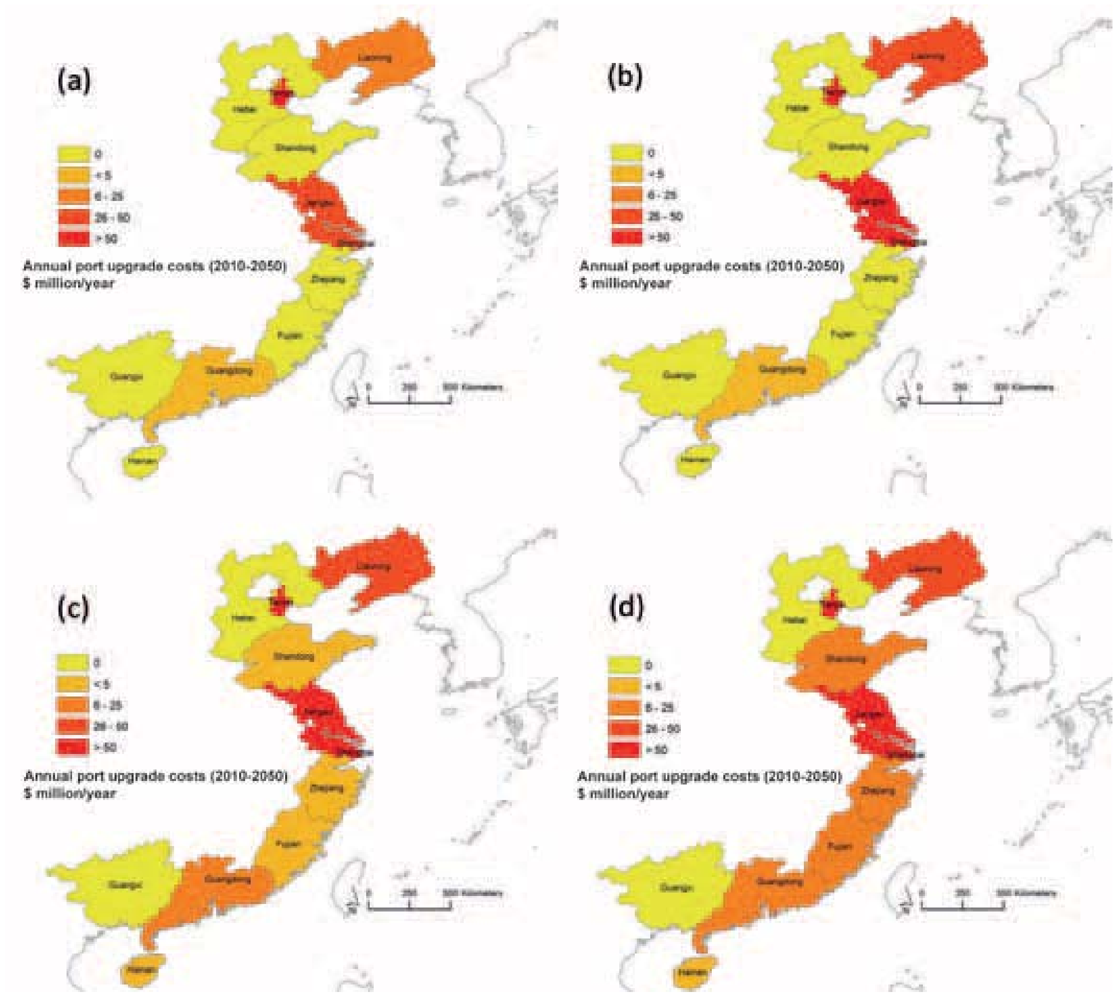
As mentioned earlier for the PRC, there are ports listed in Lloyds List (2009) that do not have data suitable for the methodology used here (Table 17). These ports tend to be classified as very small to medium in size (following the classification by World Port Source), but may still substantially increase upgrade costs. To assess the impact of missing data, additional data was obtained for 77 of the 131 ports in Japan, increasing the number of ports considered in a separate analysis for this country from 23% to 82%. This has a significant effect on the potential costs; for example, under the "Medium" scenario, estimated port upgrade costs increase by 92% from $95 million/year to $162 million/year, while for the "High" scenario, the increase is 70% (Table 18). These new results for Japan in Table 18 give a sense of the uncertainty on the results in Table 17, and the improved results for Japan are used in subsequent discussion and analysis.

The Republic of Korea has five ports for which there is no data, including Donghae, a medium seaport, whose website indicates significant throughput of trade not captured in these costs.[20] The PRC has 101 of 131 ports, which do not have traffic data reported in Lloyds List (2009). Considering

[20] This data is not in a form suitable for the methods used here.

the potential increase in costs if these ports were included, the costs calculated here are felt to be reasonable, if a minimum, cost estimate.

Figure 8 **Total Costs to Upgrade Port Areas in the People's Republic of China, by Coastal Province/Autonomous Region/Municipality, under the (a) No Change, (b) Low, (c) Medium, and (d) High Scenarios, 2010–2050**



Source: Authors.

Table 18 **Comparison of Average Annual Port Adaptation Costs in Japan Using Additional Data Provided** ($ million/year)

	Number of Coastal Ports		Scenario			
Data	Total	With Data	No Change	Low	Medium	High
Japan (Lloyds List 2009)	131	30	0.00	0.14	37.60	95.19
Japan (new data)	131	107	0.00	2.32	72.06	161.72

Source: Authors.

4. Discussion

The adaptation costs and their limitations are discussed in this chapter, which include a consideration of incremental costs due to climate change alone, and the wider costs of coastal management, including non-climate change issues.

Adaptation Costs: Synthesis

Table 19 summarizes the adaptation costs for medium scenario for the provinces of the People's Republic of China (PRC), and that of Japan and the Republic of Korea. Table 20 presents the national costs for all scenarios while Table 21 shows the incremental costs of climate change only. Figure 9 illustrates the relative contribution of the different incremental cost components.

Table 19 **Average Annual Adaptation Costs at National and Province Levels under the Medium Scenario, 2010–2050** ($ million/year)

Location	Beach Nourishment	Sea Dikes		Port Upgrade	Total Adaptation Costs
		Capital	Maintenance		
Japan	56.42	709.77	293.16	72.06	1,131.41
Republic of Korea	0.71	516.50	217.60	20.05	754.86
People's Republic of China	145.98	963.53	418.19	312.79	1,840.49
People's Republic of China, by Coastal Province/Autonomous Region/Municipality					
Fujian	0.00	129.39	54.02	3.19	186.60
Guangdong	52.05	202.98	89.68	39.90	384.61
Guangxi	63.33	36.64	14.98	0.07	115.02
Hainan	0.46	68.13	27.11	0.97	96.67
Hebei	4.13	27.92	12.97	0.00	45.02
Jiangsu	2.94	121.04	54.78	67.51	246.27
Liaoning	0.90	96.17	40.62	32.76	170.45
Shandong	6.49	115.74	51.12	2.44	175.79
Shanghai	8.64	28.53	14.01	82.95	134.13
Tianjin	3.29	8.88	4.27	79.34	95.78
Zhejiang	3.75	128.10	54.63	3.67	190.15

Source: Authors.

Table 20 **Average Annual Adaptation Costs at National Level for All Scenarios, 2010–2050** ($ million/year)

Scenario	Country	Beach Nourishment	Sea Dikes: Capital	Sea Dikes: Maintenance	Port Upgrade	Total Adaptation Costs
High (with cyclones)	People's Republic of China	154.77	2,116.31	741.12	378.63	3,390.83
	Japan	61.91	1,618.00	554.75	161.72	2,396.38
	Republic of Korea	1.00	1,504.69	515.78	34.93	2,056.40
High	People's Republic of China	154.77	1,346.95	507.17	378.63	2,387.52
	Japan	61.91	1,136.98	392.32	161.72	1,752.93
	Republic of Korea	1.00	791.73	281.46	34.93	1,109.12
Medium	People's Republic of China	145.98	963.53	418.19	312.79	1,840.49
	Japan	56.42	709.77	293.16	72.06	1,131.41
	Republic of Korea	0.71	516.50	217.60	20.05	754.86
Low	People's Republic of China	122.03	630.55	295.52	237.19	1,285.29
	Japan	48.78	337.55	155.85	2.32	544.50
	Republic of Korea	0.36	277.25	129.51	1.00	408.12
No change	People's Republic of China	94.75	364.48	167.78	164.06	791.07
	Japan	40.20	44.70	15.65	0.00	100.55
	Republic of Korea	0.00	83.49	35.71	0.00	119.20

Source: Authors.

As with the Economics of Adaptation to Climate Change (EACC) study, increased protection by sea dikes is the major contribution to defense costs in this study. Capital costs are dominant (>50%) in each case, although maintenance costs are also significant and grow with time as the stock of dikes required to adapt to climate change grows. Unlike the EACC study, however, port upgrade costs are the next most important component in the adaptation costs in the three countries, most particularly in the PRC where these correspond to 15% of costs in the "Low" scenario, and reduced to 8% of costs in the "High (with cyclones)" scenario. These relatively high port upgrade costs reflect the importance of ports and trade to these three economies, especially for the PRC. Beach nourishment is a relatively minor cost, when compared to the data in the EACC study, with the absolute and relative costs being largest in the PRC.

"Adaptation" has lower total costs than "no adaptation" when adaptation costs and damages are combined. Figure 10 demonstrates this for Zheijiang Province in the PRC for all the different scenarios considered, including the "no change" scenario. In a "without adaptation" scenario, costs grow much more quickly than "with adaptation."

However, these costs estimates have important limitations that need to be noted and are discussed in the following section.

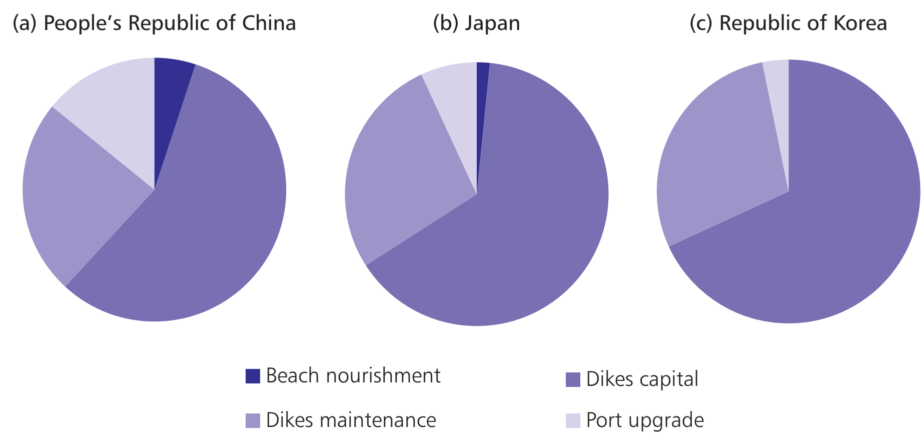
Table 21 **Average Annual Incremental Adaptation Costs at National Level for All Scenarios, 2010–2050** ($ million/year)

Scenario	Country	Beach Nourishment	Sea Dikes Capital	Sea Dikes Maintenance	Port Upgrade	Total Adaptation Costs
High (with cyclones)	People's Republic of China	60.02	1,751.83	573.34	214.57	2,599.76
	Japan	21.71	1,573.30	539.10	161.72	2,295.83
	Republic of Korea	1.00	1,421.20	480.07	34.93	1,937.20
High	People's Republic of China	60.02	982.47	339.39	214.57	1,596.45
	Japan	21.71	1,092.28	376.67	161.72	1,652.38
	Republic of Korea	1.00	708.24	245.75	34.93	989.92
Medium	People's Republic of China	51.23	599.05	250.41	148.73	1,049.42
	Japan	16.22	665.07	277.51	72.06	1,030.86
	Republic of Korea	0.71	433.01	181.89	20.05	635.66
Low	People's Republic of China	27.28	266.07	127.74	73.13	494.22
	Japan	8.58	292.85	140.20	2.32	443.95
	Republic of Korea	0.36	193.76	93.80	1.00	288.92

Note: The "No change" scenario results are excluded.

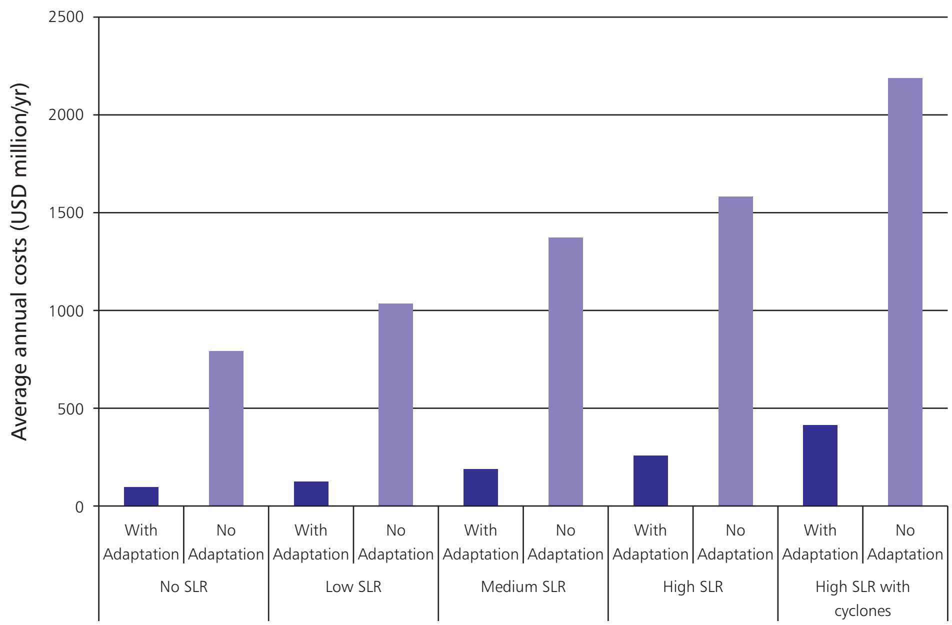
Source: Authors.

Figure 9 **Relative National Costs of Annual Average Incremental Adaptation, Medium Scenario for (a) the People's Republic of China, (b) Japan, and (c) the Republic of Korea**



Source: Authors.

Figure 10 Average Annual Costs With and Without Adaptation to Sea Floods in Zhejiang, People's Republic of China, All Scenarios, 2010–2050[a]



SLR = sea-level rise.

[a] Costs are those associated with dike upgrade, beach nourishment, land loss, forced migration, and flood damages.

Source: Authors.

Limitations

There are a number of limitations on the results of this study that are important to consider. Some of the key issues are as follows:

- Unit costs of defenses,
- The maintenance of preexisting dikes,
- The backwater effect of sea-level rise,
- The role of human-induced subsidence,
- Other human drivers of coastal change, and
- The need for integrated hazard management.

These issues are now discussed in turn.

The unit costs of the dikes are taken from Hoozemans et al. (1993). These costs may underestimate unit costs, especially in urban areas where land values can be very high and the limited space is a major constraint on how defenses can be built. The analysis of Jonkman et al. (2012) found that unit dike costs based on recent projects in Louisiana, USA; the Netherlands; and Viet Nam are significantly higher than earlier estimates. Factors affecting these unit costs include local economic factors (material and labor costs), design choices related to the alignment of the system, and the types of measures for implementing the system in an urban or rural environment. Hence, this uncertainty raises possible dike costs compared to the numbers reported here.

It must be noted that the results here only focus on adaptation measures undertaken from 2010; existing dike maintenance is not included and this can be a substantial additional cost. Estimates using the Dynamic Interactive Vulnerability Assessment (DIVA) model in this study shows that annual costs to maintain the dikes built before 2010 are roughly $2.3 billion per year for the PRC, $1.6 billion for Japan, and $2.3 billion for the Republic of Korea. These exceed the annual incremental adaptation costs in Table 21.

The adaptation costs do not consider the backwater effect on rivers[21] in the different countries, which could be significant, especially in the extensive Chinese coastal lowlands (Li et al. 2004; Han et al. 1995). Good data on the number and length of rivers was not available and, hence, an analysis is not possible. Based just on three large rivers in the PRC,[22] dike upgrade costs were estimated to be $34 million–$160 million per year during 2010–2050, from a "No change" to a "High (with cyclones)" scenario. There are many other rivers where this effect can be expected to occur. Again, this uncertainty raises possible dike costs compared to the numbers reported here.

Deltaic subsidence was considered in the study analysis and this emphasizes that there are adaptation costs for relative sea-level rise, even if there is no climate-induced sea-level rise. In addition, over the 20th century, local human-induced subsidence due to groundwater withdrawal has been an important issue in many coastal areas in the study countries. This is most notable in the PRC—for example, in and around Tianjin and Shanghai in the north and Yangtze Coastal Plains and a few sites to the south, such as Fuzhou and Zhenjiang (Ruilin 2006; Yin et al. 2006)—and in Japan, for Osaka, Nagoya, and Tokyo (Yamamoto 1995). Coastal subsidence seems to be less of an issue in the Republic of Korea. There is a high awareness of subsidence in the region and significant measures have been implemented to minimize human-induced subsidence. Sea-level rise emphasizes the importance of enforcing and monitoring the effects of these policies and more broadly, it urges decision makers to take account of subsidence within coastal planning and management.

It is also important to remember that climate-induced sea-level rise and other climate changes are not the only drivers of coastal change that impact on adaptation needs (Nicholls 2007). All the other human drivers of coastal change also need to be considered and evaluated when selecting coastal management strategies. Subsidence is one relevant issue that has been discussed at length. Erosion related to sediment starvation is an another important and widespread issue (Syvitski et al. 2009) relevant in all three countries. Most coastal sediment is provided by rivers and many of these have been dammed. For example, the supply of beach sand in Japan has fallen for this reason (Uda 2010). In the PRC, the major rivers have been dammed, with the Three Gorges Dam on the Chang Jiang being the best known example (Li et al. 2004). Hence, the Yangtze delta is expected to erode, exacerbating the effects of sea-level rise (Chen and Zong 1998). This coast has had an excess of sediment over the last few thousand years and has tended to build seaward and produce new land. In the future, this will not occur and erosion is likely to threaten the coastal defenses, demanding greater upgrade than due to sea-level rise alone. While the details will vary from place to place, the general trend of erosion will exacerbate impacts and adaptation costs.

Lastly, hazard management needs to be integrated. Extreme floods due to typhoons are one of the issues that are of great concern on these coasts. However, as shown by the 2011 Tōhoku earthquake and tsunami in Japan, there are other coastal hazards that must be considered. The analysis after this event is ongoing but is likely to have a profound effect on how coastal hazards are managed, both in Japan and elsewhere around the world. Results also stress the importance

[21] The backwater effect refers to the effect of relative sea-level rise on water levels in the coastal reaches of rivers (Nicholls 2010). The distance inland that this influences can be large in coastal lowlands.

[22] Pearl, Yangtze, and Yellow Rivers.

of integrated analysis with clear management goals and how these might best be achieved. Two examples of this type of thinking are apparent in Europe—the Thames Estuary 2100 Project for London (Lavery and Donovan 2005) and the Delta Commission for the Netherlands (Deltacommissie 2008). Both studies have stressed holistic analysis, long-term perspectives, and determination of adaptation pathways that are robust across the range of scenarios investigated. This type of analysis will probably be useful in the PRC, Japan, and the Republic of Korea and has been conducted within United Kingdom–Chinese Foresight Study (see http://www.nottingham.ac.uk/geography/foresightchina/index.html).

The limitations of the analysis stresses that the incremental costs of adaptation to climate change are likely to be larger than calculated here, and the total costs of coastal adaptation will certainly be much more expensive than determined in this study. Further, this study stresses that to achieve adaptation, appropriate governance mechanisms need to be in place.

This study raises a number of issues for further research, as follows:

- The need for better predictive capacity of the future coast—future coastal changes associated with both climate and non-climate drivers;
- The need to improve methods to recognize and prioritize potential coastal adaptation options; and
- The need to improve understanding of the best way to adapt to sea-level rise (e.g., soft versus hard options, retreat and/or realignment) to minimize other impacts and costs.

5. Conclusions

This paper suggests that without adaptation measures, there will be widespread impacts in the People's Republic of China (PRC), Japan, and the Republic of Korea due to sea-level rise and possibly increases in storms. However, adaptation options that are consistent with current practice in all three countries can manage these risks at costs that seem reasonable, especially under the scenario of a growing economy as considered in these scenarios. The adaptation options that are analyzed are essentially protection, and in practice, a wider range of adaptation options should be considered.

Climate change is only one driver of coastal management and the costs of coastal management will exceed the costs presented here. In all cases, national and subnational plans that prepare for climate change in the broader context of all coastal change would be useful.

Appendix 1
Population and Gross Domestic Product Projections Used in this Study

These projections have been developed for all the sector assessments in Asian Development Bank projects and are described here by Prof. Gordon Hughes of the University of Edinburgh. As only coastal adaptation is considered here, population and gross domestic product (GDP) projections for the People's Republic of China (PRC), Japan, and the Republic of Korea only are included.

People's Republic of China

The models, which are used to establish the baseline without climate change (NoCC) and to assess the impact of climate change, rely upon projections of economic and demographic variables by province at 5-year intervals from 2010 to 2050. The starting point used for this study is a set of demographic projections prepared by the International Institute for Applied Systems Analysis (IIASA), which were used as inputs into their CHINAGRO model (Cao et al. 2006; Toth et al. 2003). The IIASA projections take into account rural–urban and inter-provincial migration rates. The Central[23] scenario projections have been adjusted to reflect the most recent estimates of population and urbanization in the 2010 census. The projections of growth rates and population composition have been adjusted to be consistent with the growth rates, age composition, and urbanization rates in the aggregate population projections for the PRC in the UN Population Division's 2010 Medium Fertility scenario and the 2009 World Urbanization Prospects (UNDP 2010 and 2011). The major demographic changes from 2010 to 2050 concern (i) the continuation of the rapid growth in the urban population—up from about 630 million in 2010 to nearly 950 million in 2050.

Almost all projections of the PRC's economic growth over the next 2 decades focus on the PRC as a whole with little or no geographical breakdown. The projections for this study are based upon a regional analysis prepared as part of IIASA's CHINAGRO model. This is a variant on a regional general equilibrium model focusing on the supply and demand for agricultural products. Value-added in sectors other than agriculture, food processing, and related activities are treated as exogenous.

The GDP projections by province used in this study have been constructed as follows:

- Data on GDP—in aggregate and per person—at current prices for 2010 was converted to 2005 constant prices and adjusted to reflect population estimates by province from the 2010 census.
- An initial set of projected growth rates for GDP at constant prices per person by region and for 5-year periods, e.g., 2010–2015…2025–2030 was derived from the CHINAGRO model and then applied to all provinces in each region. These projections were combined with the relevant population projections to generate projections of total provincial GDP at constant prices for 2015… 2030.

[23] A description of the Central population scenario as used by IIASA can be found in Cao (2000) and Toth et al. (2003).

- For the period 2030–2050, the initial growth rates in GDP per person by province from 2030 to 2050 were derived by extrapolating growth rates over the period 2010–2030 on the assumption that average growth in each 5-year period is 90% of growth in the previous 5-year period. This reflects the pattern of declining growth in GDP per person from 2010 to 2030 and is consistent with the historical experience of rapidly growing economies in East Asia.
- The initial growth rates in provincial GDP at constant prices were scaled to match the projections for the PRC's GDP based upon results generated by the aggregate general equilibrium model used by the Development Research Centre of the State Council (DRC) combined with the aggregate population projections of the United Nations.

The GDP per person at constant 2005 prices has also been adjusted for provincial price differences using the Brandt and Holz (2006) provincial price indices. This is the best that can be done with the data available, but it should be noted that the price indices are based on differences in the cost of household consumption. Ideally, the price indices used to adjust GDP per person should take into account differences in the costs of other components of final expenditure—in particular, government consumption and investment.

Japan and the Republic of Korea

The demographic projections for Japan and the Republic of Korea are based on the national projections from the United Nation's (UN) 2010 Medium Fertility scenario and the 2009 World Urbanisation Prospects supplemented with national information.

Japan. Japan has 47 prefectures that are aggregated into eight regions—Hokkaido, Tohoku, Kanto, Chubu, Kansai, Chugoku, Shikoku, and Kyushu—conventionally used by the government for statistical purposes. The regions differ greatly in size and population with a population range in 2010 of 5.5 million for Hokkaido to 45 million for Kanto, which includes the metropolitan area of Tokyo. However, the smaller regions are distinct geographical units with specific climatic conditions varying from cool summers and cold winters in Hokkaido to the subtropical climate of Kyushu and Ryukyu islands. For this reason, the analysis for Japan is based upon the eight regional units with data constructed by aggregating data for the prefectures in each region.

The National Institute of Population and Security Research has published population projections for total population and age structure by prefecture at 5-year intervals up to 2035 (Nishioka et al., 2011). These were adjusted pro rata to be consistent with the UN's projections up to 2035. The ratios between the values for each prefecture and the national averages were kept constant at their 2035 values in order to extend the projections by prefecture for the remaining periods to 2050. The data on urbanization rates by prefecture is only available up to 2010, so the urbanization rates by prefecture were projected by keeping the relative urbanization rates across prefectures constant but ensuring consistency with the projected growth in urbanization in the UN projections. One point to note is that the UN has adopted a definition of urbanization that is different from the standard in Japanese official data, yielding much lower values for reported urbanization. The projections have followed the Japanese definition while maintaining the growth rates in urbanization from the UN data, since it is not possible to generate estimates by prefecture based on the UN approach.

The national projections for GDP per person at 2005 purchasing power parity (PPP) prices are based upon the projections used in the Economics of Adaptation to Climate Change (EACC) study but using actual figures for Japan in 2010—as published by the Organisation for Economic Co-operation and Development (OECD)—as the base values. The EACC growth rates were applied from 2010 onward. Prefecture projections were generated by assuming that the ratios of prefecture values to the national averages for the base year(s) remain unchanged over time. The base ratios of GDP per person by prefecture to GDP per person for the whole country were calculated from GDP per person at factor cost for 2007 adjusted by the regional cost of living index (with all Japan = 100) for 2007.

Republic of Korea. The Republic of Korea has a population and land area that is similar to several provinces in the eastern half of the PRC. On the other hand, treating the country as a single geographical unit would mask potential differences in the impact of climate change between the northern and southern parts of the country, as well as between areas that border the eastern and western coasts of the Republic of Korea. Hence, the 16 provinces and cities have been combined into three regions for the analysis. As for Japan, the regional estimates are constructed by aggregating separate statistics and projections for each province and city. The regions of the Republic of Korea are defined as covering the following provinces and cities:

- Korea North—Seoul, Incheon, Gangwon, and Gyeonggi;
- Korea South–East—Busan, Daegu, Ulsan, Gyeongsangbuk, and Gyeonsangnam; and
- Korea South–West—Daejeon, Gwangju, Chuncheongbuk, Chuncheongnam, Jeollabuk, Jeollanam, and Jeju.

In 2007, Statistics Korea[24] published demographic projections by province based on the 2005 census, but the report is only available in Korean. The summary in English does not suggest that there will be major changes in the provincial composition of population and population structure. Hence, information on population and other variables by province in 2010 have been adjusted to match the UN projections, maintaining the relationship between the values for different provinces. As for Japan, there is a difference between the definitions used to calculate urbanization rates in the Korean and UN statistics, though in this case, the reported urbanization rate is considerably lower in the national statistics than in the UN statistics. The projections follow the national definition for the same reason as for Japan.

The national projections for GDP per person at 2005 PPP prices are based upon the projections used in the EACC study but using actual figures for the Republic of Korea in 2010—as published by the OECD—as the base values. The EACC growth rates were applied from 2010 onward. Prefecture or provincial projections were generated by assuming that the ratios of prefecture and/or province values to the national averages for the base year(s) remain unchanged over time. The base ratios of GDP per person by province to GDP per person for the whole country were calculated from GDP per person for 2010 without any adjustment for regional price differences.

The primary demographic and GDP projections for each of the provinces, regions, or countries are shown in Tables A1.1–A1.2.

[24] http://kostat.go.kr/portal/english/index.action

Table A1.1 **Total Population Used in this Study** (in milllions)

Country	Coastal Province/ Autonomous Region/ Municipality	Name	2010	2020	2030	2040	2050
People's Republic of China	2	Tianjin	13.0	15.7	17.5	19.0	20.0
	3	Hebei	72.2	74.2	74.1	71.8	67.5
	6	Liaoning	44.0	43.3	41.5	38.5	34.7
	9	Shanghai	23.1	29.3	33.7	37.7	40.8
	10	Jiangsu	79.1	80.1	78.9	75.3	69.8
	11	Zhejiang	54.7	57.7	59.2	58.9	56.9
	13	Fujian	37.1	39.8	41.6	42.1	41.4
	15	Shandong	96.3	98.6	98.1	94.6	88.7
	19	Guangdong	104.8	121.7	131.9	138.7	141.7
	20	Guangxi	46.3	45.3	43.1	39.7	35.5
	21	Hainan	8.7	9.6	10.3	10.8	10.9
Japan	41	Hokkaido	5.5	5.2	4.7	4.3	4.1
	42	Tohoku	11.7	10.9	9.9	9.1	8.6
	43	Kanto	45.0	44.5	42.7	40.3	38.3
	44	Chubu	18.1	17.6	16.7	15.7	14.9
	45	Kansai	20.7	19.8	18.5	17.2	16.3
	46	Chugoku	7.5	7.1	6.5	6.1	5.8
	47	Shikoku	4.0	3.7	3.3	3.1	2.9
	48	Kyushu	14.5	13.9	13.0	12.2	11.5
Republic of Korea	51	Korea_N	24.9	25.9	26.1	25.6	24.4
	52	Korea_SE	12.6	13.1	13.2	12.9	12.3
	53	Korea_SW	10.5	10.9	11.0	10.8	10.3

Source: Population data were provided by Gordon Hughes of the University of Edinburgh, generated as part of an ADB research on the impacts of climate change.

Table A1.2 **Gross Domestic Product Per Person at Purchasing Power Parity Used in this Study** ($ at 2005 international prices)

Country	Coastal Province/ Autonomous Region/ Municipality	Name	2010	2020	2030	2040	2050
People's Republic of China	2	Tianjin	12,718	22,172	35,250	51,889	71,879
	3	Hebei	6,349	11,068	17,597	25,903	35,883
	6	Liaoning	8,138	13,229	20,640	30,177	41,559
	9	Shanghai	13,041	23,917	39,848	61,247	88,051
	10	Jiangsu	9,907	18,169	30,271	46,527	66,889
	11	Zhejiang	9,956	18,259	30,422	46,759	67,223
	13	Fujian	7,616	12,590	19,254	27,505	37,133
	15	Shandong	8,529	14,869	23,640	34,799	48,205
	19	Guangdong	7,609	12,578	19,236	27,480	37,098
	20	Guangxi	3,712	6,135	9,383	13,404	18,096
	21	Hainan	3,634	6,007	9,186	13,123	17,717
Japan	41	Hokkaido	24,982	27,843	31,364	35,586	40,095
	42	Tohoku	26,632	29,694	33,467	37,982	42,795
	43	Kanto	33,857	37,842	42,752	48,584	54,740
	44	Chubu	33,625	37,533	42,338	48,070	54,161
	45	Kansai	29,349	32,728	36,888	41,866	47,171
	46	Chugoku	28,797	32,102	36,164	41,028	46,227
	47	Shikoku	26,372	29,403	33,133	37,599	42,364
	48	Kyushu	25,296	28,203	31,774	36,051	40,619
Republic of Korea	51	Korea_N	23,629	28,303	33,253	39,892	48,635
	52	Korea_SE	24,649	29,524	34,688	41,613	50,733
	53	Korea_SW	24,068	28,828	33,870	40,632	49,537

Source: Population data were provided by Gordon Hughes of the University of Edinburgh, generated as part of an ADB research on the impacts of climate change.

Appendix 2
Adaptation Methodologies

Dike Maintenance and Operation Costs

Some of the best cost estimates are available from the Netherlands. Verhagen (1998) estimated that the 3,600 kilometer (km) Dutch primary dike system was worth 26 billion guilders[25] (at 1991 values). This cost was assumed to cover the cost of a total dike rebuild. Unit maintenance costs per km were 25,000 guilders/year for river dikes, and were 85,000 guilders/year for sea dikes. The higher costs for sea dikes reflect that these are subject to wave loading, in addition to high still-water levels.

Kok et al. (2008) reports the national length of river and lake dikes as 1,441 km, and the length of seawalls and delta dikes as 1,880 km. Sandy coasts (which are maintained by beach nourishment) account for the remaining 268 km of defense length. For Dynamic Interactive Vulnerability Assessment (DIVA) calculations, river and lake dikes are jointly classified as river dikes (as they do not take direct force of waves), and seawalls and delta dikes are jointly classified as sea dikes (as they have to withstand the greater wave impacts).

A proportional relationship was assumed between the value of dikes and the length of each dike type (approximately 40% for river dikes and 60% for sea dikes). Maintenance cost was multiplied by the length of the dike type to give maintenance cost in guilders per year.

$$\text{Percentage of maintenance cost per year} = \left(\frac{\text{Maintenance cost}}{\text{Total value}}\right) \times 100$$

Hence, based on this Dutch data, the maintenance costs of river dikes are estimated as 0.3% and sea dikes are estimated as 1.1% of the initial construction costs.

There are other sources, again mainly from the Netherlands. IPCC CZMS (1990b) estimated that a 1-meter high sea dike with regular maintenance will be maintained at a cost of 50% of construction cost. UNCTAD (1985) estimates that breakwaters have a 50-year design life, so combining these values suggests maintenance costs are about 1% per year. UNCTAD (1985) estimates the maintenance cost as a percentage of the initial cost of port structures—quay steel piling with reinforced concrete deck (1%), reinforced concrete piles and deck (0.75%), including rock-filled embayments (0.75%), and breakwaters (2%).

Professor Marcel Stive, professor of coastal engineering, Delft Technical University, reports that over the last 10 years, Rijkswaterstaat spent approximately €250 million on 2,875 km of primary defenses. Estimating construction costs from IPCC CZMS (1990b), maintenance cost equates to 1.7% of the capital cost.

British Columbia's (Canada) Drainage, Ditch and Dike Act (Revenue Services of British Columbia 1996) states that an annual levy for drainage, ditch, and dike maintenance fund cannot exceed 5% of the cost of the original works. It is anticipated that this is an upper limit of the funding required.

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[25] The guilder was used in this paper since it was the currency used by the Netherlands until 2002 when it was replaced by the euro.

Furthermore, the Dike and Channel Maintenance and Habitat Subcommittee (Fraser Basin Council 2001) of Fraser Basin in British Columbia estimate $5.5 million/year for routine maintenance, and an additional $4.0 million/year for major river dike repairs. Assuming construction costs from IPCC CZMS (1990b), maintenance cost equates 0.8% for minor maintenance and 0.6% for major works, combined maintenance is estimated as a total of 1.4% of capital costs.

For drainage projects, a rule of thumb was used with operation and maintenance costs (such as weed clearance and desilting), accounting for 2% of the construction costs.

Hence, a range of estimates of maintenance and operational costs were identified, with river dikes being consistently lower in cost, reflecting the lack of wave loadings. Operational costs reflect the costs of drainage landward of the dike, such as drain clearance and pumping costs: without drainage this land would often become waterlogged or flooded due to rainfall and rising water tables. Locally, maintenance and operational costs can be as high as 5%, but this is untypical and a maximum of 2% appears a reasonable generic maximum case for sea dikes. Taking a conservative view, maintenance and operation costs were assumed as follows:

- River dikes: 0.5%
- Sea dikes: 1.0%

These costs could be in error by a factor of 100%, and further investigation of these costs in more diverse settings is recommended. This should include how they might be expected to evolve under a scenario of rising sea level.

These costs were implemented in Nicholls et al. (2010) and are applied here.

Port Upgrade

The aim of this part of the study is to estimate the costs associated with the adaptation of ports to sea-level rise at country and administrative region levels. As the main form of adaptation to sea-level change is assumed to be raising land levels, adaptation costs are assumed to be only those associated with raising current port areas to maintain their elevation relative to sea level and preserving current risk levels for inundation. The estimated costs do not include explicit cost and/or benefit considerations—it is assumed that these strategic and valuable areas will need to be maintained to 2050 (and beyond). Only existing port areas are considered and they are assumed to be flat. Any new developments between 2010 and 2050 are presumed to be constructed with an appropriate allowance for sea-level rise.

Consistent data on port areas across the three countries (People's Republic of China (PRC), Japan, and the Republic of Korea) was not available as

- data existed but was either not readily available, or at a scale not useful in the national to regional analysis;
- data was available but incomplete, inconsistent, or ambiguous (largely due to the different methods of recording port traffic); or
- information did not exist.

The methodology adopted for this study, therefore, is based on that developed by Delft Hydraulics (now part of Deltares) in their report "Sea-Level Rise: A World-Wide Cost Estimate of Basic Coastal Defense Measures" (IPCC CZMS 1990a), which reported the global costs of protection against a

1-meter rise in sea level, and developed in the World Bank Discussion Paper on the Economics of Coastal Zone Adaptation to Climate Change (Nicholls et al. 2010). These reports found that primary data on port area was quite limited and, using the expert judgment and experience of Delft Hydraulics staff, a method was developed to estimate the port area from the statistics of the tonnage moved. These calculated areas were assumed to require elevation by the relative sea-level rise scenarios; no change in these areas by 2050 was incorporated.

Source Data

The most comprehensive data source on ports was found to be Lloyds List's Ports of the World directory (Lloyds List 2009). This provides port-level data listed by country, which contains the following:

i. Port name,
ii. Port activity (if the port is still commercially active),
iii. Port location (degrees and minutes),
iv. Port facilities (including what type of cargo the port is able to accommodate),
v. Traffic (tonnage and number of containers [twenty-foot equivalent units or TEUs] for a given year), and
vi. Tides (tidal range and/or tidal levels).

Individual port data for the selected countries was recorded in a spreadsheet and then transferred into geographic information system (GIS) software (ArcGIS), which showed the geographic position of individual ports. This allowed easy classification of the ports, according to location, as either river, coastal, or offshore. To allow the inclusion in the analysis of ports located in deltas or estuaries, which are subject to the direct effects of sea-level change, an "up river" limit was established for those classified as coastal using the description of tidal influence in the original data. Ports upstream of this limit were excluded from the analysis. Note that some ports located inland on major rivers, for example the Yangtze in the PRC, may be subject to changes in future water levels because of the "backwater" effect on river levels due to rising sea levels, but these are excluded from this analysis. Ports located "offshore" were also excluded from the analysis. This resulted in a total of 237 ports being included in the analysis—the PRC, excluding Taipei,China (89), Japan (131), and the Republic of Korea (17). The locations of these ports are shown in Figure A1.

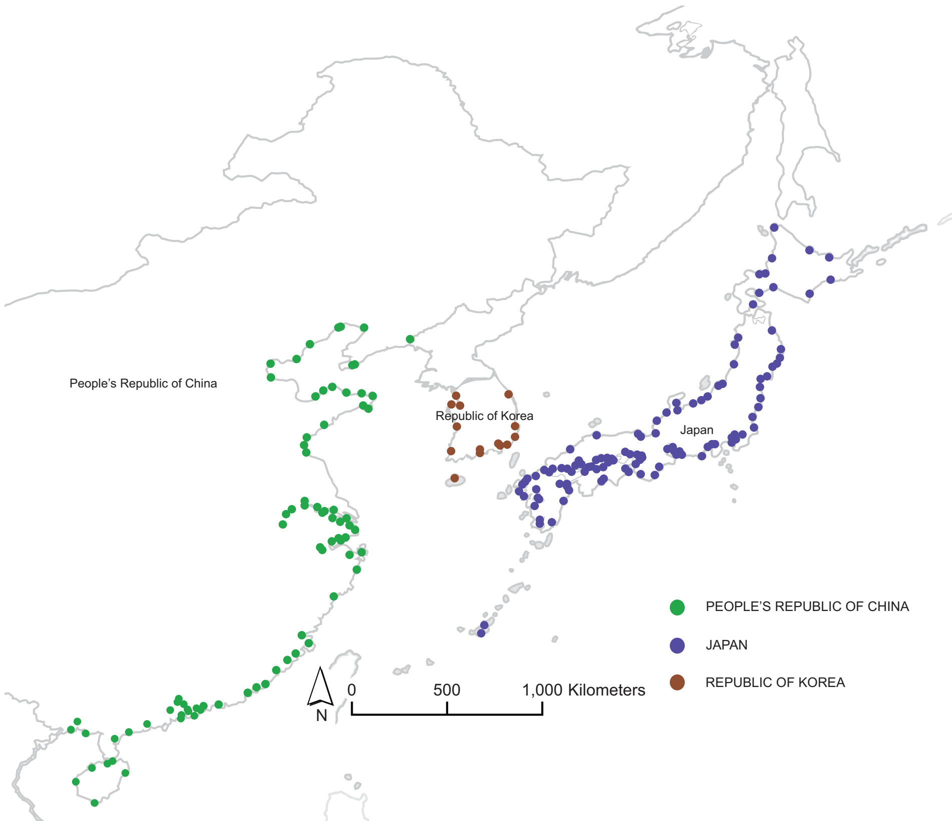
The ports were also categorized according to size (very small–very large) and type (classifications used: harbor, seaport, pier wharf or jetty, ferry, and LNG terminal) following the classification used by the World Port Source.[26]

Tonnage and Containers

Two categories of traffic are recorded in Lloyds List (2009)—tonnage and TEUs. The tonnage and TEUs handled reported in the Lloyds List (2009) are assumed to represent the current capacity of the port although it is recognized that this may change over time. Potential changes in traffic to 2050 are not considered. Ports with no reported tonnage and/or TEUs are included to provide an indication of the scale of potential additional costs for each country. Calculations were carried out for all three countries using the Lloyds List (2009) data. Supplementary, more comprehensive, traffic data was made available for the ports in Japan so an additional calculation was also made for this country.

[26] www.worldportsource.com

Figure A1 **Map Showing Coastal Ports Listed in Lloyds List 2009 for the People's Republic of China, Japan, and the Republic of Korea**



Source: Authors.

Separate area calculations were undertaken for the tonnage and TEU data available. Tonnage was transferred directly into the spreadsheet and, if a range of port facilities were indicated (e.g., general cargo, dry bulk, Ro/Ro, liquid bulk), it was divided by the mixed cargo rate above to generate area for the port. As a TEU is a volume-based unit, translation into other units is necessarily imprecise. With reference to the design and specification of containers, the most common dry cargo maximum gross weight is approximately 24 tons.[27] This value was, therefore, used in the equation below to determine the area required for the number of reported TEUs, as follows:

$$Y = (N *24)/(16* 106) \qquad \text{Equation 1}$$

Y = area (km^2)

N = number of TEUs handled

24 = tonnage equivalent for a container

16* 106 = tonnage equivalent for containers that can be handled in 1 km^2 (IPCC CZMS 1990a)

[27] See http://www.emase.co.uk/data/cont.html, http://www.freightraders.co.nz/containerspecs.html, http://www.bslcontainers.com/products41.php)

Traffic to Area Calculations

The methodology for translating reported traffic used values from IPCC CZMS (1990a). Based on information from the Port of Rotterdam, the 1990 report determined tonnage—space relationships for a range of cargo types and an amalgamated rate, which represents the quays, storage areas, roads, general areas (offices, etc.), and industrial areas within the port area. In this report three rates were used, as follows:

- Mixed cargo: 3 * 10^6 tons handled per km^2 of port area,
- Bulk/oil: 30 * 10^6 tons handled per km^2 of port area, and
- Containers (TEUs): 16 * 10^6 tons handled per km^2 of port area.

Areas were derived for individual port areas by adding the tonnage and TEU area equivalent values calculated using the rates above. These were then aggregated to administrative region and country level to provide a total area estimate.

Costs of Upgrade

As new data was not readily available, the cost of the upgrade to port ground levels is based on the unit rates in the IPCC CZMS (1990a) of $15 million per square kilometer (km^2) to raise ground levels by 1 meter (i.e., $15 million/$km^2$/m). This was estimated based on Dutch procedures including design, execution, taxes, levies, and fees and the assumption that the operation would take place as one event. A country cost factor (which considered the presence of a "wet" construction industry, availability and costs of human and construction resources, acquisition costs, possibility of mobilization of [foreign] equipment, and possible size effects) translates these costs proportionately for other countries. The country cost factor reported for the PRC is 1.2, 2 for Japan, and 1 for the Republic of Korea.

To standardize the results, costs were inflated from the original IPCC CZMS (1990a) report to 2005 using the US Retail Price Inflation (annual average),[28] which shows a cumulative inflation increase of 73% over this period. This inflation increased unit costs from $15 million to $26 million/$km^2$/m.

Projected Relative Sea-Level Change

Local rates of relative sea-level change were generated for each port using the Dynamic Interactive Vulnerability Assessment (DIVA) model and database. DIVA was used to project the cumulative amount of climate-induced sea-level change by 2050 (global mean change calculated from 1990) under global low, medium, and high emissions scenarios. The scenarios used are consistent with the Inter-Governmental Panel on Climate Change (IPCC) A2 emissions trajectory (Nakicenovic et al. 2000). For the same time period, using the port location in ArcGIS, the local amount of uplift and/or subsidence was calculated for each port using annual rates from the DIVA coastal segments database, supplemented by more detailed rates for the 40 deltas investigated in Ericson et al. (2006). These amounts were then combined to provide a single amount of relative sea-level change. Human-induced subsidence in deltaic areas was not included as comprehensive data regarding rates was not available.

[28] http://www.halfhill.com/inflation.html

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Cost of Adaptation to Rising Coastal Water Levels for the People's Republic of China, Japan, and the Republic of Korea

This publication explores the potential costs for coastal adaptation from 2010 until 2050 in East Asia due to climate-induced sea-level rise and possibly more intense tropical cyclones. The results are estimates of possible adaptation needs, which illustrate the possible magnitude of adapting to the future impacts of climate change on three important coastal countries: the People's Republic of China, Japan, and the Republic of Korea. This study is part of the technical assistance Economics of Climate Change and Low Carbon Growth Strategies in Northeast Asia, financed by ADB and the Korea International Cooperation Agency.

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