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ASSESSING CLIMATE CHANGE IMPACTS, SEA LEVEL RISE AND STORM SURGE RISK IN PORT CITIES: A CASE STUDY ON COPENHAGEN

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ABSTRACT

This study illustrates a methodology to assess economic impacts of climate change at city scale, focusing on sea level rise and storm surge. It is based on a statistical analysis of past storm surges in the studied city, matched to a geographical-information analysis of the population and asset exposure in the city, for various sea levels and storm surge characteristics. An assessment of direct losses in case of storm surge (i.e. of the damages to buildings and building content) can then be computed and the corresponding indirect losses – in the form of production and job losses, reconstruction duration, amongst other loses – deduced, allowing a risk analysis of the effectiveness of coastal flood protections, including risk changes due to climate change and sea level rise. This methodology is applied in the city of Copenhagen, capital of Denmark, which is potentially vulnerable to the effects of variability in sea level, as a low lying city.

The analysis concludes that Copenhagen is not highly vulnerable to coastal flooding. In the absence of protection, however, the total losses (direct and indirect) caused by the current 120-yr storm surge event, at 150 cm above normal sea level, would reach EUR 3 billion. In the absence of protection, moreover, future sea level rise would significantly increase flood risks beyond this level. For instance, with 25 cm of mean sea level rise (SLR) total losses caused by a future 120-yr event would rise from EUR 3 billion to EUR 4 billion, to EUR 5 billion with 50 cm of mean SLR, and to almost EUR 8 billion with 100 cm of SLR.

As extreme sea level events (referred to as “storm surge events”) are not particularly high in Copenhagen, the city is relatively easy to protect with dykes and sea walls and the residual risk is low: while annual mean losses can reach several billions of Euros with protection of less than 1m, they decrease very rapidly with protection height, with less than 100,000 Euros per year for 180 cm. Given that the construction cost of a coastal flood protection system for Copenhagen is estimated to be a few hundred million Euros, it is a rational decision to protect the city with very high dikes, which is actually the case in most locations in the city. However, in some locations and in the most pessimistic IPCC scenarios, additional investment will be required by 2030. And because flood exposure will increase regardless of the protection level, the consequence of protection failure will increase with sea level rise. Faultless maintenance will, therefore, become even more crucial than today.

Copenhagen’s high protection level and low risk to sea level rise and storm surge events is not widespread across world cities. To assess the economic cost of climate change and sea level rise in other cities, the methodology is applied on a virtual city – based on Copenhagen without its current levels of protection – and provides additional general insights into the impact of sea level rise on coastal cities. It is found that the increase in risk due to climate change is likely to be unacceptable in many cities, calling for an upgrade of flood protection in response to sea level rise. Even with upgraded defences which maintain unchanged the flood probability, the mean annual loss, i.e. the flood risk, increases because of the enlargement of the area subject to flooding. Flood probabilities, therefore, will have to be decreased to maintain the current level of risk. Moreover, while flood probability can be reduced to extremely low levels with appropriate protective measures, sea level rise will always increase the consequences of defence failure or overtopping by affecting increasingly large areas of the city. These results call for the introduction of adaptation in long-term planning to consistently take into account all dimensions of climate change. Mitigation policies can also reduce the potential impacts of climate change on coastal cities by limiting the pace of future sea level rise.

JEL classification: Q54, Q01, Q58, E20, O18, R10.
Keywords : Climate; Natural Disasters; Global Warming; Sustainable Development; Government Policy; General Macroeconomics; Regional, Urban, and Rural Analyses; Regional Economics.

FOREWORD

This report is one in a series under the OECD project on Cities and Climate Change. The project aims to explore the city-scale risks of climate change and the benefits of both (local) adaptation policies and (global) mitigation strategies.

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- Stephane Hallegatte, consultant to the OECD & lead author of this study at hallegatte@centre-cired.fr

More information about the project and related OECD working papers and publications in this area can be found at the OECD website - www.oecd.org/env/cc/cities, or contact:

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1. Summary and Introduction

Estimating climate change economic impacts is a difficult task, because of the complexity of the interface between climate change, society and the world economy. This report illustrates a methodology to estimate economic impacts of climate change at city scale, focusing as an illustration on sea level rise and storm surge. Climate change impacts in coastal cities are expected to represent a major challenge this century, with millions of exposed people and thousands of billions of USD of exposed assets at the global scale (Nicholls et al., 2007).

The study is on coastal flood risk, sea level rise and storm surge in port cities. It is divided into two components. The first examines the exposure and risks from coastal flooding Copenhagen today and the implications of sea level rise. The second component uses these data to create a virtual city, less well defended than Copenhagen but with the same exposure characteristics, with which we demonstrate a more generic methodology to assess flood risks and to design adaptation policies.

In this study we consider only impacts from flooding due to storm surge and sea level rise (i.e. all other impacts, such as flooding due to heavy precipitation, are disregarded). Accordingly, the proposed methodology does not pretend to assess the total macroeconomic cost of climate change. Clearly, adaptation policies must take into account the full range of impacts. Through some adjustments, however, this methodology could be applied to different impacts or sectors; only the taking into account of all impacts would allow for a complete analysis of climate change impacts. The methodology developed and tested in this report is one small step towards enabling a more comprehensive economic assessment of climate change impacts at city scale. Better understanding of these impacts will inevitably assist local and national policymakers to understand the local benefits of global mitigation and to design effective, city-scale adaptation responses.

The methodology applied in this report is based on a series of steps: (1) a statistical analysis of past storm surges in the studied city; (2) a geographical-information analysis of the population and asset exposure in the city, for various sea levels and storm surge characteristics; (3) an assessment of direct losses in case of storm surge (i.e. of the damages to buildings and building content); (4) an assessment of the corresponding indirect losses – in the form of production and job losses, reconstruction duration, amongst other loses – using an adaptive regional input-output model (ARIO, Hallegatte, 2008); (5) a risk analysis of the effectiveness of coastal flood protections, including risk changes due to climate change and sea level rise.

This methodology is applied in Copenhagen (København), the capital of Denmark, and the centre of the Swedish-Danish Oresund (Øresund) region. As a low-lying city with a significant amount of property lying close to the water level, Copenhagen is potentially vulnerable to the effects of natural variability in sea level and, on decadal timescales, anthropogenic sea level rise. The city has a population of around 1.2 million (2005 numbers for the metropolitan area). Many thousands of these people live in areas with an elevation of less than one metre above sea level.

Key Outcomes Specific to Copenhagen

Our analysis concludes that Copenhagen is not highly vulnerable to coastal flooding today. In the absence of protection, potential losses would nevertheless be large. For instance, the total losses (direct and indirect) caused by the current 120-yr storm surge event, at 150 cm above normal sea level, are estimated to reach EUR 3 billion with no protection. In the aftermath of such an event, thousands of jobs would be lost and thousands would be created in the construction sector. Other types of impact have been disregarded here, but may also be important (e.g., casualties, illness, psychological trauma, disruption of social networks, loss of national competitive strength and market positions, loss of cultural heritage, city attractiveness, etc.). Even with the relatively narrow set of economic impacts considered here, the reconstruction process would last several years and cause a significant shock to the local and the national economy.

In the absence of protection, future sea level rise would significantly increase flood risks beyond this level. For instance, with 25 cm of mean sea level rise (SLR) total losses caused by a future 120-yr event would rise from EUR 3 billion to EUR 4 billion, to EUR 5 billion with 50 cm of mean SLR, and to almost EUR 8 billion with 100 cm of SLR. The timescale of these increases in losses cannot be determined, because of uncertainty in future sea level rise. Indeed, in the most optimistic scenarios (low emission, low climate sensitivity, low response of sea level), SLR should not exceed 25 cm by the end of this century. In the most pessimistic IPCC scenario, SLR would reach 25 cm in 2050 and up to 60 cm in 2100. In alternative scenarios, made necessary be limitations in the modelling exercises reported in the IPCC (Oppenheimer et al., 2007), SLR could exceed 1 m by 2100 (see, e.g., Rahmstorf, 2007; Hansen, 2007).

Assessing the consequences of one event (i.e. the 120-yr event) is not enough to assess aggregate risk across time. A typical measure of the risk level is the *mean annual loss*, which is calculated as the sum of the occurrence probability of all possible events multiplied by the total losses they would cause and is equal to the expected value of annual flood losses. The mean annual loss takes into account all possible storm surges, and depends on the protection level.

As extreme sea level events (referred to as "storm surge events") are not particularly high in Copenhagen, the city is relatively easy to protect with dykes and sea walls and the residual risk is low: while annual mean losses can reach several billions of Euros with protection of less than 1m, they decrease very rapidly with protection height. They are lower than 100,000 Euros per year for 180 cm protection, and null for protection higher than 2 m.

The construction cost of a coastal flood protection system for Copenhagen is estimated to be a few hundred million Euros. However, additional costs of protection infrastructure (e.g., on harbour accessibility or aesthetic considerations) will also have to be considered as a factor in decision-making about investment choices. Also, the protection system includes dikes and sea walls but the presence of sea walls also requires an efficient drainage infrastructure. This is necessary to prevent the city from being flooded by heavy rainfall. In the presence of high dikes, a move from gravity-drainage to pumps may be necessary. Consequently, investment in "hard" (infrastructure) adaptation measures to coastal flood risks will need to be made in conjunction with improved rainfall flood management. Further, the design of drainage infrastructure must also take into account future sea-level rise projections.

Considering the potential flood losses and the protection cost, our study suggests that it is a rational decision to protect the city with very high dikes. Information about Copenhagen's current protection infrastructure against high sea levels suggests that the city is actually very well protected against possible storm surges. In some locations, current protection appears to be much higher than the largest possible event (e.g., Amager Island), and can thus protect the city against storm surges, even with significant sea level rise in the future[1]. In other locations, defence upgrades will be necessary with sea level rise to maintain flood risk near zero. The concerned coastline segments are relatively limited but include important locations (e.g., the harbour and the city historical centre). It will be necessary to anticipate the need for these investments to implement them in due time. Such long-term planning thus requires explicit

[1] Due to the importance of protected assets in these areas (including the Copenhagen metro and the tunnel to Sweden), the protection level has been designed particularly large, to hedge against any surprise or measurement and design error.

consideration of the uncertainties in climate change and sea level rise projections (as well as socio-economic factors) to ensure the improvements are robust under a range of plausible outcomes.

Risk is already increasing in the least well defended locations (e.g., Hvidovre). In these locations, additional investment will be required by 2030 at the latest in the pessimistic IPCC scenarios. Because flood exposure will increase regardless of the protection level, the consequence of protection failure will increase with sea level rise. Faultless maintenance will, therefore, become even more crucial than today.

Generic Outcomes for Impacts & Adaptation to Sea Level Rise at a City-Level

Copenhagen's high protection level and low risk to sea level rise and storm surge events is not widespread across world cities. To assess the economic cost of climate change and sea level rise in other cities, this report proposes a methodology to assess flood risks with and without protection, which should assist with the design of local adaptation policies and measures. The application of this methodology on a virtual city – based on Copenhagen without its current levels of protection -- provides additional general insights into the impact of sea level rise on coastal cities:

(i) In many coastal cities, climate change and sea level rise have the potential to significantly increase coastal flood risks in absence of upgrading of current flood protection infrastructure. With no adaptation, the increase in risk due to climate change is likely to be unacceptable in many cities, calling for an upgrade of flood protection in response to sea level rise. There are several ways of upgrading flood protection in coastal cities. A common criterion is to maintain unchanged the flood probability. This can be done by raising flood defences by the same height as sea level rise – in other words by maintaining the current level of defence. Our analysis shows, however, that if the probability of flooding is maintained, mean annual loss, i.e. the flood risk, increases because of the enlargement of the area subject to flooding. In response to sea level rise, therefore, it is more relevant to maintain the level of flood risk by taking into account the change in value at risk. To maintain flood risks at a given level, the height of the protection against sea level rise has to be larger than the amplitude of sea level rise, even with the assumption that storm surges and waves will remain unchanged.

(ii) It is necessary to anticipate the need for adapting to climate change, even in low-vulnerability locations. This calls for the introduction of adaptation in long-term planning, consistently taking into account all dimensions of climate change (e.g., sea level rise, change in storm characteristics, change in heavy precipitations, and rise in mean and extreme temperature). This task will require, in particular, carrying out more detailed and higher-resolution assessments of flood risks; a precise mapping of at-risk areas; and the development of protection and response plans (including early warning) at the local level. Controlling coastal flood risks will require repeated investments over this century. If protection upgrades are not made in due time, flood risks will increase rapidly, putting large numbers of people and assets at risk. It will be particularly important to upgrade flood defences in a proactive manner, without waiting for disasters with significant costs to local and national economies to signal the increase in risk. It is also important to build defences in a way that allows for flexibility, taking into account uncertainties in projections and making it possible to upgrade them if sea level rise is larger than expected. Finally, to reduce unnecessary capital replacement costs all planning and new infrastructure investments must take account of the risk over the entire lifetime of the investment.

(iii) Even if flood defences are upgraded to maintain today's level of risk, mean sea level rise will still lead to a large increase in flood exposure. This means that while flood probability can be reduced to extremely low levels with appropriate protective measures, sea level rise will always increase the consequences of defence failure or overtopping by affecting increasingly large areas of the city. The increase in exposure due to climate change will make it critical not only to upgrade flood defences, but also to maintain them rigorously, since the consequences of failure would be very large. Also it requires "soft" adaptation measures, such as emergency plans and warning systems, to prepare for the possibility of failure.

(iv) Greenhouse gas mitigation policies reduce emissions and can limit the atmospheric concentration of greenhouse gases. This is the only way to limit climate change and future sea level rise over time. Nevertheless, the largest effects of mitigation on sea level rise, and therefore the benefits of policy, would occur after 2100, with the main benefits before then being a slowing of the pace of sea level rise. This means that, in general, adaptation to address rising coastal flood risk is necessary to deliver high avoided impact benefits in the short to medium-term (i.e. in the next few decades). On the other hand, stabilisation of atmospheric concentration levels through emission reduction is the only way to reduce and limit the largest risks of sea level rise and coastal flood risk over the long-term. Thus both global mitigation and local adaptation will be needed in a comprehensive coastal flood risk management strategy.

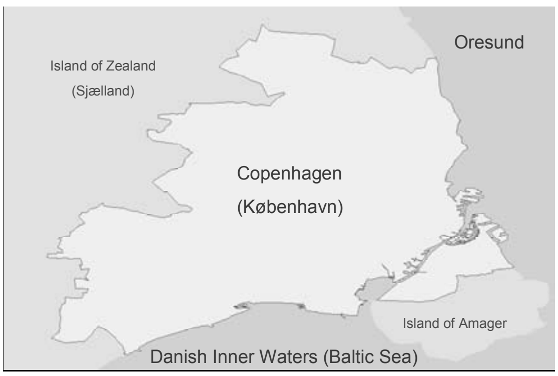
This report begins in Section 2 with an overview of the geography of Copenhagen, past storm surges in the city, its vulnerability to present-day sea levels, and the possible implications of anthropogenic climate change for sea levels in the city. Section 3 presents an analysis of the exposure of population and assets (residential, commercial, industrial and agricultural) to sea level rise in the present and future climate. Then, Section 4 uses a simplified vulnerability function and an economic input-output model of the Capital Region of Denmark to investigate the potential direct and indirect losses for the city, including current protection. This section concludes that the city is not highly vulnerable to sea level rise because of its high protection level. Because such a protection level is not widespread in world coastal city, Section 5 discusses adaptation and mitigation options to limit flood risks in the numerous cities that are not extremely well protected today.

2. Context

2.1. Geography of Copenhagen

Copenhagen (København) is located on the east side of the Danish island of Zealand, and partly upon the island of Amager (55°43' N 12°34' E) (Figure 1). The coastline of Copenhagen lies along the Danish Inner Waters and essentially upon the Baltic Sea. The city is separated from Sweden by the Oresund: the strait of water that joins the Baltic Sea to the North Sea. Copenhagen is a low-lying city, with the highest ground around 45 m above sea level. The elevation is lowest on the island of Amager and around the coastline (particularly the southern coast) of the city. Roughly half of the area of the city upon the island of Amager, as well as large areas of the southern coastline of the city, are at an elevation less than 2m above sea level.

Figure 1. Schematic view of Copenhagen, Denmark

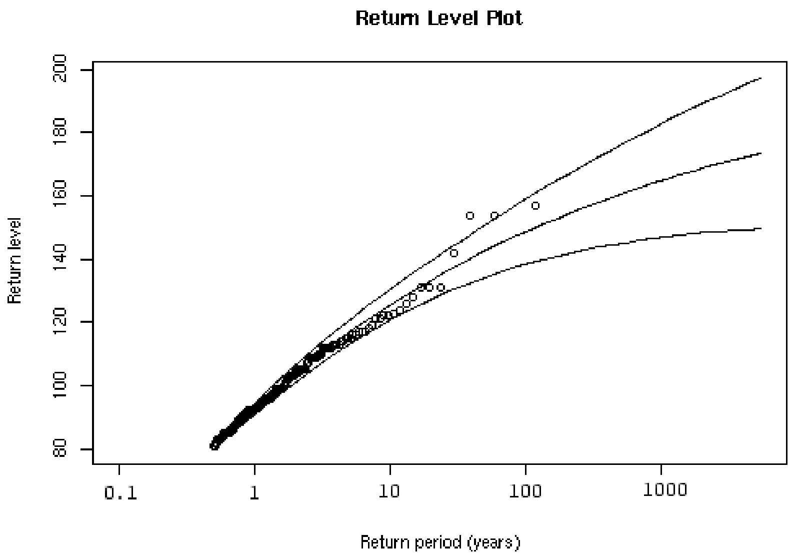


In terms of total insured value (TIV), most of the assets of Copenhagen are in the Residential sector (more than 120 billions Euros), while Industrial and Commercial sectors represent, respectively, about 8 and 50 billion Euros. Agriculture is marginal in the region.

2.2. Current variability in sea levels in Copenhagen

The low elevation of the city leaves its population and assets potentially exposed to variations in sea level. However, the city's position upon the Danish Inner Waters and Baltic Sea means that it experiences relatively small tidal changes in sea level. More significant changes in sea level are caused by atmospheric pressure differences across the Baltic region. The largest changes can occur during extreme events, such as storm surges. These events are caused by the strong winds in low pressure storm systems, known as extratropical cyclones. As the storm passes over the sea, the wind causes wave height to increase, increasing water levels at nearby coasts that can lead to flooding. Storm surges tend to occur more frequently and intensely along the North Sea coast (i.e. away from Copenhagen) than in the Danish Inner Waters. This is due to the greater 'fetch' (length of water the wind passes over) in the North Sea and the larger number of Atlantic storms that track from west to east across the sea. Copenhagen is less exposed to storm surge as its geographic position protects it from most storms except those arriving from the south.

Figure 2. Storm surge return water level (cm) corresponding to various return-periods, up to 1000 years



Note: The 117 years of data are reproduced with circles. The presented data was de-trended for extreme analysis.

While generally smaller, surges in the Danish Inner Waters can be just as destructive as those along the North Sea coast as the region is the most densely populated. Copenhagen itself is well protected by the surrounding topography and therefore, storm surge events are relatively rare. However, large surges are not unheard-of; the city can be vulnerable when low pressure systems track northwards over the continent and into the Baltic.

The Danish Coast Authority[2] (Kystdirektoratet) provided data on local sea level in Copenhagen from 1890 to 2007, produced by the Danish Meteorological Institute (DMI). This data set contains 256 events during which water level was at least 80 cm above the mean sea level. From this data, it is possible

[2] We would like to thank Carlo Sørensen for his help to get this data.

to assess the frequency of high water events of various amplitudes, using a Peak Over Threshold (POT) approach (See Coles, 2001). The shape parameter of the Generalized Pareto Distribution (GPD) is found significantly lower than 0 with a p-value lower than 0.1% (ξ estimate: -0.155 with corresponding standard error 0.05). This implies that the underlying surge distribution is light tailed and upper bounded at 2.02 m. According to the analysis presented here, the water level of the 20-, 50- and 100-yr return-period events are, respectively, 133.3 cm, 142.5 cm and 148.6 cm (Figure 2)[3]; slightly lower than the average for the Danish Inner Waters. The distribution parameters estimated here are consistent with the statistical analysis performed at the Danish Coast Authority, but may be conservative as considerably larger surges predating measurements (e.g. in 1872) have been observed along parts of the Copenhagen coastline.

Table 1 gives information on historic storm surges that have affected the Danish Inner Waters. The largest recorded event occurred in 1872; a strong storm (equivalent to a category 3 hurricane) tracked northwards across Europe and into the Baltic, causing a 3 m storm surge that led to severe flooding around the Danish Inner Waters (particularly in Lolland and Falster, the two islands south of Copenhagen). A detailed measure of water level in the Copenhagen harbour is not available as records start in 1890. The largest events in the record occurred in 1902 (154 cm above normal sea level) and 1921 (157 cm), but no information about flooded areas or damages are available. The largest storm surges in recent history occurred during the winters of 2006 and 2007. On the 1st November 2006, for instance, an exceptionally strong storm developed south of Iceland and intensified past the west coast of Norway before travelling into the Baltic. Water was forced down from the Kattegat (to the north of Zealand and the Oresund) and from the Baltic. The ensuing build-up of water led to record water levels in the region, with the sea level in Odense (on the Island of Fyn to the west of Zealand) reaching two metres above normal (a more than 100-yr return-period event) and the level in the Copenhagen harbour reaching 131 cm. Also, on the 19th January 2007, the water level in the harbour was measured 142 cm above normal sea level. These events did not lead to significant damages in Copenhagen.

The risk of coastal flooding in Denmark is currently low. Indeed, the areas worst affected by storm surge events are not densely populated and are well protected by sea walls and dikes. Further, the weather forecasting and warning systems established in Denmark have proven to be efficient to prevent human and economic losses from extreme events. Also, extreme storm surges in Copenhagen are limited and cannot exceed 2 metres according to our statistical analysis, making it very easy to protect the city with sea walls and dikes.

Table 1. Historical storm surges in the Danish Inner Waters

Date	Main locations affected	Size of surge
Nov 1872	Lolland and Falster – Køge and Kobenhavn flooded – East coast of Jutland. 80 deaths, 50 ships destroyed	Up to 3.3 m in Slesvig
Dec 2003	Southern parts of Kattegat, Odense fjord, Baelthavet	115 cm in the Copenhagen harbour
Nov 2006	Southern part of Kattegat, Odense and in Baelthavet had record water levels	131 cm in the Copenhagen harbour
Jan 2007	Southern parts of Kattegat, Odense fjord, Baelthavet	142 cm in the Copenhagen harbour

[3] According to these estimates, the water level corresponding to the m-year event is given by:

$$r_m = u + \sigma/\xi\cdot((m\cdot nobs\cdot rate)^{\xi} - 1),$$

where u is 80cm; σ is 18.91; nobs=365; rate = $5.53 \cdot 10^{-3}$ and ξ=–0.154. This function is plotted in Figure 2.

2.3. The effects of climate change on sea levels around Copenhagen

Observed sea level change. Global mean sea levels rose by around 17 cm over the twentieth-century, driven largely by the thermal expansion and melting glaciers, ice caps and ice sheets associated with anthropogenic global warming. On top of this global trend, there are significant regional differences in sea level change due to changes in ocean circulation and atmospheric pressure. Because of natural variability, it is more difficult to detect a climate-change signal in the local sea level in Copenhagen than in global sea level. Over the last century, a linear trend of 0.44 mm per year (i.e. 4 cm per century) can be observed in Copenhagen water level data from the city Coastal Authority. The difference between this observed local trend and the global rise in sea level is due to local factors (changes in ocean and atmospheric circulation and local uplift[4]) and to measurement and trend-extraction errors. The respective influence of these factors is still unclear.

Expected global sea level rise. Global sea levels are projected to continue to rise as the world warms, increasing mean sea level rise at a local level. The 2007 Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) projected that global mean sea levels would rise by 18 – 59 cm above 1990 levels by the 2090s (where the lower bound corresponds to the lower estimate for the lowest emissions scenario, and the higher bound corresponds to the upper estimate for the highest scenario). These projections, however, do not fully include contributions from the melting ice sheets (due to the limitations of the modelling techniques used; see Oppenheimer et al., 2007). Rahmstorf (2007) uses a different technique to estimate future sea level change. This technique uses the observed relationship between global sea levels and temperature to project future sea levels from temperature projections. While very simplistic, this technique has the advantage of using real data and avoiding many of uncertainties introduced through using global climate models. Rahmstorf (2007) projects that global sea levels could increase by around 50 – 140 cm above 1990 levels by 2100. This analysis uses both IPCC and Rahmstorf results in order to bracket uncertainty to better understand and plan for plausible range of climate change outcomes.

Expected regional sea level rise. In terms of regional changes, the IPCC found that sea level rise could be greater than the global average around northern Europe. Their Fourth Assessment report report gives evidence that, for a medium emissions scenario (21 – 48 cm rise by the 2090s), sea levels could rise by an additional 15 – 20 cm around Denmark (IPCC 2007). However, these estimates are considered highly uncertain and so are not used in this study. Any local vertical land movements would need to be added to estimate the overall mean sea level change. As Copenhagen is experiencing uplift, this will offset a portion of the increase in sea levels due to anthropogenic warming. To simplify the assumptions and make the findings more generic, here we include only the global sea level rise component in our calculations in this study. However, it must be noted that for adaptation planning, more detailed estimates of local vertical land movements and uncertainties in regional climate change-driven sea level rise must be considered.

Expected change in storm surges. On top of these mean changes in sea level, the water height will continue to vary over time as a result of weather-related effects (including storm surges). Climate change affects the amplitude of these variations in two ways, firstly by simply raising the water level (in line with the rise in background water level), and also (potentially) by changing the frequency of the variability through, for example, changes in storminess. Storms, in particular extratropical cyclones, cause storm surges through a combination of the effects of winds in forcing higher wave heights and local sea level change due to the lower atmospheric pressure associated with the storm. An increase in the frequency of extratropical cyclones would reduce the return-period of present-day storm surge events; whereas an

[4] The National Space Institute of the Technical University of Denmark estimates that the land uplift in Copenhagen is about 1.2 mm per year (information kindly provided by Per Knudsen).

increase in the intensity of events could increase the return-period of weak events and reduce the return-period of intense events. Both could potentially increase the risks associated with storm surges.

It is not yet clear how climate change will influence the characteristics of extratropical cyclones. Climate physics tells us that a warming climate would have confounding effects on extratropical cyclones. However, while the body of evidence in this area gives a fairly clear picture that extratropical cyclones could become less frequent in both hemispheres, there could be a larger number of the most intense storms.[5] The most robust result is that there will be a poleward shift in the position of the storm tracks,[6] and therefore, some regions can expect to experience a lower frequency of storms, while others a higher frequency of storms. In Europe, studies project an increase in storm track density (the number of storms) over North western Europe, in particular, the UK and Scandinavia.[7] There is also evidence that the intensity of storms will increase over Europe.[8]

Long-term records of sea levels around Europe already show signs of an increasing trend in the frequency of extreme sea levels (i.e. a reduced return-period for intense events)[9]. A number of modelling studies suggest that, in the future, increases in extreme wave height are likely to occur in the mid-latitude oceans.[10] Woth *et al.* (2006) found that, for the North Sea, a 100-yr event could become 10 – 20 cm higher than today by the 2080s. They find that extreme events would increase even more significantly, with a 200-yr event along the North Sea coast increasing by 60 – 70 cm. Lowe *et al.* (2005) find that when the effects of atmospheric pressure, mean sea level rise and natural land movements are taken into account, a 50-yr return-period storm surge event becomes approximately 40 – 60 cm higher than today around the eastern coast of Denmark by the end of this century (for a medium-high emissions scenario). In the Baltic Sea, Meier (2006) found that water levels associated with a 100-yr event increase more rapidly than increases in mean sea levels. While most storm surge activity in the Baltic is concentrated in the eastern part of the sea, significant increases in the height of 100-yr surges were found in the Danish Inner Seas (under medium to high emissions scenarios). It should be noted that, in general, these models tend to underestimate the strength of extreme surges.

3. Insured Exposure Analysis

The exposure is the measure of the population and the assets that would be affected by a flood *in absence of flood protection*. Exposed population and assets should thus not be confused with at-risk population and assets in presence of protection. Exposure, however, is a useful metrics as it provides the basic information needed to assess the need for flood protections. In this section, exposure was calculated based on the area of land that would be inundated with different sea levels and on population and asset distribution.

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[5] e.g., Lambert and Fyfe (2006); Yin (2005); Lambert (2004); Leckebush and Ulbrich (2004); Lozano (2004); Fyfe (2003); Geng and Sugi (2003); Lambert (1995).

[6] e.g. Bengsston and Hodges (2006); Bengtsson *et al.* (2006); Salathe (2006); Fischer-Bruns *et al.* (2005); Yin (2005); Fyfe (2003); Geng and Sugi (2003); Kushner (2001).

[7] Bengsston *et al.* (2006); Lozano (2004); and Fischer-Bruns (2005).

[8] Bengsston *et al.* (2006) note an increase in the frequency of the most intense storms in Europe (despite seeing no significant increase globally), whilst Lozano (2004) finds an eastward shift in the most intense storms over the British Isles (as well as a general increase in intensity).

[9] Woodworth and Blackman (2002); and Bouligand and Pirazzoli (1999).

[10] e.g. Wang *et al.* (2004) ; and Caires *et al.* (2006).

Importantly, only insured assets are considered in this section. Since the 1991 Flood Act, the flood insurance scheme in Denmark is a public provided and (partly) publicly managed, tax-financed compensation scheme. The only tasks to be performed by insurance companies are to collect flood tax, receive claims forms from people having suffered losses and provide expert assistance when losses are assessed. As a consequence, all private properties are insured, and insured assets include all residential homes, personal property, businesses, and commercial property. Based on this, we assume that the insured residential, commercial and industrial exposure is roughly equal to the total exposure for these sectors. On the other hand, uninsurable assets, i.e. transport, energy and water infrastructures and government buildings, are not taken into account in the analysis presented in this section, but will be considered in Section 4.

Population and industry exposure where determined by mapping population and industry distribution data onto a Digital Terrain Model (DTM). Population data was obtained from Landscan 2002 (constrained within metropolitan extent limits) and verified against UN 2005 population data (UN 2005). The metropolitan area was defined using postcode information (from RMS data). Industry exposure data was based on the industry exposure data from the RMS European Winterstorm Model.

The DTM was generated from the 90 m (horizontal resolution) elevation database of the Shuttle Radar Topography Mission (SRTM). Exposures by elevation were then extracted from the DTM at 1 m vertical intervals. Finally, cumulative exposures were calculated for each of the sea level events, through interpolating linearly between the vertical intervals. At the pixel level, the SRTM elevation data can have errors of up to 10 m, which is large compared with sea level changes we are considering. These errors, however, are much lower in flat areas, where flood risks are concentrated, and have a large long-wavelength component (at the continent scale) that is not a problem when investigating local elevation differences (see a complete analysis in Rodriguez et al., 2005). In the present analysis, moreover, elevation maps were created by analysing continuous contours isolines in the dataset, thereby smoothing out much of the short-wavelength errors. In spite of these corrections, however, individual pixels can have significant errors, and this dataset is not adequate, e.g., for the engineering design of sea walls and dykes. Nevertheless, when aggregated over larger areas (e.g., neighbourhoods), this data is able to provide a fair estimate of the elevation and can, therefore, be used to estimate the exposed population and assets in the city.[11] Considering this limitation, the present study aims at estimating present and future flood risks in Copenhagen and assessing the need for protection and adaptation measures. If they are found necessary, designing such measures would then require an additional study based on higher-resolution exposition and elevation datasets. The subsections below describe the key findings. Further exposure maps are given in Appendix A.

3.1. General exposure findings

The exposure analysis has shown that around 2% of the population (21,907 people) live below an elevation of 1 metre, 4% (44,446 people) live below an elevation of 2 metres and 13% (151,859 people) live below an elevation of 5 metres above sea level (Figure 3). Figure 4 demonstrates that the most exposed areas of the city lie on the island of Amager and along the coastline of the larger island of Zealand (particularly to the south). These places are those that need flood protections, as described in Section 4.3. The most densely populated area of Copenhagen, to the west of the centre, is at relatively low vulnerability, as it lies away from the coast at an elevation of at least 5 m above sea level, and in some parts more than 10 m.

[11] A visual comparison of these results with a Danish high resolution DTM provided by Steffen Svinth shows good agreement with respect to vulnerability by city region.

Figure 3. Total (and percentage) population exposed at raised sea levels

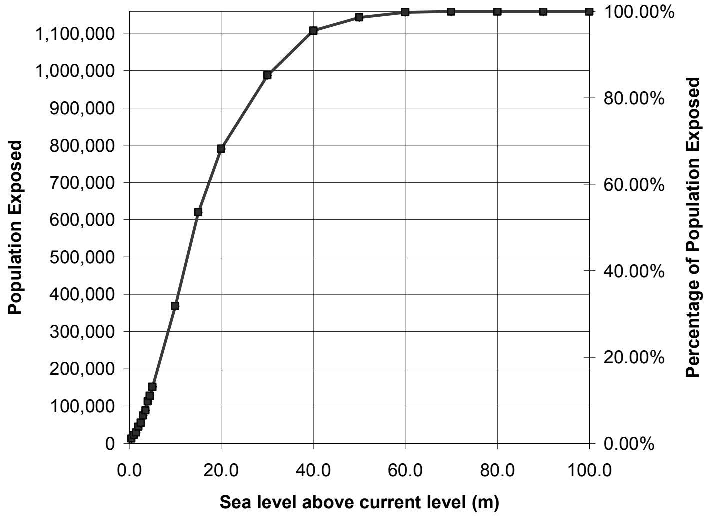
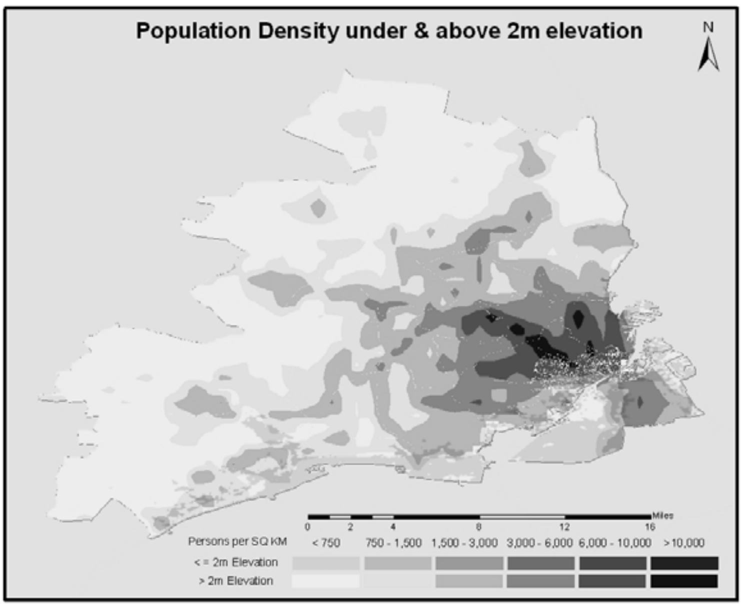
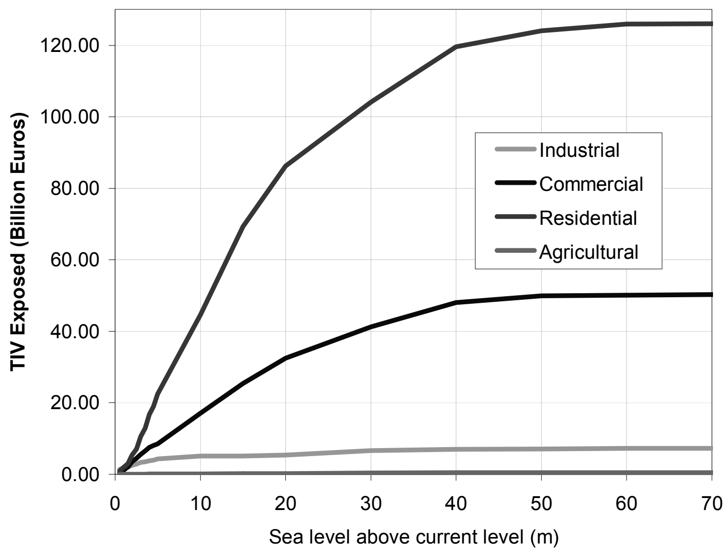


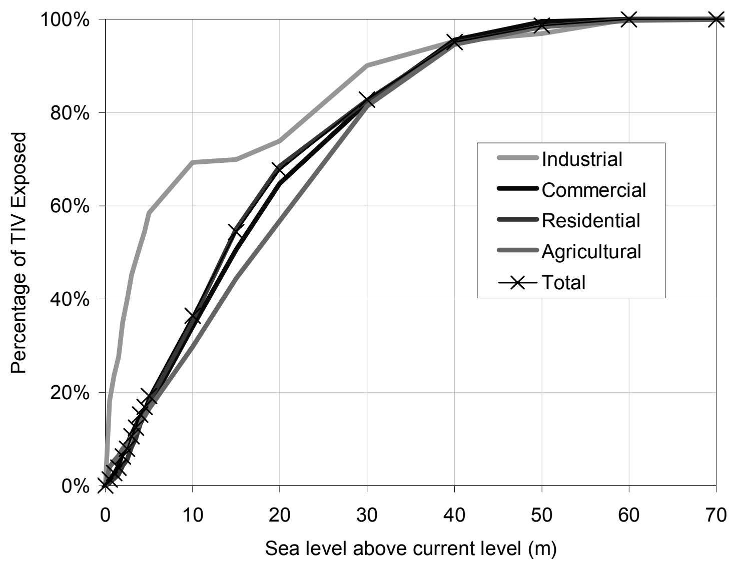
Figure 4. Population density situated in areas with an elevation below (orange) and above (green) 2 m elevation above sea level. Orange areas show where flood protections are necessary (see a description of Copenhagen protections and residual risk in Section 4.3 and Figure 18).



Residential land-use makes the single largest contribution to the overall total insured value (TIV), followed by commercial land-use (Figure 5). The relative exposure of different land-use types changes with elevation. In terms of TIV, the industrial sector is most exposed to low levels of sea level increase due to its location by the coast. Around 24% (EUR 1.7bn) of the insured industry value of Copenhagen lies below an elevation of 1 metre, and 18% (EUR 1.3bn) lies below 0.5 metres. Most of this lies along the facing coasts of Zealand and Amager, and on the southern coast (Appendix A, Figure A5). A sea level 4 m above the current normal level would expose half of the industrial TIV.

Figure 5. Total Insured Value (TIV) exposed (top), and percentage of total TIV exposed (bottom), at raised sea levels for industrial, commercial, residential and agricultural land-use types





Residential land-use becomes the largest value contributor to exposed TIV for a sea level rise of more than 1 m above current normal level. Many of the high value residential areas on the island of Amager are exposed to sea level rise of only a few metres (Appendix A, Figure A3). Just over 4% (EUR 5.4bn) of total residential value is exposed at a sea level rise of 2 metres. Commercial exposure is concentrated in a few high-value pockets (Appendix A, Figure A4), with a vertical profile of exposure similar to the residential sector. Agricultural total insured value is relatively low, unsurprising for an urban area.

Figure 6. Total exposures above and below 2 m elevation above sea level. Orange areas show where flood protections are necessary (see a description of Copenhagen protections and residual risk in Section 4.3 and Figure 18).

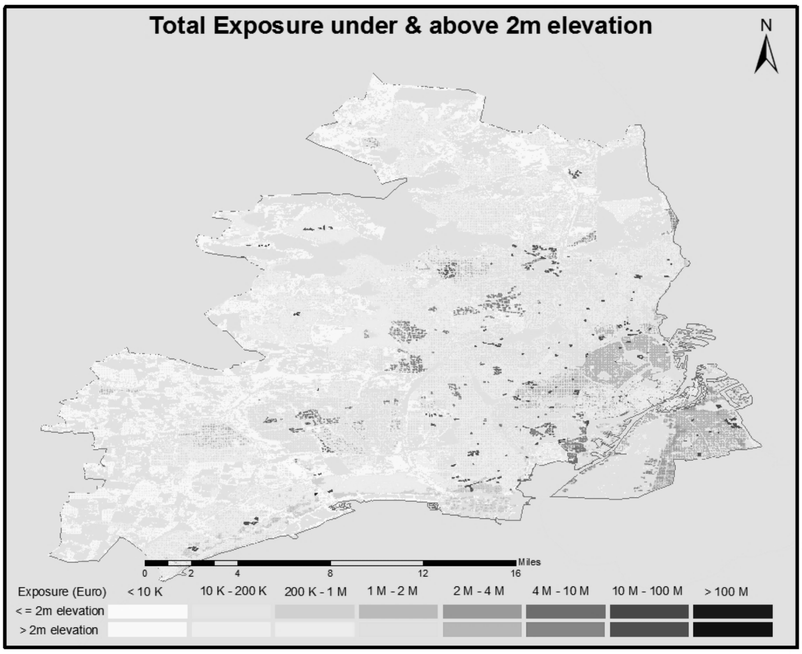


Table 2. TIV Exposure for various elevation range with respect to current mean sea level (in millions Euros)

Elevation Range	Residential		Commercial		Industrial	
	Structure	Content	Structure	Content	Structure	Content
0m - 0.5m	640	270	236	71	393	933
0.5m – 1m	737	311	699	210	119	283
1m - 1.5m	691	292	495	427	84	199
1.5m – 2m	1735	732	841	554	165	390
2m - 2.5m	1183	499	534	436	105	249
2.5m – 3m	2476	1045	377	657	117	276
3m - 3.5m	1567	661	725	217	65	155
3.5m – 4m	2768	1168	742	223	68	162
4m - 4.5m	1507	636	498	149	62	148
4.5m – 5m	2514	1061	102	307	88	209

Table 2 summarizes the insured asset exposure for different elevation ranges, measured with respect to current mean sea level, in millions of Euros. This table distinguishes between the structure exposure (i.e. the buildings themselves) and the content exposure (i.e. what is in the buildings).

3.2. Expected changes in insured exposure due to sea level rise alone

Over the next century, sea level around Copenhagen could expose many more thousands of people and billions of Euros in assets to flooding. To investigate this issue, two sea level events are considered in this study. These are shown in Table 3. The first represents the mean change in sea level rise only, as described in Section 2.3. The second event combines global sea level rise and a temporary storm surges of 150 cm (corresponding to a 120-year return period).

Table 3. Sea level scenarios for Copenhagen

		Sea level (above 1990 levels) (m)			
		1990	2030	2050	2100
1	Mean sea level rise	0	0.1 – 0.2	0.2 – 0.4	0.5 – 1.4
2	Storm surge scenario	1.5	1.6 – 1.7	1.7 – 1.9	2.0 – 2.9

These events are defined to encompass a broad range of possible futures. Understanding the full range of possibilities is essential for planning risk management strategies. To represent this broad range of scenarios, the long-term sea level rise scenario is based on both Rahmstorf (2007) and IPCC (2007). This is because the IPCC scenarios alone do not include in a satisfactory manner all components of sea level rise and therefore do not capture the full range of possible outcomes. Our scenario incorporates the uncertainty bound defined by Rahmstorf (2007). This uncertainty captures both future emissions uncertainty and the uncertainty in the relationship between global sea level rise and temperature. The scenarios do not take into account any regional variations in mean sea level (due to atmospheric circulation or uplift/subsidence). To estimate the exposure to climate change with storm surges, we take the example of a storm surge of around 1.5 m.

This study focuses on the 21st century with coastal flood risks investigated for sea level rise of up to 140 cm. It should be mentioned, however, that most of the rise in sea level due to climate change will occur after 2100 and that, over the very long term, much larger sea level rises are possible. According to the IPCC (2007), if global temperature is sustained at more than 2-3°C above the pre-industrial temperatures, the Greenland ice sheet may melt entirely, leading to as much as 6 m of sea level rise over several millennia. Considering the lifetime of many coastal investments (e.g., buildings, port infrastructure), additional analysis of coastal flood risks further in the future and for larger amplitudes of sea level rise would be useful.

Table 4 summarises Copenhagen exposures for these two sea level events, assuming unchanged population and assets. The impact of future socio-economic changes are explored in Section 3.3.

Table 4. Exposures in population and insured values for the two sea level events.

		Population Exposed (thousands)	Total Insured Value (TIV) Exposed (Billions Euros)				
			Residential	Commercial	Industrial	Agricultural	Total
Sea level rise under climate change	2030	3.3 – 5.2	0.2 – 0.4	0.1 – 0.1	0.3 – 0.5	0.0 – 0.01	0.7 – 1.0
	2050	5.1 – 10.4	0.4 – 0.7	0.1 – 0.2	0.5 – 1.1	0.01 – 0.02	1.0 – 2.0
	2100	13.0 – 27.6	1.0 – 2.7	0.3 – 2.0	1.3 – 2.0	0.02 – 0.03	2.6 – 6.7
120-yr surge (~150cm today) with sea level rise	1990	29.1	2.94	2.14	2.01	0.03	7.12
	2030	33.0 – 35.2	3.6 – 3.9	2.5 – 2.7	2.2 – 2.2	0.03 – 0.03	8.3 – 8.9
	2050	35.2 – 41.4	3.9 – 4.9	2.7 – 3.3	2.2 – 2.5	0.03 – 0.04	8.9 – 10.7
	2100	44.4 – 71.2	5.4 – 9.9	3.5 – 5.3	2.6 – 3.2	0.04 – 0.05	11.5 – 18.5

Exposure to mean sea level. Assuming the population and city remained the same, by 2030 around 0.2 – 0.4% of the population, or 3,300 – 5,200 people, are estimated to be exposed, i.e. at some risk of coastal inundation and dependent on adequate sea defences even in absence of storm surge. The sea level, and hence, number of people exposed, increases strongly after 2050, raising the number of people exposed five to six-fold, with 13,000 – 27,600 people exposed by 2100 (1.0 – 2.0% of the population).

Exposure to storm surges and mean sea level rise. As a result of rising mean sea levels, the exposures associated with a 120-yr storm surge could more than double by the end of the century, in an unchanged city. By 2030, the exposure from such an event is estimated to rise to around 33,000 – 35,200 people, and a TIV of EUR 8.3 – 8.9bn. By the end of the century, the exposure is estimated to reach around 44,400 – 71,200 people, or 3.2 – 5.1% of the population, and a TIV of EUR 11.5 – 18.5bn.

Section 2 described how climate change could directly raise the likelihood of extreme storm surge events through changing storm characteristics. While it is impossible to approximate the scale of the change to return-periods, recent evidence suggests that the return-period for a given amplitude of storm surge will reduce in the future due to increased storminess around North western Europe; that is, the extreme high water levels may become even more frequent than suggested above.

3.3. Expected changes in insured exposure due to socio-economic drivers

These values are calculated using the current economic situation in Denmark. Of course, socio-economic and population changes will influence exposure in the future.

According to the 2005 UN population growth scenario, the Danish population should increase by 2% by 2070. Assuming that the Danish urbanisation rate will increase from 86% today to 90% in 2070 and that all Danish city will grow at the same rate, the Copenhagen population would increase by 7% by the 2070's. This population increase is small and it is unlikely that the global risk profile of the city would change substantially due to population growth. Over the long term, however, risk-oriented land-use policies can influence risk levels: the replacement of old building or industrial property can be prohibited or discouraged in at-risk areas, and new developments can be favoured in less-exposed locations. In this analysis, however, it is assumed that no such policy is implemented, and that urbanized areas will basically remain unchanged in the future. However, it is expected that existing properties in these unchanged urbanized areas will be replaced through normal processes, increasing in value in response to economic growth. Based on the OECD economic scenario for economic growth in Denmark, indeed, all exposed values could be multiplied by 3.5 due to GDP growth. Taking into account these population and economic projections, exposure to a 150 cm storm surge could touch in the 2080-2100 period between 47,500 – 76,200 people with a TIV around EUR 40.3 – 64.8bn.

The OECD scenario is only one of many possible scenarios given the large uncertainties in future socio-economic and population changes. To take into account these uncertainties, it is common to carry out sensitivity analyses, using many scenarios to investigate how results are sensitive to socio-economic drivers and hypotheses.

While increased economic growth increases exposure, it also increases resilience in the affected economy, making it more capable to deal with disasters and reconstruction. The most relevant figures to assess disaster seriousness, therefore, are the exposed population – in absolute numbers – and the ratio of exposed asset value to total asset value. These figures are likely to increase only marginally in the future in Copenhagen, as it is unlikely that the population of Denmark will increase rapidly in the future, and given that the urbanization process is almost complete in this country. As a consequence, no large change in socio-economic drivers is expected to modify our findings.

For this reason, the rest of this report will disregard the role of socio-economic trends on flood risks, to focus on the effect of climate change on the city as it is today, with current population and assets.

4. Flood Losses Analysis in Copenhagen

There is a complex link between exposure to high sea level and the destruction and losses caused by such episodes. First, a building that is affected by a flood is not 100-percent destroyed. Thus, direct losses caused by an event are usually significantly lower than the exposure to this event. Second, high sea levels are frequent events, and cities are protected against the most frequent of them. In Section 4.1 and 4.2, we will first assume that the city is not protected and assess potential losses. This analysis provides the information required to design an optimal protection strategy. The actual protection of the city today, and the actual current flood risks in Copenhagen, are considered in Section 4.3. Moreover, as outlined in Section 3, considering the limited urban changes that are expected in the future in Copenhagen, this analysis is based upon Copenhagen as we find it today (i.e. an unchanged city over time).

4.1 Assessing direct losses in absence of protection

In this section, we focus on the direct losses caused by storm surges, i.e. on the repair and replacement cost of damaged buildings and equipment. Of course, this cost is only a fraction of total cost, and additional components of total cost (e.g., production loss, job loss) will be investigated later in the study.

For each sea level, it is possible to estimate exposure as a function of flood depth, assuming that no protection has been implemented (Table 4). Then, using *vulnerability curves,* which provide a loss ratio, i.e. the ratio of damages to total exposure as a function of flood depth[12], it is possible to estimate the losses to insured assets that are due to any sea level.

As mentioned in Section 3, non-insured assets, such as public infrastructure, were not included in the exposure analysis. To provide an unbiased estimate of flood risk, however, it is essential to include these assets. Unfortunately, very little information and data are available on this question, and one has to rely on best-guess estimates, based on past experiences. Here, we will use the well-documented consequences of the Katrina landfall in New Orleans to help assess infrastructure losses.

According to the Louisiana Recovery Authority,[13] the Katrina losses were distributed as follows:

- Residential homes and personal property (USD 27-35 billion).
- Businesses and commercial property (USD 25-29 billion).
- Infrastructure including roads, bridges, utilities (USD 15-18 billion).

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[12] Illustrative vulnerability data provided by Risk Management Solutions. It should be noted that early warning, disregarded here, can help reduce content losses. For instance, valuable equipment and furniture can often be saved by households if the event is forecasted early enough. The vulnerability data used here, however, take into account the average effect of early warning and mitigation measures. In the future, improvements in the ability to forecast storms and storm surges may reduce content losses significantly.

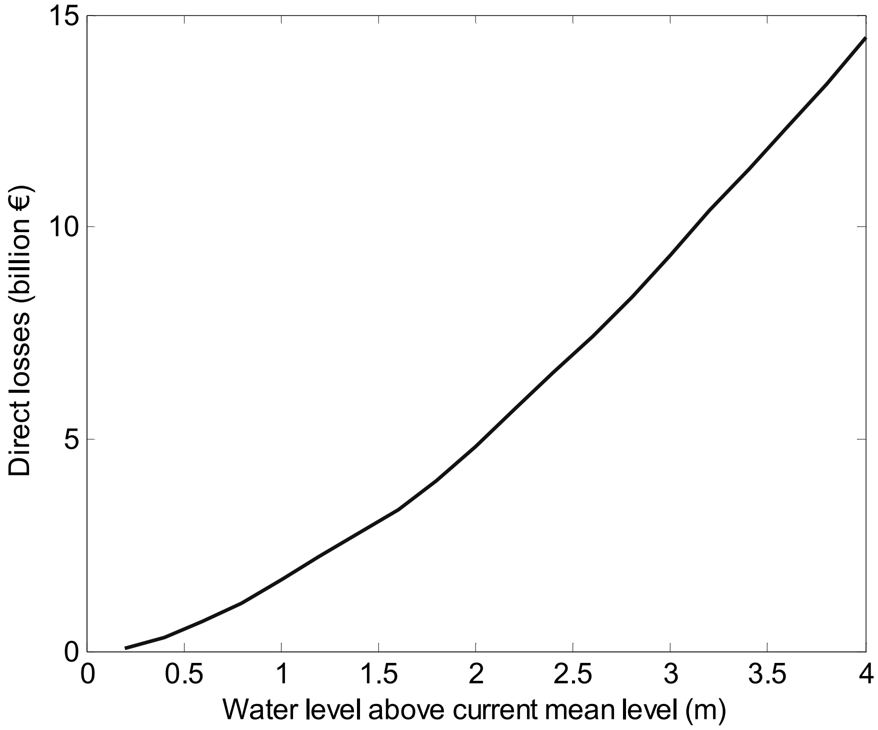
[13] http://www.lra.louisiana.gov.

- State facilities and public/private education and health care facilities (USD 6-8 billion).

We will assume, therefore, that uninsured losses (infrastructure plus state facilities) represent about 40% of insured losses (residential homes and personal property plus business and commercial). This estimate is also consistent with other studies in the UK.[14]

Figure 7 shows the direct loss estimates (insured + uninsured), as a function of the water level in Copenhagen, and in absence of protection infrastructures.

Figure 7. Direct losses as a function of sea level with respect to current mean level, in absence of protection



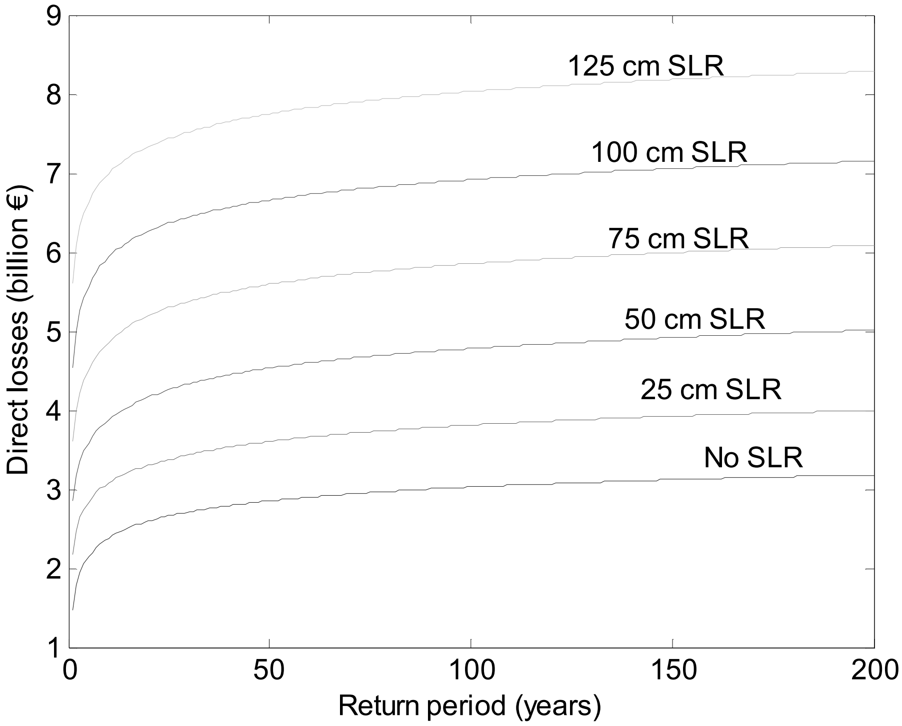
It is worth mentioning that these estimates do not take into account important parameters of flooding: local differences in water level, water velocity, flooding duration, various building types in different areas, etc. Taking into account these factors would require modelling explicitly the water flows, which is outside of the scope of the present study. This study, therefore, assess the magnitude of potential losses at the city scale, but a more detailed approach would be necessary, e.g., to assess losses neighbourhood per neighbourhood.

Using the flooding levels associated with various return-periods estimated in Section 2.2. (Figure 2), it is also possible to calculate, for different amplitudes of sea level rise, the losses associated with any return-period, in absence of protection. This is shown in Figure 8, where each line links the direct losses due to a flooding to its return-period, as a function of sea level rise and assuming that no flood protection is present. For example, in the current situation with the current sea level, a 120-yr event would cause direct losses amounting to about EUR 3.1 billion, for an exposure of EUR 7.1 billion. The mean loss ratio is, therefore, equal to 40%. For a sea level rise of 50 cm, a 120-yr event would cause direct losses

[14] See, e.g., Penning-Rowsell *et al.* (2002).

amounting to about EUR 4.8 billion, i.e. a 55% increase compared with a situation without sea level rise. This figure shows that, without protection, sea level rise increases flooding risks in a significant manner. The figure again does not take into account possible changes in intensity, trajectory and frequency of storms, which may increase or reduce storm surge risks.

Figure 8. Direct losses caused by the flooding of Copenhagen, as a function of the event return time, and for various level of sea level rise



4.2. Assessing total losses in absence of protection

Direct losses (the repair cost of the damages) are only a fraction of total costs due to a disaster. Several authors have suggested that the direct costs, generally evaluated by insurance companies, may be poor proxies of overall costs, particularly in the case of large-scale events (Tierney, 1995; Pielke and Pielke, 1997; Lindell and Prater, 2003; Hallegatte *et al*., 2007; Hallegatte, 2008). Direct costs can be amplified due to a number of different factors: (i) by spatial or sectoral diffusion into the wider economic system over the short-term (e.g. through disruptions of lifeline services) and over the longer term (e.g. sectoral inflation due to demand surge, energy costs, company bankruptcy, larger public deficit, or housing prices); (ii) by responses to the shock (e.g. loss of confidence, change in expectations, indirect consequences of inequality deepening); (iii) by financial constraints impairing reconstruction (e.g. low-income families cannot finance rapidly the reconstruction of their home); and (iv) by technical constraints slowing down reconstruction (e.g. availability of skilled workers, difficulties in equipment and material transportation, difficulties in accommodating workers).

In our approach, total costs are estimated, consisting of (i) the *direct* cost, i.e. the portion of the produced value-added that has to be dedicated to reconstruction instead of normal consumption; (ii) the *indirect* cost, i.e. the reduction of the total value added by the economy, because of the disaster. Here, therefore, the direct cost of an event is the repairing or replacement cost (at the pre-event price level) of the assets that have been damaged or destroyed. Direct costs are routinely estimated by insurance companies after each disaster. The indirect cost is the reduction in production of goods and services, measured in terms of value added to avoid double-counting issues. Indirect costs include business interruption in the event aftermath, production losses during the reconstruction period, and service losses in the housing sector. For example, if a EUR 1 million production facility is destroyed and immediately rebuilt, the total loss is EUR 1 million; if reconstruction is delayed by one year, the total loss is the sum of the replacement cost (direct cost) and of the value of one year of production (indirect cost). For housing, the destruction of a house with a one-year delay in reconstruction has a total cost equal to the replacement cost of the house plus the value attributed to lost housing services during one year.[15] The value of such production losses, in a broad sense, can be very high in some sectors, especially when basic needs are at stake (housing, health, employment, etc.). This distinction can also be represented in terms of stock (direct) and flow (indirect) losses.

Indirect losses are difficult to estimate, but must be included to ensure a fair cost-benefit analysis of protection infrastructures or mitigation actions. Here, the Adaptive Regional Input-Output (ARIO, see Hallegatte, 2008) model is used to assess these losses in the Copenhagen region. The model is based on IO tables and a hybrid modelling methodology, in the spirit of Brookshire *et al*. (1997). This dynamic model takes into account changes in production capacity due to productive capital losses and adaptive behaviour in disaster aftermaths. It should be noted that the uncertainty in results is still large, and therefore, results should be interpreted as indicative of the scale of potential damages. The model takes into account (i) the propagation of effects among sectors of reduced productions due to disaster damages; (ii) the propagation of effects among sectors of reduced demands due to disaster damages; (iii) the large demand in the construction sector due to reconstruction needs; (iv) the economic-agent behaviours to cope with disaster consequences (e.g., by increasing their production when demand is large, or by finding alternative suppliers when the original ones cannot produce); (v) the limitations in resource movement between sectors (e.g., the construction sector cannot grow instantaneously by hiring workers from other sectors; it is limited by the availability of qualified workers); (vi) the interaction with outside the affected regions (through imports and exports). Importantly, the model assumes that the economy will eventually return to its initial situation.[16] Also, impacts outside the Copenhagen region are not assessed, because these impacts are distributed over a large number of economic actors, and are therefore small (often negligible) on a per capita basis.

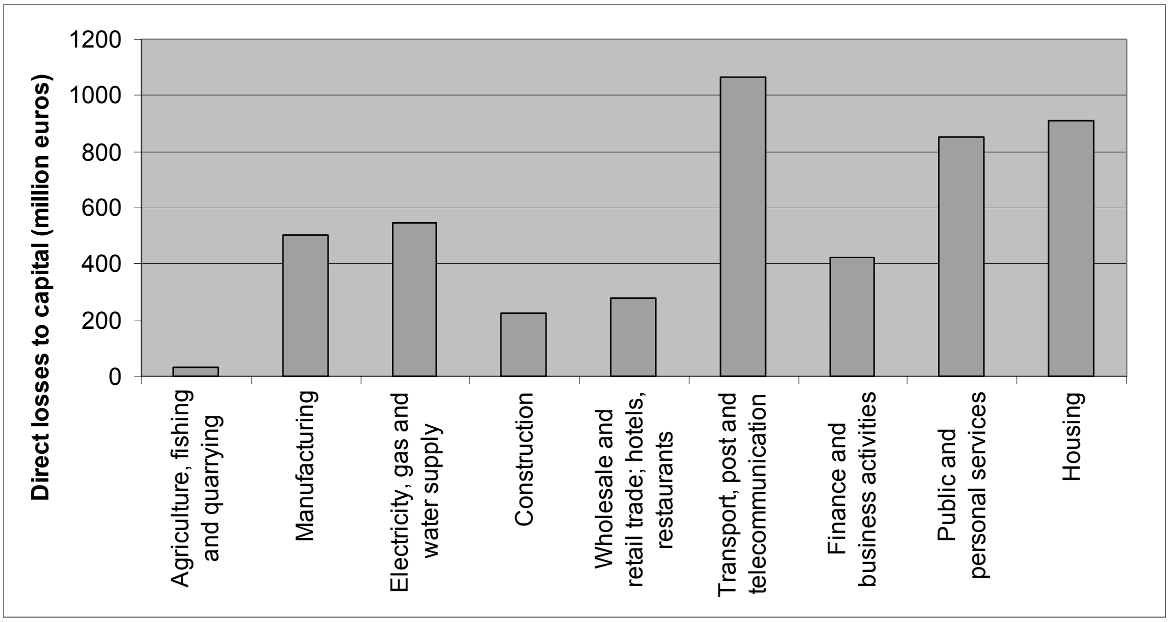
The model is applied to the Copenhagen region (“The Capital Region of Denmark”) using macroeconomic data from StatBank Denmark. The Danish economy has eight main sectors: (1) Agriculture, fishing and quarrying; (2) Manufacturing; (3) Electricity, gas and water supply; (4) Construction; (5) Wholesale and retail trade; hotels, restaurants; (6) Transport, post and telecommunication; (7) Finance and business activities; (8) Public and personal services. From the Danish Input-Output tables, a regional IO table for the Copenhagen region is built using simples rules based on the size of each sector in this region (see Hallegatte, 2008 for details).

Sectoral losses due to flooding are calculated based on the direct losses assuming that: Residential losses affect only households; Industrial losses affect sectors 2, 3, 4, and 6, according to the respective size of these sectors; Commercial losses affect sectors 5, 7 and 8, also according to their size. The 40% of uninsured additional losses are distributed between utilities (35%), transportation (35%), and public and personal services (30%). An example of the estimated sectoral losses for a 2m sea level above current level is provided in Figure 9. This corresponds roughly to the 120-yr event with a 50 cm sea level rise. The indirect effects of such an event are estimated in the following section.

[15] There is also a gain arising from the fact that, after reconstruction, assets are more recent than before the event. Considering infrastructure, production capital and housing, however, this gain is of second order.

[16] For instance, businesses are assumed to lose clients and market shares over the short-term, but clients are assumed to return eventually to their original suppliers over the long-term, restoring original market shares.

Figure 9. Estimated sector-per-sector losses due to a sea level 2 m above current sea level, in absence of protection



4.2.1. Case study: 2 m sea level rise

As an illustration, this section provides results for the 2 m case, assuming the absence of protection, or that such an event overtops installed defences. Using the ARIO model, the local IO table and the loss distribution per sector, one can simulate the consequences of the flooding on the local economy. This simulation is reproduced in Figure 10, which displays the change in value added (VA) in the 8 sectors as a function of time. The simulation shows both the reduction in VA in most sectors, and the VA increase in the construction and manufacturing sectors due to reconstruction needs. The losses and the gains balance each other, and the total loss in VA for the region is actually negative: the increase in production in the construction and manufacturing sectors is larger than production losses due to capital losses. The corresponding VA gain is of EUR 95 million. This VA gain is due to the mobilization of unused resources and is a positive effect of the disaster as it creates jobs and income. It has to be mentioned, however, that this additional production is used to repair and reconstruct what has been damaged by the flood, and should not be considered as additional consumption. Since there is a gain in total value added, the shock would not be detrimental at the macroeconomic scale, but it could be very problematic at the sector level (e.g., in the utility sector). Note that value added change is not a gain for all disasters: VA losses increase nonlinearly with direct losses and, from the 2.8 m event with EUR 8 billion in direct losses, total VA losses become positive.

The model also provides an assessment of the "production loss" in the housing sector. Indeed, houses and residential buildings produce a housing service that plays a major role in ensuring local well-being. The decrease in housing services because of damaged houses and buildings has, therefore, to be taken into account. The model, because it reproduces the reconstruction period and duration, can assess the total loss in housing service production. In the 2 m case, the model estimates this loss at EUR 260 million. The sum of all indirect impacts, therefore, is equal to EUR 165 million (accounting for the VA gain noted above).

Figure 10. Sector per sector change in value added (in %), for a sea level 2 m above current sea level, and in absence of protection

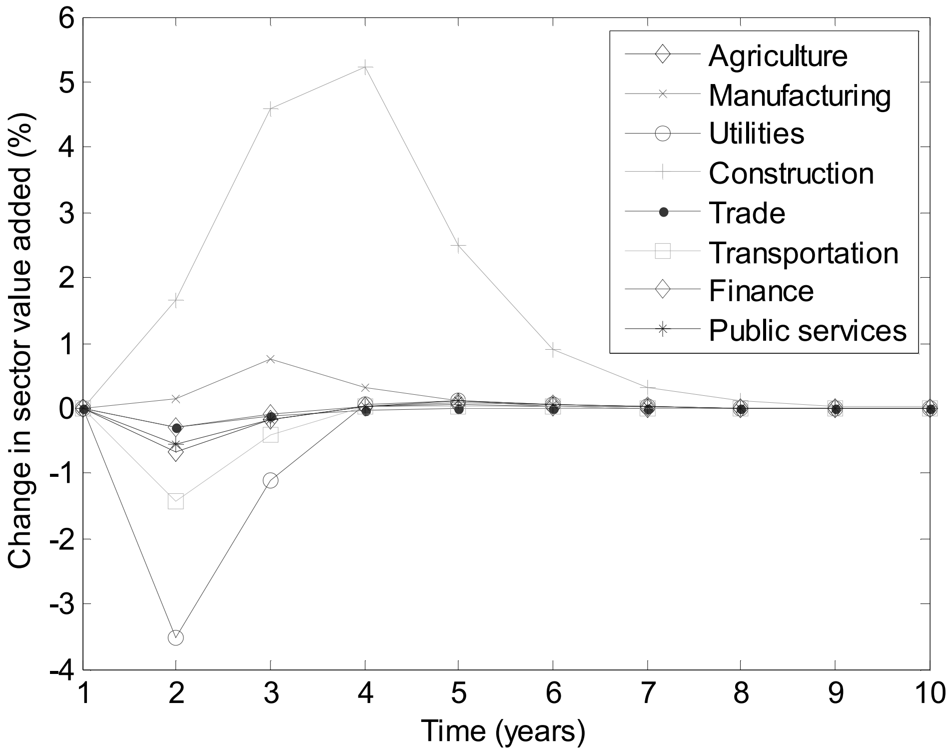
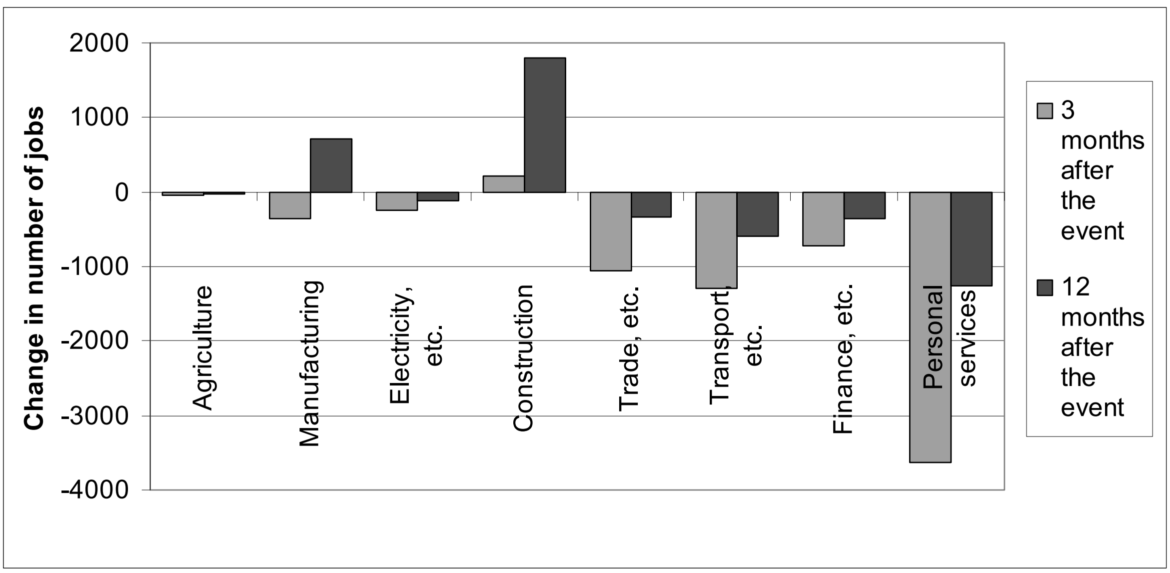


Figure 11 provides the job losses in the different sectors, 3 months after the shock (when disaster consequences are almost only negative), and 12 months after the shock (when reconstruction demand stimulates activity in the construction and manufacture sectors).

Figure 11. Change in number of job per sector (positive is for additional jobs, negative is for job losses) due to the 2 m event, 3 months and 12 months after the event, in absence of protection



Figures 10 and 11 demonstrate that, over the short term, all sectors but construction lose from the disaster, with 7,500 jobs lost 3 months after the shock. The sectors of (1) Wholesale and retail trade, hotels and restaurants, (2) Finance and business activities, (3) Transport, post and telecommunication, and (4) Public and personal services are particularly affected by the shock. Moreover, the use of ARIO to model the consequences of Katrina in Louisiana (Hallegatte, 2008) showed that employment losses in these sectors with many small businesses (e.g., personal services) were underestimated, as the model is not able to account for bankruptcy and business closure. It seems, therefore, that public aid should be directed toward these sectors in disaster aftermath.

The figures also show the positive economic consequences of the disasters: one year after the event, the reconstruction is underway and the construction and manufacture sectors are net creator of jobs, while lost jobs in other sectors are reduced by more than 50 percent. Nevertheless, the disaster still leads to 500 lost jobs at the aggregate level one year after the shock.

Two important points need to be mentioned. First, the model does not reproduce the very first weeks following an event, during which lifeline perturbations and emergency operations impair the functioning of the economic system. Additional production losses occur during this period, but they are assumed one order of magnitude lower than the production losses estimated here. Second, the model assumes that all reconstruction costs are supported by insurance or auto insurance, and households do not need to reduce consumption to pay for the reconstruction. This assumption is, however, fully acceptable for Denmark.

4.2.2. Link between direct losses and total losses

Indirect economic losses are found to be significant in this analysis and are strongly nonlinear with respect to direct losses. This nonlinearity arises from two factors. First, a larger disaster causes larger production losses at a given point in time. Second, a larger disaster leads to a longer reconstruction period and, therefore, production losses last for a longer period. These two factors are illustrated in Figure 12, which shows the reconstruction dynamics in the 2 m and 4 m cases. In the 4 m case, value added losses one year after the shock exceed 1.5% of the pre-event level, while they are only about 0.5 percent in the 2 m case. Moreover, total production is back to its initial level one year after the shock in the 2 m case, while it takes three years in the 4 m case. Full reconstruction is almost completed 8 years after the event in the 4 m case, against only 5 years in the 2 m case.

Due to additional production in the construction and manufacturing sector, VA losses in the production sectors remain limited or negative, ranging from EUR -95 million for the 2 m event to EUR 517 million in the 4 m event. Most indirect losses stem from the housing sector, where delayed reconstruction – due to production capacity constraints in the construction sector – has a large impact. Housing service losses reach EUR 257 million for the 2 m event and EUR 1.4 billion for the 4 m event. This type of loss is highly nonlinear, as illustrated by Table 5 and Figure 13. This figure shows the indirect losses, including housing services, as a function of water level. It shows that, up to the 1.5 m event (EUR 3.1 billion of direct losses), indirect losses are negligible. Above this value, however, they increase rapidly to reach EUR 2 billion in the 4 m event (EUR 15 billion of direct losses).

Table 5. Components of the total flood losses, as a function of water level above current mean level, in absence of protection

Event sea level wrt current mean level (m)	Direct losses (million EUR)	Indirect losses			Total Losses (direct + indirect) (million EUR)	Lost jobs after 3 months (thousands)
		Value added losses (million EUR)				
		Loss in productive sectors	Loss in housing services	Total value added losses		
1	1,668	-58	72	14	1,682	3
2	4,837	-95	257	162	4,999	7
3	9,341	64	682	747	10,088	14
4	14,478	517	1,446	1,964	16,442	21

Figure 12. Change in total value added (excluding housing services) as a function of time, for the 2 m and 4 m events in Copenhagen, in absence of protection

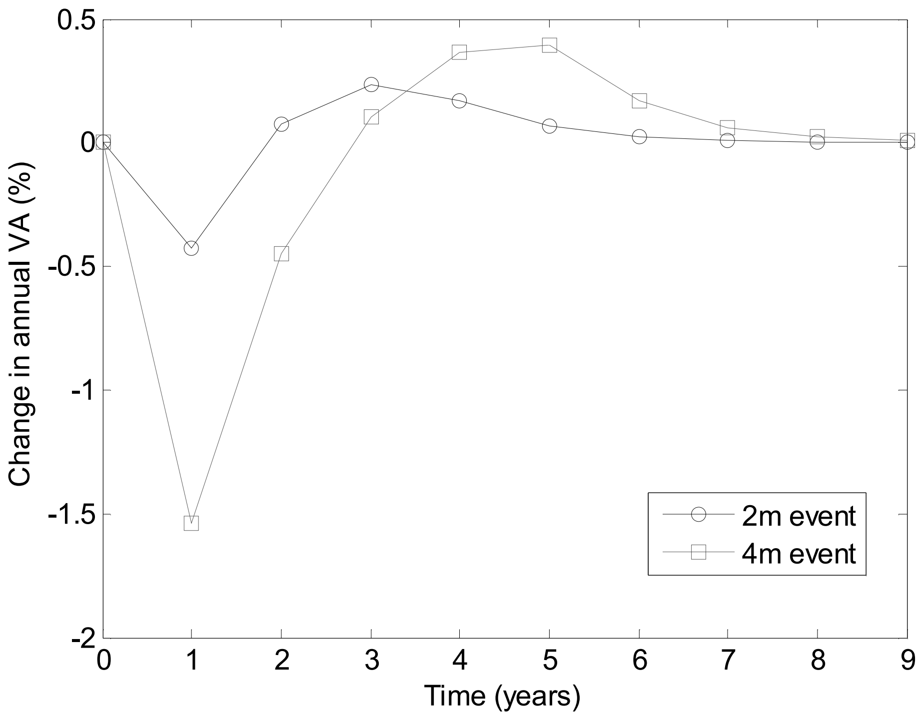
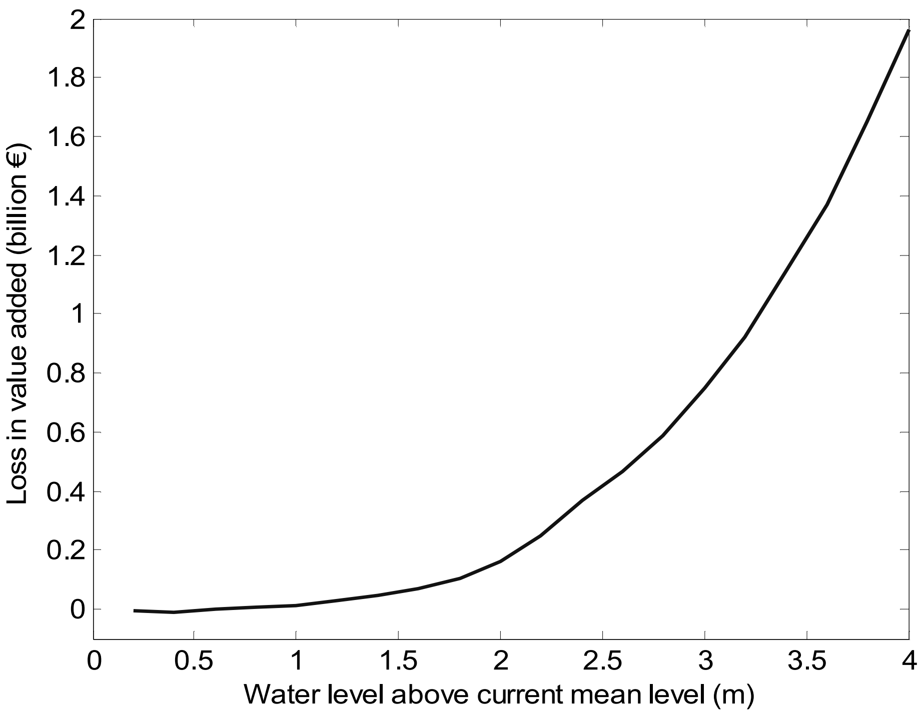


Figure 13. VA losses (productive sectors plus housing sector), as a function of water level above current mean level, in absence of protection



4.2.3. Link between sea level and total economic losses in absence of protection

From the information provided by the ARIO model and the assessment of direct losses due to various sea levels, we can estimate the overall economic consequences due to each of these sea levels. This is provided by Figure 14 and 15, which shows the total economic losses (direct losses plus production losses plus loss in housing services) and the total job loss 3 months and 12 months after the event.

Figure 14. Total economic losses as a function of sea level above current level, in absence of protection

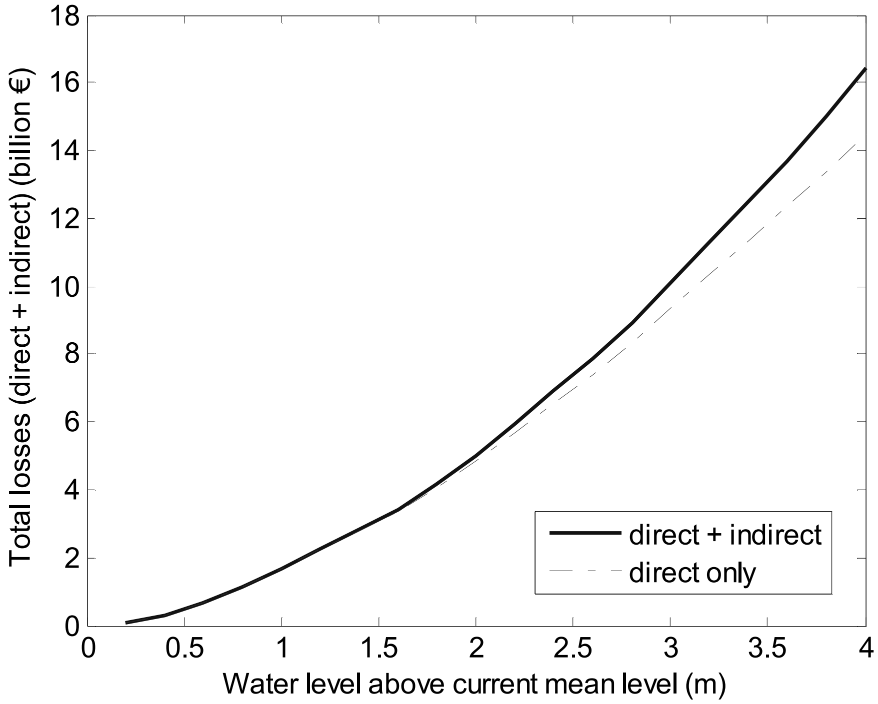
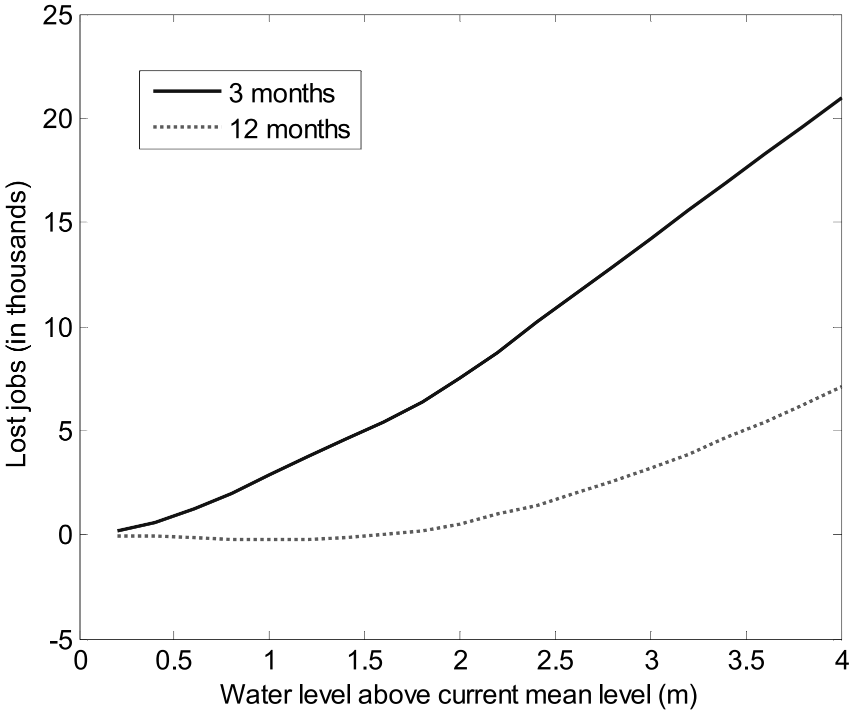


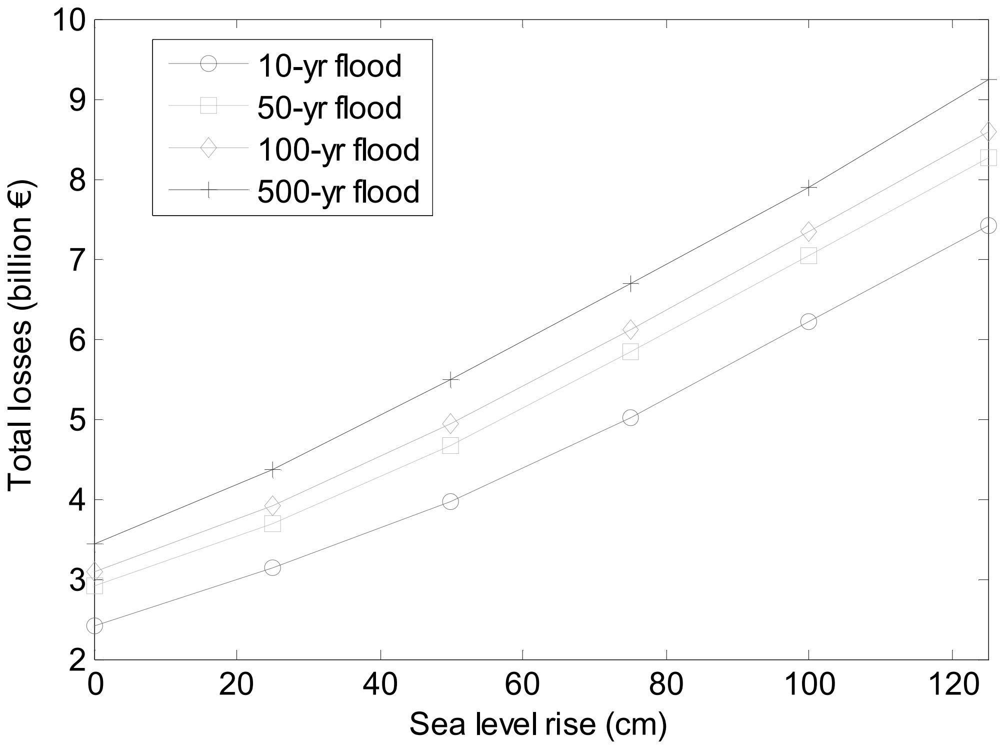
Figure 14 shows that indirect losses remain small compared to direct losses for all the events considered here, suggesting that adaptation measures have to focus on direct loss reduction (using dikes or reinforced buildings) rather than on indirect loss reduction (using insurance or support to small businesses). Figure 15 shows that job loss 3 months after the event can reach more than 20,000 jobs for the 4 m events. Most lost jobs, however, are recreated rapidly, as job loss are always lower than 7,000 one year after the storm. It should be mentioned that, while the aggregated job totals recover, there are still job losses in some sectors, with totals compensated by job creation in the construction sector. This shift could cause social problems requiring public action, including shortage of qualified workers in the construction sector. Further, short- to long-term structural unemployment among residents in non-construction professions could arise due to skill and qualification mismatches as employment in the other sectors recovers at a slower pace.

Figure 15. Lost jobs, 3 and 12 months after the event, as a function of sea level above current level



From the return level of high water level calculated in Section 2.2, and assuming that the water levels are only shifted by sea level rise, it is possible to calculate total losses as a function of return time. The results assuming no protection are reproduced in Figure 16. For instance, for no sea level rise, the water level with a 50-yr return time would cause total losses amounting to EUR 2.9 billion with no protection. With a 50 cm sea level rise, these losses increase to EUR 4.7 billion, a 60% increase. For the 120-yr event, losses are estimated at EUR 3.1 billion in the absence of SLR. Losses reach EUR 5.0 billion with a 50 cm sea level rise, also a 60% increase, and EUR 7.4 billion with a 1 m SLR, a 140% increase.

Figure 16. Total losses caused by the flooding of Copenhagen, as a function of the rise in mean sea level, and for various event return times, in absence of protection



4.3 Coastal protection in Copenhagen, residual risks, and future risks

The previous analysis provides estimates for exposure and loss potentials, information which is needed to design optimal flood protection through cost-benefit analysis or risk management strategies. A typical measure of the risk level is the mean annual loss, which is calculated as the sum of the occurrence probability of all possible events multiplied by the total losses they would cause.

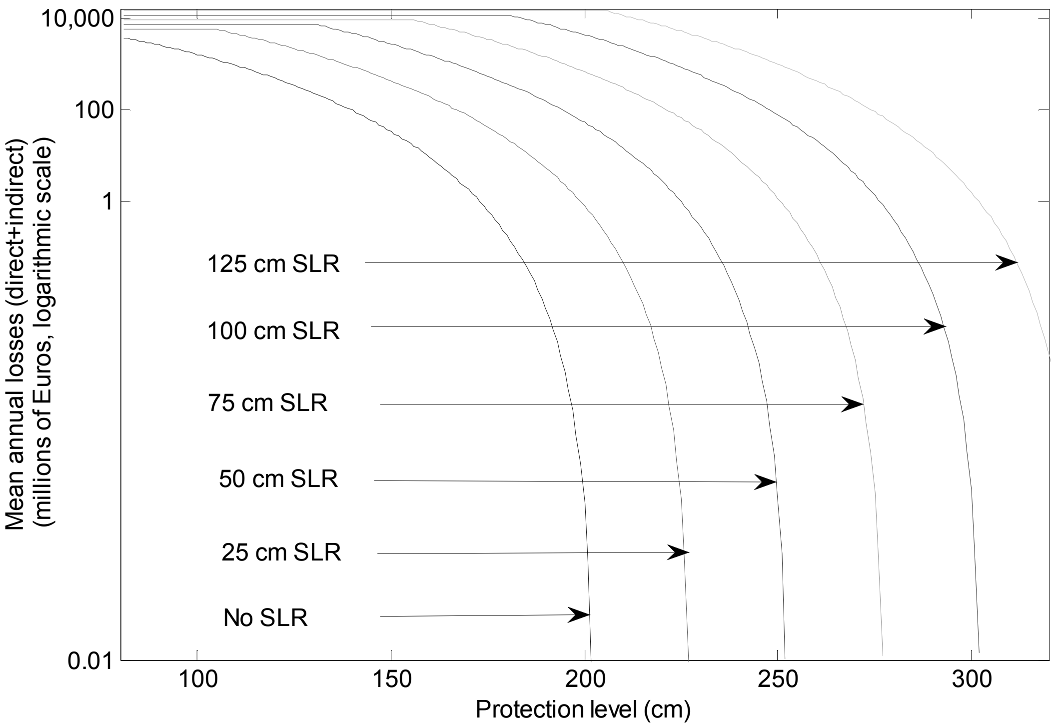
Figure 17 shows an assessment of mean annual losses (direct + indirect) as a function of the protection level, which is assumed uniform in the city, and for several levels of SLR. Our statistical analysis of storm surge considered only surges of more than 80cm, so protection below this level cannot be assessed. We also assume that an overtopped dike is totally inefficient to control coastal floods. This is oversimplified, of course, as even an overtopped dike – provided it does not fail completely – can limit the amount of water that enters the city, therefore reducing the flooded area.

The "No SLR" line in this figure shows that Copenhagen is currently easy to protect against storm surges: while annual mean losses can reach several billions of Euros with protection of less than 1m, they decrease very rapidly with protection height. They are lower than 100,000 Euros per year for 180 cm protection, and null for protection higher than 202 cm. Interestingly, this rapid decrease in mean annual loss arises from the probability of occurrence, which decreases very rapidly as water level increases (see Section 2.2 and Figure 2), not from the event losses, which are increasing almost linearly with water level (see Section 4.2 and Figure 14). In other terms, this decrease does not arise from the topography of Copenhagen, but from the characteristics of storm surges in its location, i.e. from the fact that the city is protected from the strongest storms by its localization.

Copenhagen has a coastline of about 60 km, and the building cost of 1m-high dikes is estimated to be about USD 2.5 million per km (Hoozemans *et al*., 1993). Using this as an assumption, it is possible to estimate the construction cost of coastal flood protection to be a few hundred millions of Euros for the city, for height of less than 2 or 3 meters. In particular, in the range of dike heights that are necessary given the sea level rise projections considered here, construction costs are not expected to exhibit strong nonlinearities. Considering the potential flood losses shown in Figure 17, it seems rational to protect the city with very high dikes. Taking into account the uncertainty in the different steps of our analysis, and especially the uncertainty concerning the highest possible storm surges assessed in Section 2.2, it is rational -- even in absence of sea level rise -- to protect the city with dikes that are higher than 202 cm.

Figure 17 also shows why it is necessary to have higher protection over time as sea level rises: with 202 cm protection, the annual mean loss is zero in our analysis with current sea level, but increases to EUR 1 million with 25 cm of SLR, EUR 52 million with 50 cm of SLR, and EUR 4.2 billion with 100 cm of SLR. With 300 cm protection, mean annual losses are non-zero only if SLR is larger than 1 meter; with 350 cm protection, even 125cm of SLR does not lead to any losses.

Figure 17. Mean annual losses, in million of Euros per year, as a function of the protection level, assumed uniform in the Copenhagen



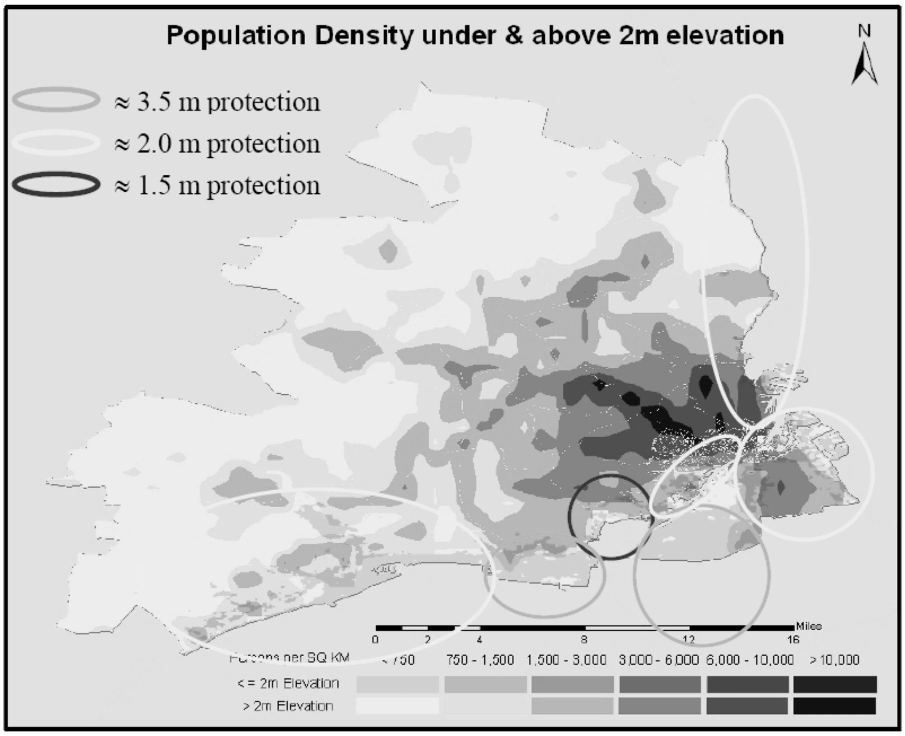
Note: when protection is less than 80cm higher than sea level (the horizontal lines in the figure), our methodology is not applicable.

Information about Copenhagen on existing protection suggests that the city is very well protected against storm surges. This is consistent with the results of our analysis (see Figure 18). First, in the Copenhagen city centre and in the harbour, quays are at more than 2m above current sea level. Considering the maximum possible storm surge in the current climate is estimated at 2m in our analysis (Section 2.2), this protection level suggests that the historical centre – where population density is very high – is not at risk of coastal floods today. In locations that are at-risk according to Fig. 4 and 6, protection is present in the form of dikes:

- The industrial area “Avedøre Holme”, located on the south coast of Copenhagen and highly industrialized (see Fig. 6), is protected by 350-cm dikes.
- The eastern part of the Amager island (mostly residential) is protected at the 2m level,
- The western part of the Amager island is currently protected at a level of 350 cm and is expected to be protected at higher standards in more distant future, up to 590 cm,
- The South stretch (Hvidovre) is protected at 150 cm, i.e. at the 120-yr return period,
- The South western coast (West for Avedøre Holme) is protected at 200 cm.

Considering this protection level, it seems that Copenhagen is very well defended, and in some places even over-protected (e.g., western part of Amager island)[17]. As a consequence, even a large amount of sea level rise could be managed by the current protection system. Only a few areas could be affected by storm surges with the current sea level (e.g., Hvidovre) and with higher sea levels (e.g., historical centre of Copenhagen and the harbour). In these areas, protection will have to be upgraded to prevent coastal flood risk from increasing rapidly across the ranges of sea level rise considered here. The concerned coastline segments are relatively limited but include important locations (e.g., the harbour and the city historical centre).

Figure 18. Population density under and above 2m elevation, and coastal protection, indicated by colored ellipsoids (green for 3.5m protection; yellow for 2.0m protection and red for 1.5m protection). In the current situation, only areas in red are vulnerable to storm surge; along this century, however, all areas in yellow will require protection upgrades.



[17] Due to the importance of protected assets in these areas (including the Copenhagen metro and the tunnel to Sweden), the protection level has been designed particularly large, to hedge against any surprise or measurement and design error.

In places that are the most vulnerable today (e.g., Hvidovre and its 150cm protection), improved defences are likely to be profitable in the current situation. A more detailed analysis with higher-resolution dataset would be needed to confirm this result. In the future, regardless, sea level rise will make it necessary to improve defences. Corresponding costs will, again, lie between a few tens and a few hundred million Euros.

Also, it is important to mention that coastal flood defences should not (and do not) consist only of dykes and sea walls. The presence of sea walls requires efficient drainage infrastructure to prevent the city from being flooded by heavy rainfall. In particular, in the presence of high dykes, a move from gravity-drainage to pumps may be necessary. Consequently, adaptation to coastal flood risks must be made in conjunction with improved rainfall flood management. Further, the design of drainage infrastructure must take into account future sea level rise projections.

Also, additional market and non-market impacts should be taken into account in protection costs. Market impacts include the functioning of the harbour, dike maintenance, drainage and pumping infrastructures, while non-market impacts include aesthetic considerations and city attractiveness. For very large increases in sea level, these costs may become significant and will need to be balanced against the benefits of "hard" protection. For instance, building dikes in addition to the quays in the historical centre may have negative aesthetic effects, and possibly an impact on city attractiveness.

Nevertheless, sea level rise will lead to a large increase in flood exposure. Even though flood probability and risk can be reduced to extremely low levels with high levels of protection, the consequences of defence failure or overtopping greatly increase with sea level rise (see Table 4 and Figure 16). This increasing exposure makes it critical not only to upgrade flood defences, but also to rigorously maintain them, since the consequences of failure would be very large. Also, it will be necessary to improve emergency plans, as failure is always possible and the management of large-scale floods requires early warning and disaster preparedness and organization.

Finally, past experience demonstrates that the retrofit of coastal defence structures is a lengthy process requiring forward thinking and planning. For example, there was a 30 year lag between the decision to build the Thames barrier and its actual implementation. This analysis suggests that it is necessary to start thinking about long-term adaptation in coastal cities today, even if the risks of climate change are not imminent.

5. A methodological roadmap to design adaptation measures and assess mitigation benefits in coastal cities

We have seen that Copenhagen has an extremely high level of protection and so is at relatively low risk from coastal flooding and thus may not be the best of cities for study of climate change risk and policy benefits.[18] However, such a high level of protection is far from widespread among the world coastal cities. For this reason, we use a *virtual city* representation of Copenhagen to demonstrate a methodology designed to assess the economic impacts of climate change. As noted above, assessment of economic impacts of sea level risk in coastal cities permits decisionmakers to better design adaptation policies and measures and to assess mitigation benefits. In this *virtual city*, we consider Copenhagen with coastal

[18] The protection levels reported in this study within the larger Copenhagen agglomeration were compiled during the course of this research. Interestingly this information came forward only after several months of interactions with national and local authorities. It was not readily available at the outset of the project. The project itself appears to have provided a stimulus for better information flow amongst local actors and national authorities and to have facilitated consideration of changing risks of coastal flooding under various plausible scenarios of sea level rise due to climate change.

defences at the level of 150 cm. According to our statistical analysis of storm surge (Section 2.2), a water level at 150 cm above the mean level is associated to a return-period of 120 years, which is already a high level of protection by comparison with other cities worldwide (e.g., New York is protected at a lower level; see Nicholls et al. 2007).

Analysis of this virtual city allows us to draw more general insights into the vulnerability of coastal cities to sea level rise and storm surge extreme events.

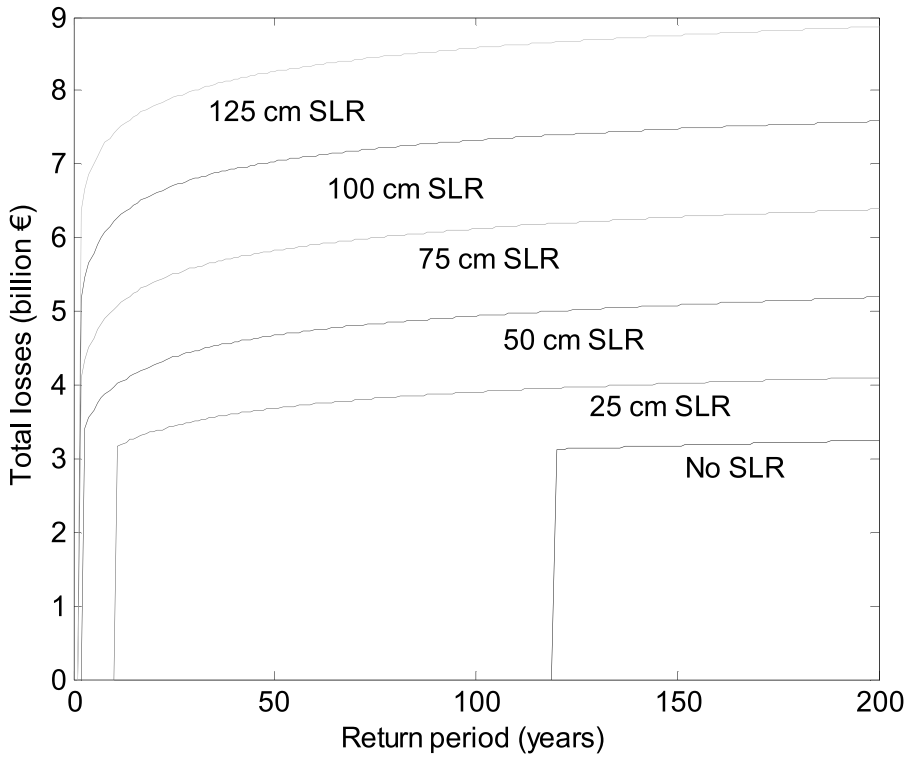
5.1 Protection and benefits from adaptation

The virtual city is currently protected against storm surge up to the 150 cm level. In Figure 19, the "No SLR" line shows how total losses change with the return period, with the current sea level. When the surge is below 150 cm, it is assumed that losses are null; when the surge is above 150 cm, losses are assumed to be unchanged by the protection. With sea level rise, protections will be upgraded; several assumptions are possible about these upgrades. They are described below.

Unchanged protection. A possible assumption is that the protection will not be modified in the future. In this case, total losses are reproduced in Figure 18, which shows total losses as a function of the return-period, for different amplitudes of mean sea level rise. This figure shows clearly that protection will have to be upgraded in case of sea level rise: even with only a 25 cm SLR, the city protection level would decline from 1-in-120 years to 1-in-10 years. The decadal event would cause up to EUR 3 billion of losses.

These results can be translated into assessments of flood risks, i.e. of the mean annual losses from coastal floods, using Figure 17. In the current situation, with dikes protecting the city from storm surge up to 150 cm, the mean annual losses are equal to EUR 30 million. With 25 cm of SLR and the current level of protection without improvements, annual losses would increase from EUR 30 million to EUR 385 million. With 50 cm of SLR, they would reach EUR 2.4 billion. For larger SLR and unchanged defences, annual losses cannot be estimated as urban floods could occur several times each year, making our assessment methodology inapplicable. These results show that climate change and sea level rise require the retrofit of coastal flood defences in *the virtual city*.

Figure 19. Total losses caused by the flooding of the virtual city, as a function of the event return time, and for various level of sea level rise, assuming unchanged protection, at 150 cm above current mean sea level

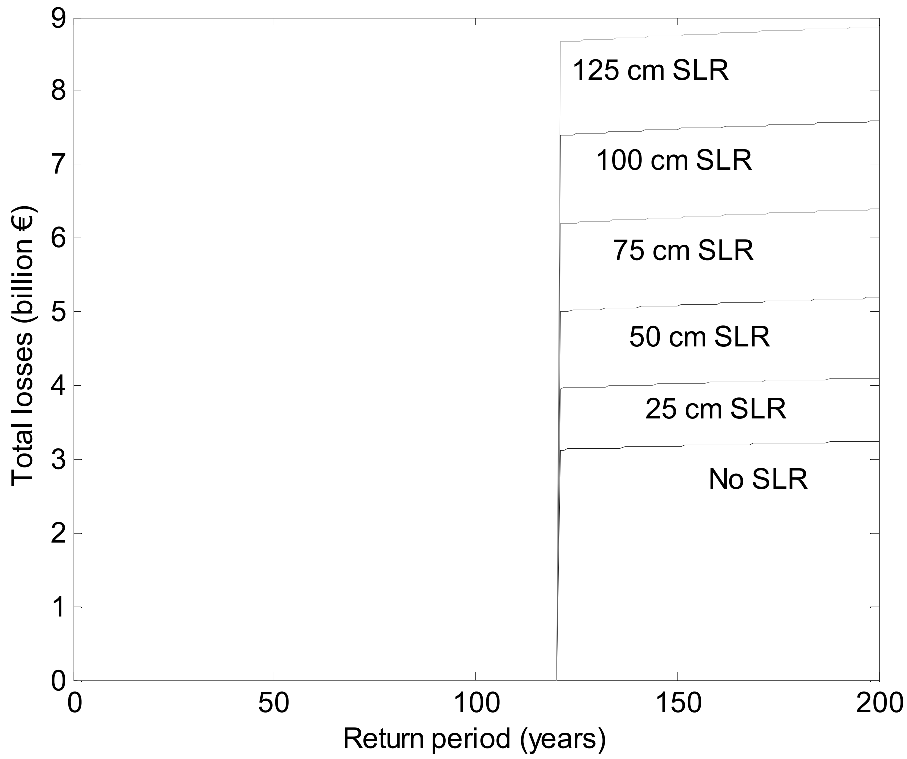


This result illustrates how a limited rise in sea level can increase flood risks where protections are designed to cope only with present-day conditions: in this *virtual city*, 25 cm of SLR is enough to make the present-day 120-year event occur every 10 years on average, and multiply mean annual losses by ten. In many coastal cities, therefore, flood protection will require significant defence upgrades to avoid unbearable increases in flood risks. If sea level rise in this century is large, these upgrades will need to be implemented in the next decades to prevent significant economic losses.

Maintained flooding probability. Since protection upgrades will be needed, Figure 20 assumes that flood protection is modified to maintain a 1-in-120 years protection standard. Doing so requires raising flood defences by the same height as sea level rise: in case of a 25 cm SLR, flood defences must be made 25 cm higher.

Figure 20 shows that such a protection upgrade can eliminate the risk from events with a return-period lower than the protection standard (here 120 years). If an overtopping event occurs, however, the losses would be much larger than without SLR. This effect would increase the level of risk, defined as the product of the probability of a hazard by its consequences.

Figure 20. Total losses caused by the flooding of the virtual city, as a function of the event return time, and for various level of sea level rise, assuming maintained flooding probability



Note: In the figure, we assume that the city remains protected against the 120-yr event.

As a consequence, maintaining the flooding probability unchanged would lead to a large increase in risk. For instance, a 25 cm SLR with a defence upgrade keeping flood probability unchanged would make annual flood losses rise from EUR 30 million to EUR 38 million, i.e. a 27% increase. A 50 cm SLR would make them reach EUR 48 million, i.e. a 60% increase. Table 6 provides the annual flood losses for amplitudes of SLR from 0 to 125 cm.

Table 6. Annual flood losses for different amounts of sea level rise, assuming that flood defences are upgraded to maintain flooding probability at 1-in-120 years

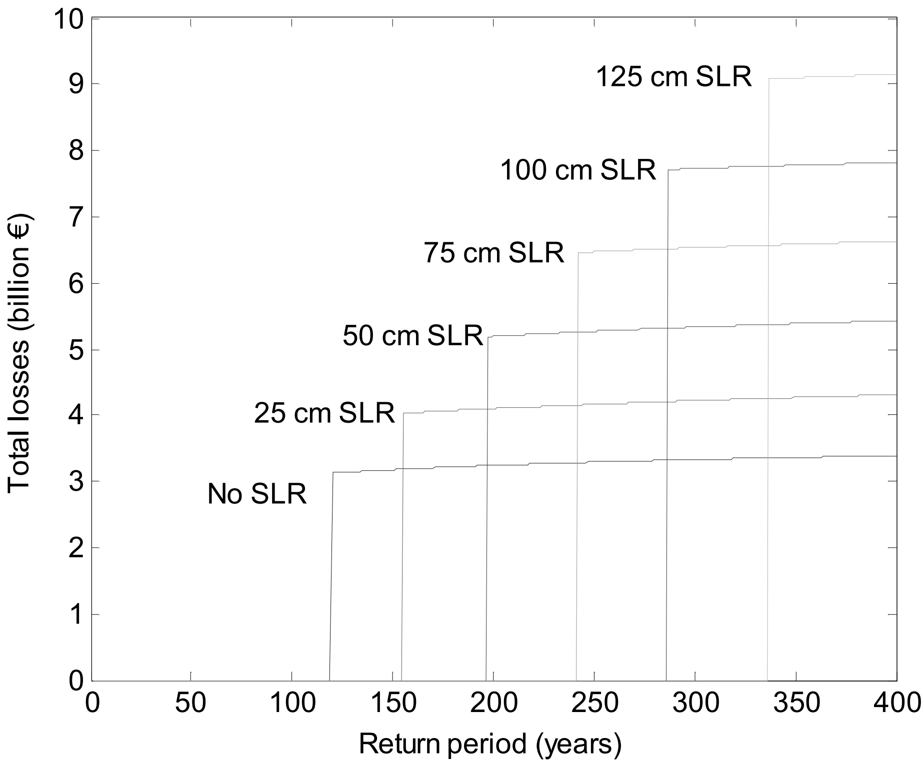
Sea Level Rise (cm)	Annual flood losses (millions of EUR)	Increase wrt no SLR
0	30	0%
25	38	27%
50	48	60%
75	59	96%
100	70	132%
125	81	171%

Figure 20 is idealized, as it assumes that an overtopped dike is fully inefficient. In reality, overtopped dikes are not totally inefficient to limit the amount of water that gets into the city. As a consequence, losses would not be totally unchanged by defences, even when they are overtopped. These simple assumptions, however, are sufficient to assess various adaptation strategies.

This result shows that increasing defences by the same amplitude as sea level rise would maintain flood frequency, but would lead to a regular increase in flood risks, and in flood losses. In locations where storm surge amplitude does not saturate rapidly, as is the case in Copenhagen, moreover, the risk increase would be even larger than in the present analysis. This result suggests, therefore, that another approach must be followed.

Maintaining flood risks. Raising flood defences by the amplitude of sea level rise maintains the flood probability, but increases flood risks. To maintain flood risks at EUR 30 million of annual losses, therefore, it is necessary to heighten flood defences by more than sea level rise. Equivalently, it means that, with SLR, the city needs to be protected against rarer events, if mean annual losses are to be kept unchanged. The protection that is needed to maintain flood risk is provided by Figure 17: as sea level rises, the protection level (on the X-axis) has to increase to maintain mean annual losses (on the Y-axis). Results are shown in Figure 22, which shows that, to maintain flood risks unchanged with 1 m of SLR, the city must be protected against the 1-in-286-yr event.

Figure 21. Total losses caused by the flooding of the virtual city, as a function of the event return time, and for various levels of sea level rise, assuming unchanged flood risk with 1m of SLR



Note: In the figure, we assume that city protections are upgraded to maintain flood risks unchanged, with annual flood losses at EUR 30 million.

Table 7. Height of the flood defences needed to maintain flood probability at 1-in-120-yr or to maintain flood risks at EUR 30 million of annual losses, as a function of SLR

Sea level rise (cm)	0	25	50	75	100	125
Flood defence height to maintain flood probability (cm)	150	175	200	225	250	275
Flood defence height to maintain flood risk (cm)	150	177	204	230	257	283

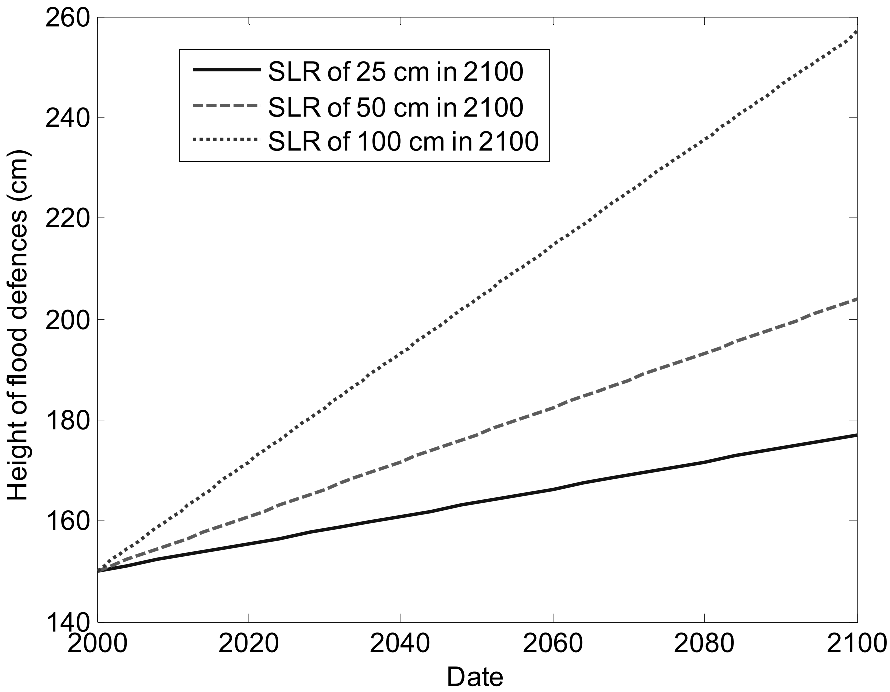
Table 7 identifies the height of the flood protections that are required to maintain flood risk in *the virtual city*. As can be seen in this table, the additional protection required to maintain flood risk is very small, from 2 cm for a 25 cm SLR to 8 cm for a 125 cm SLR. This fact is due to the saturation of possible storm surge height in this location (see Section 2.2). Cancelling the increase in flood risk, therefore, would be easy and cheap in *the virtual city*. The situation may be different in other locations where storm surges have different statistics and where exposure is larger (Nicholls *et al.*, 2007). Regardless, this result shows that the optimal height of a protection against sea level rise is larger than the amplitude of sea level rise[19], even assuming that storm surge and waves will remain unchanged.

Maintaining mean annual losses at their current level would require a regular improvement in flood defences. Figure 23 shows the flood defence height that is needed in *the virtual city* to maintain flood risk at its current level, as a function of time and for different amplitudes of SLR, assuming that sea level rises linearly over time and that current protection are at 150 cm.

This figure illustrates the fact that keeping flood risks in control will require regular and systematic risk analyses in all coastal cities, and repeated investments over this century. If protection upgrades are not made in due time, flood risks will increase rapidly, putting population and assets at risk. In particular, it will be important to upgrade flood defences in a proactive way, without waiting for disasters with significant costs to local and national economies to signal the increase in risk. A reactive strategy could only prove extremely costly.

[19] This result contradicts the methodology to assess optimal protection used in Fankhauser (1994) and Nicholls and Tol (2006).

Figure 22. Height of flood defences needed to maintain mean annual flood losses at their current level along this century, for different amplitudes of sea level rise



Note: Figure assumes that that the current protection level is at 150 cm and that sea level will rise linearly with time

5.2. Benefits from greenhouse gas mitigation

There is a high level of uncertainty in relation to sea level rise that makes it difficult to assess the benefits from mitigation policies. To get an idea of the orders of magnitude at stake and to encompass the broadest range of possible futures, which is essential for planning risk management and mitigation strategies, we explore a range of different models or world views, and assess the benefits in each case. In this section, we will examine two different models: the IPCC assessment and that of Rahmstorf (2007). To illustrate the benefits of mitigation we explore change in flood risks. We assess the reduction in impacts in 2100 when moving from the SRES/A1F1 emissions scenario to the SRES/B1 scenario (a type of 'stabilisation' scenario; see Swart *et al.* 2002), which equates to a decrease in atmospheric greenhouse gas concentration in 2100 from 1550 ppm to 600 ppm CO_2-equivalent.

Assessing mitigation benefits also requires some assumptions about which and how adaptation strategies will be implemented. Of course, in presence of an efficient adaptation process, mitigation benefits are lower than if adaptation is ineffective or ill-designed. In this analysis, we assume that the adaptation process maintains the flood probability, i.e. that coastal flood defences are heightened by the same height than sea level rise.

IPCC World. If the IPCC assessment of future sea level rise is correct, the GHG emission levels in the SRES/B1 scenario would lead to a mean sea level rise of 18 to 38 cm; those of the SRES/A1F1 scenario would lead to increases of 26 to 59 cm in 2100. Assuming an optimistic case, where mitigation policies drive emissions from the highs found in an A1F1-like baseline scenario down to the levels found in a B1-like scenario, would reduce global SLR from 26 to 18 cm. Doing so would reduce the losses caused a the 120-yr event in *the virtual city* from EUR 4.0 billion to EUR 3.7 billion, i.e. an 8% reduction.

Assuming that flood probability is maintained unchanged, i.e. that flood defences are heightened by the same amount as SLR, the mean annual losses would rise from EUR 30 million to EUR 38 million in the A1FI case and only to EUR 36 million in the B1 case. The increase in risk would, therefore, be reduced by 33% due to mitigating emissions in the 2100 timeframe. In the most pessimistic case for these same scenarios, these mitigation policies would reduce SLR from 59 to 38 cm, making the 120-yr losses decrease from EUR 5.4 billion to EUR 4.5 billion, i.e. a 21% percent reduction. Assuming the same flood defence upgrade, mean annual losses would rise to EUR 52 million in the A1FI case and EUR 43 million in the B1 case, i.e. a 40% reduction.

Rahmstorf's world. If the Rahmstorf *et al.* (2007) assessment is correct, an A1FI-like scenario would lead to a best-guess SLR of 100 cm, while a B1-like scenario would lead to a 70 cm SLR. Mitigation policies able to shift from the former to the latter would decrease 120-year losses in *the virtual city* from EUR 7.4 billion to EUR 6.0 billion, i.e. a 24% reduction. Assuming that flood probability remains unchanged (i.e. that flood defences are raised to accommodate SLR), mean annual losses from flooding would rise from EUR 30 million to EUR 69 million (an increase of EUR 39 million) in the A1FI case and to only EUR 57 million (an increase of EUR 27 million) in the B1 case. The increase in risk would, therefore, be reduced by 33% due to mitigating emissions in the 2100 timeframe.

These reductions of flood risks by 25 to 40 percent are significant, but they are much lower in absolute value than what can be achieved with adaptation measures by 2100. This can be explained by (1) the fact that *the virtual city* is very easy to protect with dikes and sea walls, thanks to the nature of extreme storm surges at this location[20]; and by (2) the long inertia of sea level rise: mitigation policies influence sea level rise over much longer timescales than what is considered here. Moreover, mitigation is the only way to limit large-scale impacts from climate change. In particular, mitigation is the only way to prevent the earth climate from crossing the threshold associated with the total melting of the Greenland ice sheet, which would lead to 5 to 6 metres of sea level rise over a few millennia. This effect of mitigation is very distant in the future, but it has to be mentioned that, facing 5 m of SLR, adaptation options are rather limited. Thus the benefits of adaptation relative to mitigation would be even larger if one considered a shorter timescale, but adaptation cannot replace the need for mitigation.

Therefore the benefits from mitigation policies through reduction in sea level rise should be assessed over much longer timescales than currently possible. Over the near term, these benefits may be limited in some cases (e.g. in cities like Copenhagen that are naturally and anthropogenically well-protected), but it is very likely that they are extraordinarily large over the very long term. Again, the situation is different in other regions, where the benefits from avoided sea level rise could be large even in the near-term (e.g., low lying cities like New York City, or low-lying regions in Bangladesh or Egypt).

Finally, even with mitigation, adaptation to sea level rise will need to continue well beyond 2100. Sea levels will continue to rise for several centuries after greenhouse gas concentrations are stabilised. For example, the IPCC estimates that if greenhouse gas concentrations were stabilised at SRES/A1B levels (850ppm CO_2-equivalent) in 2100, thermal expansion alone would lead to an additional sea level rise of between 30 and 80 cm by 2300, and more beyond that. Any melting of ice sheets would be in addition to this.

6. Conclusions

Even taking into account uncertainty in the different stages of our analysis, it is fair to conclude that Copenhagen is not highly vulnerable to coastal flooding. In the absence of protection, potential losses

[20] In the real Copenhagen, the benefits from mitigation are even negligible because the city can be protected at very low cost.

are nevertheless large. For instance, the total losses caused by the current 120-yr storm surge event, at 150 cm above normal sea level, would reach EUR 3 billion with no protection. In the aftermath of such an event, thousands of jobs would be lost (and thousands would be created in the construction sector). The reconstruction process would last several years and cause a significant shock to the economy. Future sea level rise would also significantly increase flood risk over time, for example, raising total losses caused by a future 120-yr event from EUR 3 billion to EUR 4 billion with 25 cm of mean sea level rise (SLR), to EUR 5 billion with 50 cm of mean SLR, and to almost EUR 8 billion with 100 cm of SLR. It is still impossible today to predict precisely if and when sea levels will rise in this way however the rise in sea levels considered here is within the range of plausible events given the current pace of climate change.

The main conclusions of this analysis are that:

- Copenhagen is well protected and as a result the risk of economic impacts from coastal flooding is currently low.

- Adapting to climate change comes at a cost and includes the need to integrate disaster risk management solutions in any location. For example, the costs of coastal flood protection systems – largely already in place in Copenhagen – are estimated to cost a few hundred million Euros. Effective adaptation measures need to include measures to limit coastal flood risks (i.e. dykes and sea-walls) as well as measures to improve rainfall flood management (i.e. improved drainage infrastructure such as moving from gravity-drainage to pumps) both of which need to account for higher sea levels. Also, because flood exposure will increase regardless of the protection level, the consequences of protection failure will increase with sea level rise. Faultless maintenance will, therefore, become even more crucial than today.

- Even though a coastal city might be very well protected today, the risks of climate change will require attention to the maintenance and upgrade of coastal flood protection in order to limit future risks in the face of future sea level risk and increased storm surge. In the case of Copenhagen, some flood defence upgrades may rapidly become warranted in important locations (e.g. the harbour and the city historical centre). Anticipatory adaptation is key so as to ensure that investments provide timely protection over time. Decisions to invest in coastal flood defences will also need to balance negative side-effects of such infrastructure, including more limited harbour accessibility or aesthetic considerations.

It is also important to build defences in a way that allows for flexibility, taking into account the uncertainties in projections and making it possible to upgrade them if sea level rise is larger than expected. Finally, all planning and new infrastructure investments must take account of the risk over the entire lifetime of the investment to reduce unnecessary capital replacement costs.

The application of our methodology on a virtual city, modelled after Copenhagen with limited flood protection, provides more general insights into the impact of sea level rise on coastal cities:

(i) In many coastal cities, indeed, climate change and sea level rise have the potential to significantly increase coastal flood risks in absence of upgrading of current flood protection infrastructure.

(ii) There is a need to anticipate and plan adaptation to climate change, even in low-vulnerability locations, calling for the introduction of adaptation into long-term planning, to consistently take into account all different dimensions of climate change (e.g., sea level rise, change in storm characteristics, change in heavy precipitations, and rise in mean and extreme temperature). This task will require, in particular, carrying out: (1) more detailed and higher-resolution assessments of climate change risks, (2) a precise mapping of at-risk areas, and (3) the development of protection and response plans (including early warning) at the local level.

(iii) Even if flood defences are upgraded to maintain today's probability of flooding, mean sea level rise will still increase exposure to flooding. As a consequence, maintaining flood risks will require upgrading flood defences to heighten them by more than sea level rise. Depending of storm surge local characteristics, this additional height can be more or less important This larger exposure also means that while flood risk can be reduced to low levels with appropriate protective measures, sea level rise will always increase the consequences of defence failure or overtopping by affecting increasingly large areas of the city. The increase in exposure due to climate change will make it critical not only to upgrade flood defences, but also to maintain them rigorously, since the consequences of failure would be very large. It also highlights the need to adopt "soft" measures, such as emergency plans and warning systems, to prepare for the possibility of failure.

(iv) Mitigation policies reduce emissions and the atmospheric concentration of greenhouse gases and, therefore, over time limit climate change and future sea level rise. For example, policies that reduce the CO_2-equivalent[21] atmospheric concentrations in 2100 from 1550 ppm CO2eq (A1FI-like scenario) to 600 ppm CO2eq (B1-like 'stabilisation' scenario) could decrease coastal flood risk in *the virtual city* in 2100 by about 25 to 40 percent (assuming that flood defences are upgraded to maintain the current probability of flooding). Nevertheless, the estimated benefits from mitigation are relatively small due to the low vulnerability of *the virtual city*, and because of the very long inertia of sea level rise. The largest effects of mitigation on sea level rise, and therefore the benefits of policy, would occur after 2100. As a result, adaptation to address rising coastal flood risk is the most effective means to deliver high benefits in the medium-term (i.e. in the next few decades). On the other hand, stabilisation of atmospheric concentration levels through global emission reductions is the only way to limit the largest risks of climate change over the long-term. Thus both mitigation and adaptation will be needed in any comprehensive coastal flood risk management strategy.

The analysis carried out here has several caveats which are important to highlight when considering these results. The assessment of economic impacts associated with sea level rise and coastal flooding has been simplified in several ways. In particular, the analysis treats built infrastructure vulnerability very roughly. Flood duration and water velocity are also not taken into account in loss assessment, and flood defences are not explicitly modelled and the consequences of overtopping are not represented in any detail. There is large uncertainty in particular concerning damages to infrastructure and other uninsured properties, while the modelling of indirect losses is incomplete and disregards important dimensions of social well-being (e.g. casualties, illness, psychological trauma, disruption of social networks, loss of national competitive strength and market positions, loss of cultural heritage, city attractiveness, etc.). Finally, this analysis focuses on this century alone, however we know that adaptation options, such as dikes, are efficient only up to a certain point that will inevitably be exceeded in the distant future. The long-term consequences of climate change are an important argument in favour of mitigation policies and these should not be disregarded.

[21] The CO_2-equivalent concentration is the CO2 concentration that would cause the same radiative forcing than all greenhouse gases and aerosols considered in a scenario.

Appendix A: Exposure Maps

Figure A1: Population Density above (green) and below (orange) 5 m above sea level

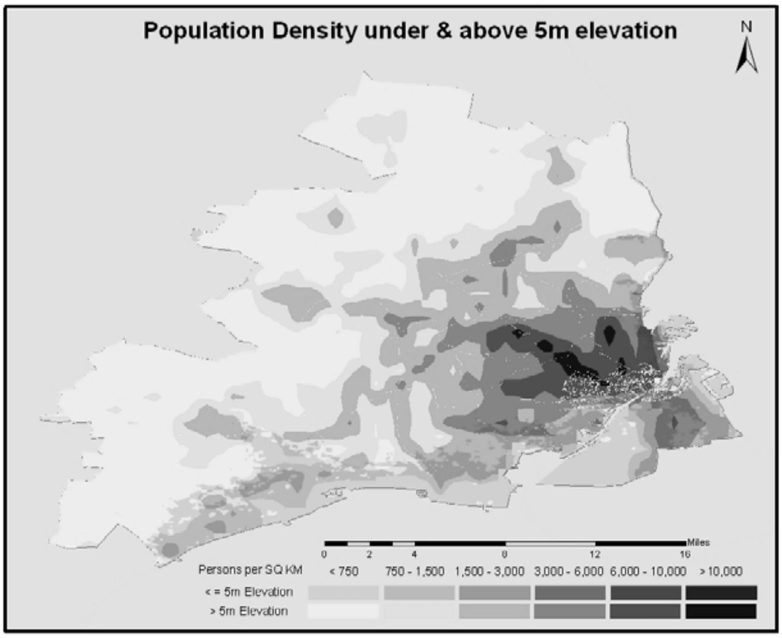


Figure A2: Total Insured Value above (green) and below (orange) 5 m above sea level

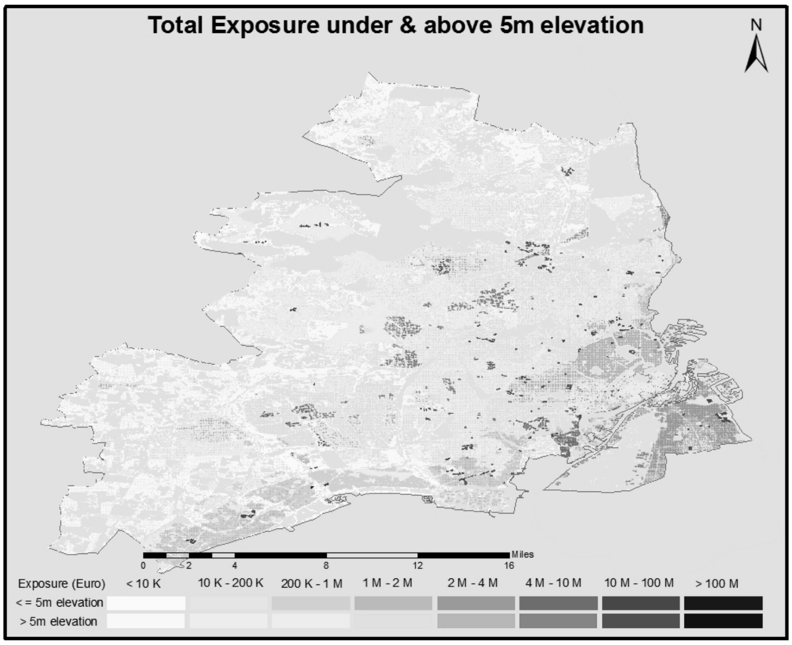
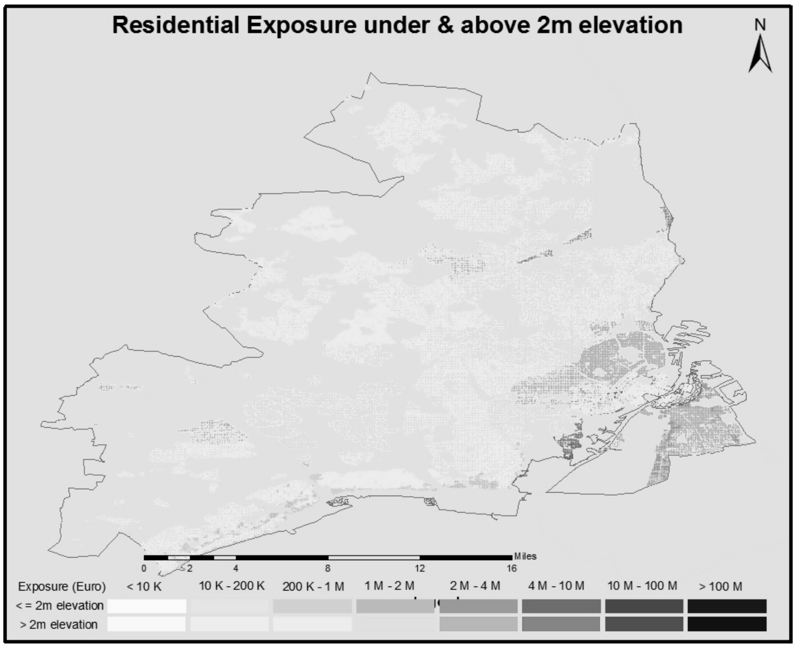


Figure A3: Residential Insured Value above (green) and below (orange) 2 m (top) and 5 m (bottom) above sea level



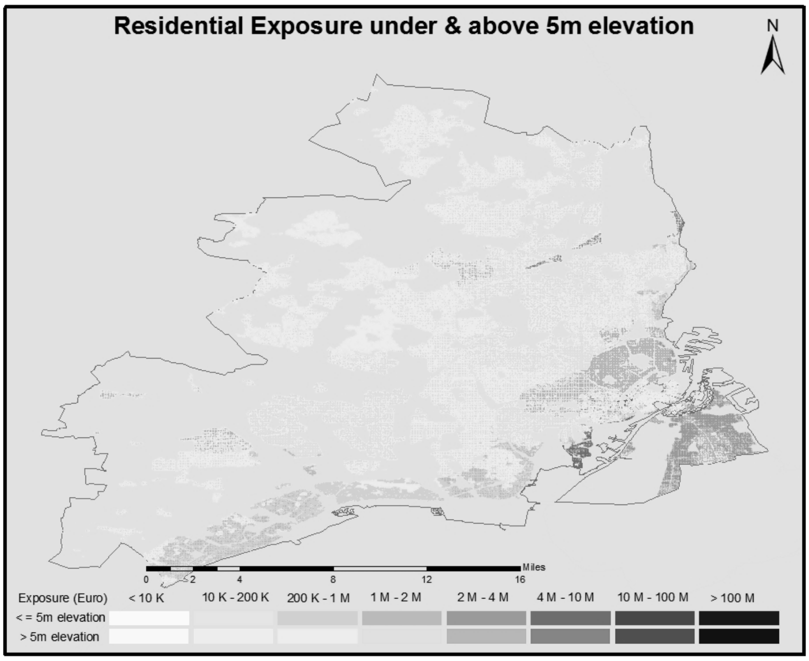
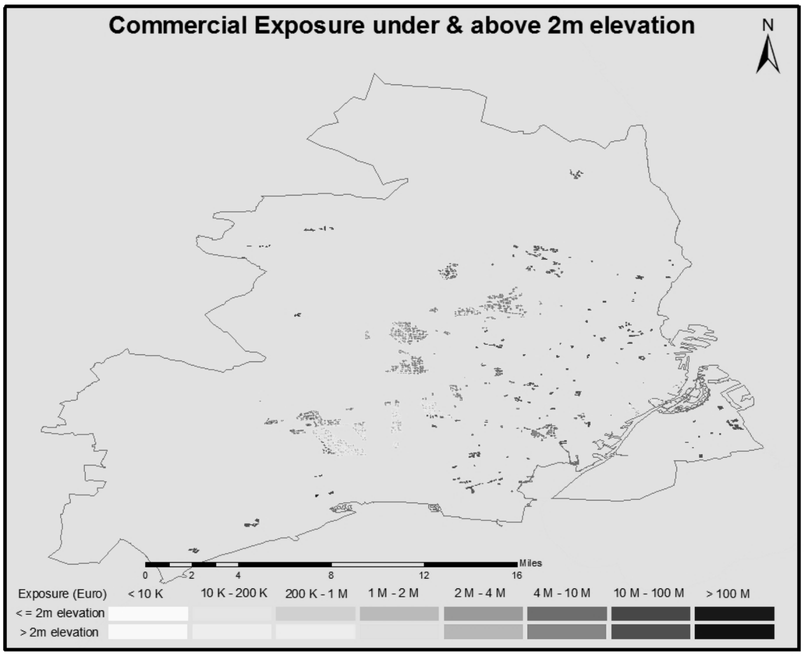


Figure A4: Commercial Insured Value above (green) and below (orange) 2 m (top) and 5 m (bottom) above sea level



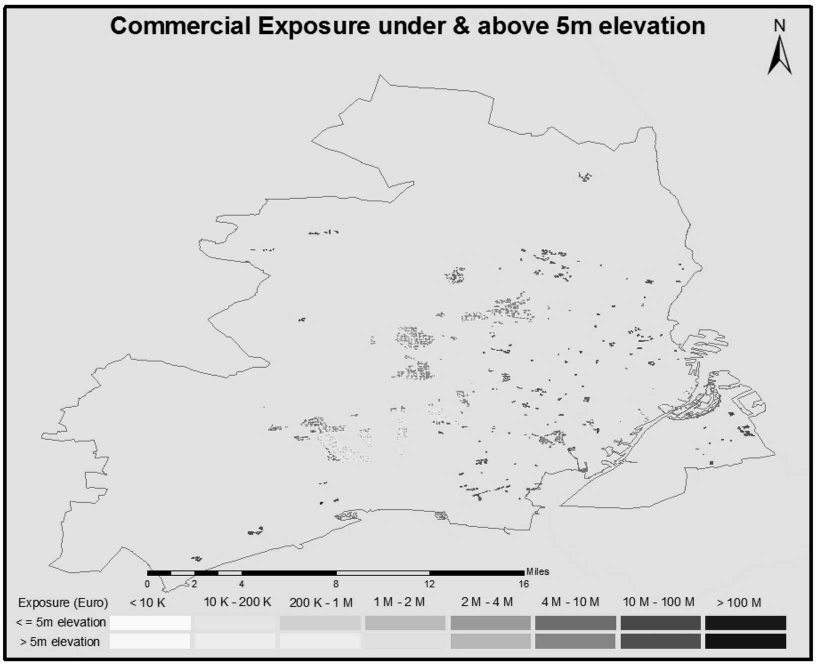
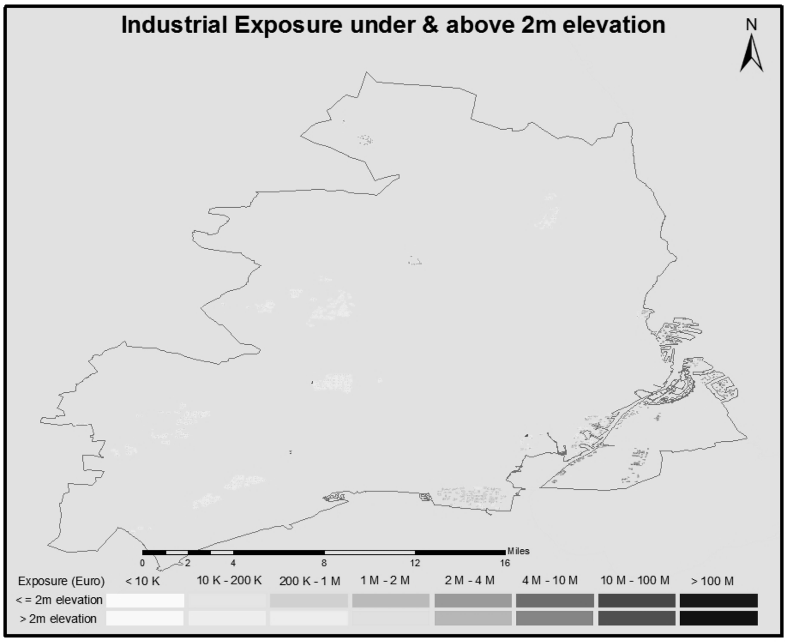
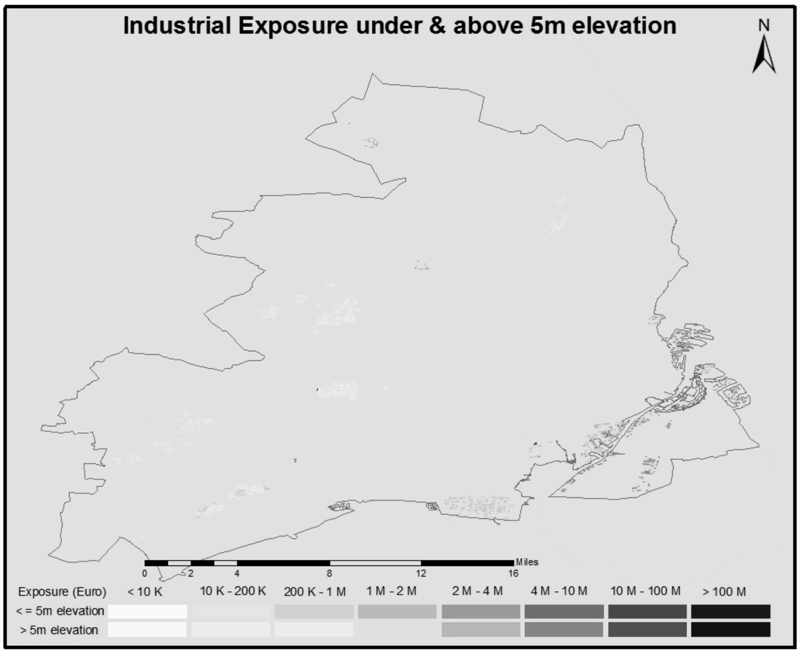


Figure A5: Industrial Insured Value above (green) and below (orange) 2 m (top) and 5 m (bottom) above sea level





REFERENCES

Bengtsson, L., K.I. Hodges, and E. Roeckner, 2006: Storm tracks and climate change. Journal of Climate, 19, 3518–3543.

Bouligand R., and Pirazzoli, P.A. 1999. Positive and negative sea surges at Brest. Oceanologica Acta, 22, 153-166.

Brookshire, D. S., S. E. Chang, H. Cochrane, R. Olson, A. Rose, and J. Steenson, 1997. Direct and indirect economic losses for earthquake damage. Earthquake Spectra, 13, 683–701.

Caires, S., V.R. Swail, and X.L. Wang, 2006: Projection and analysis of extreme wave climate. Journal of Climate, 19, 5581–5605.

Coles, S., 2001: An introduction to statistical modelling of extreme values. Springer, 208pp.

Fenger et al (2008) Danish Attitudes and Reactions to the Threat of Sea-Level Rise. Journal of Coastal Research, Vol 24, Part 2, pp. 394-402.

Fischer-Bruns, I., H. Von Storch, J.F. Gonzalez-Rouco, and E. Zorita, 2005: Modelling the variability of midlatitude storm activity on decadal to century time scales. Climate Dynamics, 25, 461–476.

Fyfe, J.C., 2003: Extratropical southern hemisphere cyclones: Harbingers of climate change? Journal of Climate, 16, 2802–2805.

Geng, Q.Z., and M. Sugi, 2003: Possible change of extratropical cyclone activity due to enhanced greenhouse gases and sulfate aerosols – Study with a high-resolution AGCM. Journal of Climate, 16, 2262–2274.

Hallegatte, S., J.-C. Hourcade, and P. Dumas, 2007. Why economic dynamics matter in assessing climate change damages: illustration on extreme events, Ecological Economics, 62, 330–340.

Hallegatte, S., 2008. An adaptive regional input-output model and its application to the assessment of the economic cost of Katrina, Risk Analysis, in press.

Hansen, J.E., 2007. Scientific reticence and sea level rise. Environment Research Letters 2, 024002

Hoozemans, F. M. J, Marchand, M. and Pennkamp, H. A., 1993. A global vulnerability analysis: Vulnerability assessment for population, coastal wetlands and rice production on a Global scale, 2nd Edition. Delft Hydraulics, the Netherlands.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D., Manning M, Chen Z, Marquis M, Averyt K B, Tignor M, Miller H L (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Lambert, S.J., 1995: The Effect of Enhanced Greenhouse Warming on Winter Cyclone Frequencies and Strengths. Journal of Climate, 8, 1447–1452.

Lambert, S.J., 2004: Changes in Winter Cyclone Frequencies and Strengths in Transient Enhanced Greenhouse Warming Simulations Using Two Coupled Climate Models, ATMOSPHERE-OCEAN, 42, 173-181.

Lambert, S.J., and J.C. Fyfe, 2006: Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: results from the models participating in the IPCC diagnostic exercise. Journal of Climate Dynamics, 26, 713–728.

Leckebusch, G.C., and U. Ulbrich, 2004: On the relationship between cyclones and extreme windstorm events over Europe under climate change. Global Planetary Change, 44, 181–193.

Lindell, M. K., and C. S. Prater, 2003. Assessing Community Impacts of Natural Disasters, Nat. Hazards Rev., 4, 176–185.

Lowe, J.A., and J.M. Gregory, 2005: The effects of climate change on storm surges around the United Kingdom. Philosophical Transactions of the Royal Society London Series A., 363, 1313–1328.

Lozano, I., Devoy, R.J.N., May, W. and Anderson, U. (2004) Storminess and vulnerability along the Atlantic coastlines of Europe: analysis of storm records and of a greenhouse gases induced climate scenario. Marine Geology, 210, 205-225.

Meier, H.E.M, 2006: Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios. Climate Dynamics, 27(1), 39–68, doi:10.1007/s00382-006-0124-x.

Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Chateau, and R. Muir-Wood, 2007. Screening Study: Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes, OECD Working Paper, available on http://www.oecd.org/document/56/0,3343,en_2649_201185_39718712_1_1_1_1,00.html

Oppenheimer M., B.C. O'Neill, M. Webster, and S. Agrawala, 2007. CLIMATE CHANGE: The Limits of Consensus, Science 317 (5844), 1505. [DOI: 10.1126/science.1144831]Penning-Rowsell, E. J. Chatterton, T. Wilson, E. Potter, 2002. Autumn 2000 Floods in England and Wales: Assessment of National Economic and Financial Losses, Middlesex University, Flood Hazard Research Centre.

Pielke, R. A. Jr., and R. A. Pielke Sr., 1997. Hurricanes, their Nature and Impacts on Society, Wiley, New-York.

Rahmstorf, 2007. Sea-Level Rise A Semi-Empirical Approach to Projecting Future, Science 315, 368–370, DOI: 10.1126/science.1135456.

Rodriguez, E., C.S. Morris, J.E. Belz, E.C. Chapin, J.M. Martin, W. Daffer, S. Hensley, 2005, An assessment of the SRTM topographic products, Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena, California, 143 pp.

Salathé Jr., E. P., 2006: Influences of a shift in North Pacific storm tracks on western North American precipitation under global warming, Geophysical Research Letters, 33, L19820, doi:10.1029/2006GL026882.

Tierney, K. J., 1995. Impacts of Recent U.S. Disasters On Businesses: The 1993 Midwest Floods and the 1994 Northridge Earthquake, Disaster Research Center, University of Delaware.

Wang, X.L., F.W. Zwiers, and V.R. Swail, 2004: North Atlantic Ocean wave climate change scenarios for the twenty-first century. Journal of Climate, 17, 2368–2383.

Woodworth, P. L. and D. L. Blackman (2002). "Changes in extreme high waters at Liverpool since 1768." International Journal of Climatology, 22(6): 697-714.

Woodworth, P. L. and D. L. Blackman (2004). "Evidence for systematic changes in extreme high waters since the mid-1970's." Journal of Climate, 17(6): 1190-1197.

Woth, K., R. Weisse, and H. von Storch, 2006: Climate change and North Sea storm surge extremes: An ensemble study of storm surge extremes expected in a changed climate projected by four different Regional Climate Models. Ocean Dynamics, 56, 3–15, doi:10.1007/s10236-005-0024-3.

Yin, J.H., 2005: A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophysical. Research Letters, 32, L18701, doi:10.1029/2005GL023684.