STORM SURGE PLAN

FOR COPENHAGEN 2017

Concerning reprint of the City of Copenhagen's Storm Surge Plan for Copenhagen

Copenhagen City Council adopted a storm surge plan for Copenhagen on 22 June 2017. The basis for decision included the annex 'Corrigenda for Copenhagen storm surge plan'.

The plan is reprinted here with corrections.

The recommendation on the plan together with annex to the City Council can be read at item 43 on the Copenhagen City Council agenda for 22 June 2017, which can be found at www.kk.dk/indhold/borgerrepraesentationens-modemateriale.

1st edition

CONTENTS

SUMMARY

Copenhagen City Council ordered a storm surge plan for Copenhagen on 10 November 2016. The plan contains a main strategic approach for storm surge protection with a level of protection and a description of the legal and financial frameworks. It recommends that

1. Copenhagen is protected by an outer protection scheme,
2. Copenhagen is protected to a level equivalent to a 1000-year storm surge in 2100,
3. work on protecting Copenhagen against storm surges from the south starts now,
4. detailing of the plan starts now,
5. the City of Copenhagen works towards a funding model that emphasises general and derived benefits of the protection scheme.

NEW DATA
The background to the storm surge plan for Copenhagen is a new risk assessment showing that there have been several large storm surges in the past thousand years in Køge Bay. Storm surges in Køge Bay may lead to large economic losses for Copenhagen. Storm surge statistics are usually prepared on the basis of measured storm surges over the past 50-100 years (read more on page 7).

STORM SURGE PROTECTION IN THE SOUTH AND NORTH
Based on the new statistics, it is recommended that storm surge protection is constructed now in the southern and eastern parts of Copenhagen. This should be done to protect against storm surges from the south, which are a more imminent threat than storm surges from the north. The whole protection scheme against storm surges from the south and north is expected from a purely financial point of view to be completed in 30-40 years.

AN OUTER SOLUTION
It is recommended that Copenhagen should be protected against storm surges by an outer protection scheme. An outer protection scheme will protect the harbour and the outer coasts with barriers, dikes and floodgates. There is already an existing dike from the motorway bridge at Kalveboderne down to Kongelunden, the Vestamager dike, which protects particularly valuable infrastructure such as the Metro (read more on page 12).

SEA LEVELS ARE RISING
The protection scheme for Copenhagen is to be arranged so that the city will be able to withstand the rise in sea level expected over the next hundred years. The rise is estimated to be between approximately 70 and 100 cm by 2100, depending on which model is used for calculation. The storm surge plan indicates the combined economics for both a 70 cm and a 100 cm rise in sea level (see more on pages 19-21).

STORM SURGE PROTECTION PAYS FOR ITSELF
It is estimated that Copenhagen will experience losses of between DKK 7.3 and 11.8 billion over the next 100 years if the city is not protected against storm surges. The combined protection of Copenhagen is estimated to cost DKK 3.5 billion in construction costs, plus 2% in annual operating and maintenance costs. Protection against storm surges from the south is socio-economically favourable, while the economic impact of protecting against storm surges from the north depends to a great extent on the actual rise in sea level over the next few decades (read more on pages 16-17). This is, however, a statistical calculation, and the possibility of a single major storm surge causing damage costing a higher sum cannot be ruled out.

FLEXIBLE SOLUTIONS
Planning should incorporate flexible solutions, so that account can be taken, for example, of the fact that the height of the protection can be further increased in the future.

LEGAL AND FINANCIAL FRAMEWORKS
It is possible to fund storm surge protection under the Coastal Protection Act, but the Act has never been put to the test in a large city. It is proposed that further work should take place on a model that includes general considerations in establishing contributions towards funding storm surge solutions (read more on pages 22-25).

MANY INITIATIVES IN THE NEXT PHASE
If the storm surge plan is adopted, a number of factors should be looked at more closely, so that practical proposals for solutions to provide protection against storm surges from the south can be indicated. The entire system of protection against storm surges must be considered together with the city's opportunities for development and the special local features of the coastline and harbour in Copenhagen.

OPPORTUNITIES FOR URBAN DEVELOPMENT
The detailing of the plan should clarify what opportunities there are to make optimum use of the investments. The solution relating to the approach to Copenhagen Harbour must be integrated with future plans for development of the areas and use of the harbour. The technical installations should also be considered together with urban development, and it should be examined how storm surge protection can interact with the city's other future projects and the qualities the city already has. The solutions should take account of the local context and if possible offer new qualities for the whole city. Specialists with the right skill sets should be involved in designing solutions.

INTRODUCTION

POLITICAL DECISIONS ON STORM SURGE PROTECTION TO DATE

PLAN / DECISION	CONTENTS
THE CLIMATE ADAPTATION PLAN	Describes the combined challenges that future climate change is expected to mean for Copenhagen. *Adopted by the City Council on 25 August 2011*
MUNICIPAL PLAN 2015	"Copenhagen must be protected against storm surges by an outer protection system, which must be planned as a combined solution that takes account of needs for coordination with neighbouring municipalities. Over the course of the next few years a target must be set for the safety level for flooding, which includes a safety elevation for the whole city and the adoption of an actual site reservation for the route for an outer protection scheme. It must also be examined whether an investment in a storm surge protection scheme can and should be linked to other development and infrastructure projects or should primarily be managed as an independent installation for storm surge protection. Planning of parts of the municipality close to the coast must take account of a future rise in sea level with a consequent risk of flooding and of a rising groundwater level. The need for local site levelling and other adaptation must be assessed in practical terms." "Excess soil in a project must be managed as far as possible in a comprehensive and sustainable process. This means, in principle that clean or slightly polluted excess soil from a building project must be regarded as a resource rather than a waste product. Excess soil must, as far as possible, be managed locally, so that costly and environmentally harmful moving is avoided, for example by using it in climate-proofing, noise screening, recreational landscapes, etc." *Adopted by the City Council on 10 December 2015*
RISK MANAGEMENT PLAN FOR KØGE BAY KALVEBODERNE	Køge Bay has been officially designated as one of ten Danish areas at risk where there is a potential substantial risk of flooding. This designation has taken place as part of the Danish implementation of the Floods Directive (Directive 2007/60/EC). A risk management plan has to be prepared for designated areas at risk. The plan provides an overview of the threat scenario in relation to floods from the sea in and around Kalveboderne. *Adopted by the City Council on 8 October 2015.* *The risk management plan is due to be revised every 6 years.*
STORM SURGE PLAN IS STARTED	Based on an investigation of new flood statistics, 'Design basis for protection against flooding of Copenhagen' (COWI 2016, in Danish), the City Council started work on a storm surge plan. At the same time, it was decided that the Climate Adaptation Plan from 2011 would not be revised, as the Cloudburst Plan and the Storm Surge Plan represent the necessary revision. *Adopted by the City Council on 10 November 2016*

BACKGROUND

Copenhagen may experience storm surges, causing large-scale destruction of houses, roads and railway lines and posing a danger to human life. The storm surge plan sets the stage for protecting Copenhagen against storm surges and minimising damage resulting from the general rise in sea level and from storm surges.

The 2011 Climate Adaptation Plan established that one of the greatest challenges in climate change adaptation will be managing the rising sea level. The Climate Adaptation Plan also estimated that it would not be until 30-40 years later that floods from the sea would be so significant that the damage could be classified as unacceptably great.

The most recent large storm surge in the Copenhagen area was in Køge Bay in 1872. There have been several major storm surges in Køge Bay since, but none on a par with the 1872 storm surge. The most recent storm surges in 2013 (Bodil), 2016 (Urd) and 2017 (unnamed) appear, according to the Danish Coastal Authority, to be capable of affecting the storm surge statistics, which are being revised by the Authority in 2017.

NEW RISK ASSESSMENT

In 2016, the City of Copenhagen received a new assessment of the risk of storm surges, which depicts a more severe risk scenario for flooding in Copenhagen as a result of storm surges and backing-up of water in the harbour. This assessment prompted the City Council to order a storm surge plan on 10 November 2016 (see political decisions to date on page 6). Protection of Copenhagen against storm surges must therefore be expected to begin earlier than assumed in the Climate Adaptation Plan.

The new assessment has analysed floods stretching almost 1000 years back in time. New storm surge statistics have been compiled, and including observed storm surges so far back in time is a new feature. Storm surge statistics are typically prepared on the basis of measured storm surges over the past 50-100 years. The new assessment includes some very powerful storm surge events far back in time that do not otherwise feature in analyses covering shorter periods.

The storm surges in Køge Bay that can cause severe damage are the result firstly of stormy weather from the west and north, forcing water from the North Sea into the Kattegat and onward to the Baltic Sea. Then there are storms from the east, which force the water back towards Køge Bay and the southern part of Amager. Figure 1 on page 8 illustrates this. If the prevailing wind at the same time is from the east, this effect is amplified, resulting in very high water levels in Køge Bay and the southern part of the Øresund.

The risk of storm surges is initially greatest from the south. The risk later rises sharply if the sea level rises as anticipated. Around 2070-2080 there will be a massive rise in the number of floods in the event of storm surges with high water levels from the north.

THE SEA LEVEL WILL RISE

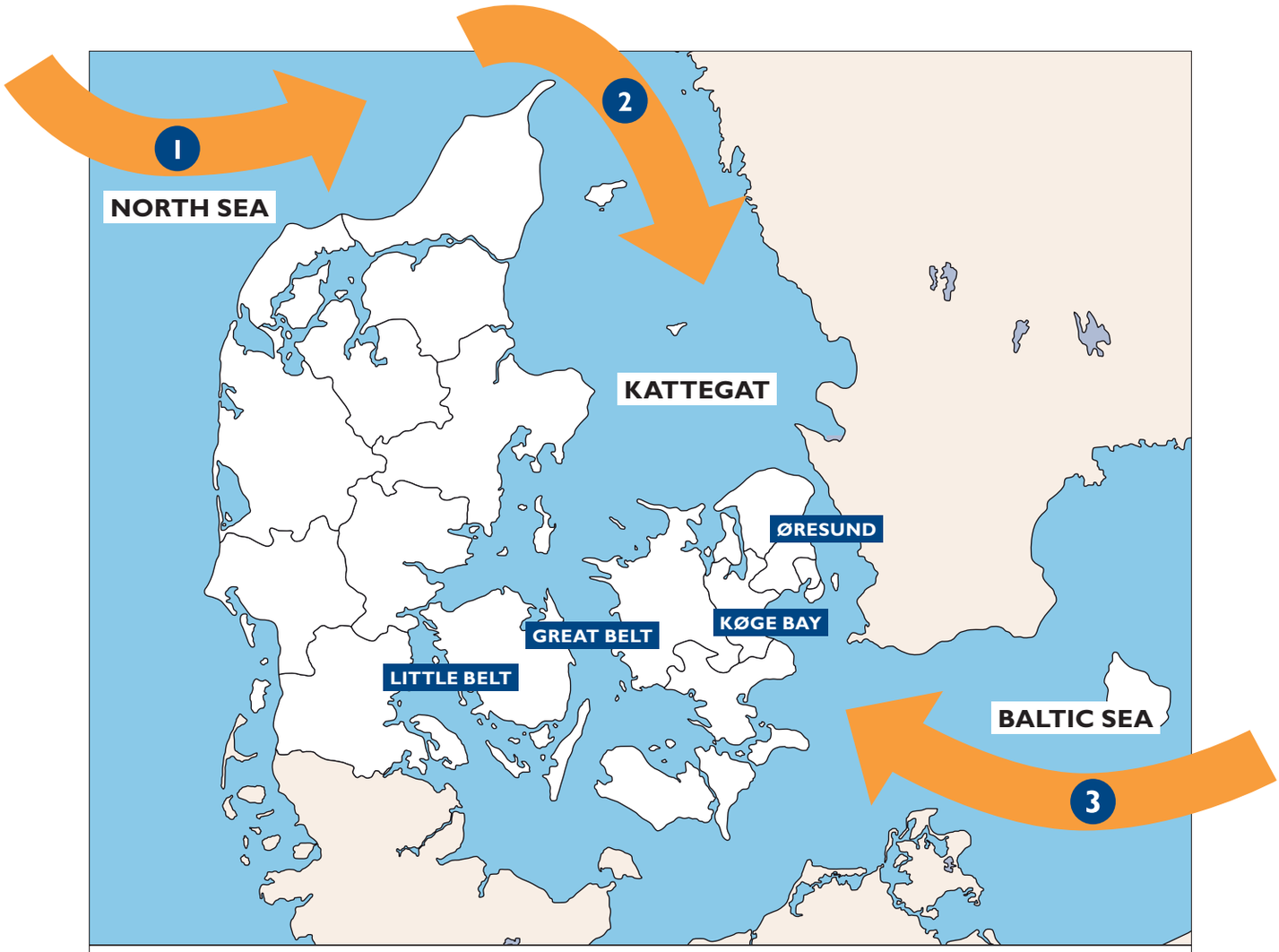
The protection scheme for Copenhagen must be arranged so that the city can withstand the rise in sea level that can be expected over the next 100 years. It is estimated that the rise by 2100 will be between around 70 and 100 cm, depending on which calculation model is used. The storm surge plan provides an insight into the combined economics for both a 70 cm and a 100 cm rise in sea level (read more on pages 19-21).

The US National Oceanic and Atmospheric Administration (NOAA) issued a report in February 2017 that projects a faster rate of rise in global sea level and describes a rise of 1 metre in 2100 as 'moderate'. According to the Danish Meteorological Institute (DMI), NOAA has taken the work carried out by the IPCC authors and updated it with the research done since.

RISES IN SEA LEVEL

Experts' assessments vary, and calculations have therefore been performed for scenarios with both 70 and 100 cm rises in sea level in screening. A rise in sea level of 100 cm was adopted as the basis for calculations in the City of Copenhagen's 2011 Climate Adaptation Plan, building on an estimate from DMI. The US National Oceanic and Atmospheric Administration (NOAA) in February 2017 described a rise of 100 cm in 2100 as 'moderate'. Read more on pages 16-17.

FIGURE 1: HOW A MAJOR STORM SURGE IN KØGE BAY CAN ARISE



1

NORTH SEA

STORM FROM WEST

Water is forced from the North Sea into the Kattegat.

2

KATTEGAT

STORM FROM NORTH

Water is forced down through the Danish belts. Large volumes of water are forced up into the Baltic Sea.

3

BALTIC SEA

STORM FROM EAST

When the storm from the north abates, the water that has been forced up into the Baltic Sea will run back towards Danish waters.

70 CM AND 100 CM RISE

The table below shows what significance rises in water level of 70 cm and 100 cm have in a 1000-year storm surge.

Reference	1990	2000	2015	2050	2100	1000-year floods Avedøre	1000-year floods Oceankaj
100 cm	0 cm	4 cm	13 cm	41 cm	100 cm	450 cm	270 cm
70 cm	0 cm	4 cm	12 cm	37 cm	87 cm	437 cm	257 cm

The difference in calculation of the two values for rise in sea level is due to two factors: firstly the time period for the rise is not the same, and secondly there is a difference in whether post-glacial rebound (uplifting) is included or not.

A rise in sea level of 100 cm, as indicated in the climate adaptation plan, covers a 110-year period from 1990 to 2100 and is calculated in a fixed height reference system (DVR90). The rise in sea level of 70 cm, as indicated by the Centre for Regional Change in Earth System (CRES), covers a 100-year period from 2000 to 2100 and is indicated in relation to ground level on land, which is rising at approx. 1.3 mm a year. To enable the two projections to be compared, they have to refer to the same height system and the same time period.

The two projections are made to refer below to DVR90 and the period 1990 to 2100. The 70 cm projections are *relative rises in sea level* **for the period 2000-2100 in Copenhagen. The rise is thus reduced by the elevation due to post-glacial rebound of approx. 13 cm in Copenhagen over this 100-year period. The actual estimated rise in sea level is thus 70 +13 = 83 cm from 2000-2100, if the fixed height references in DVR90 are counted.**

In addition, a rise in the general sea level in the Baltic Sea of approx. 4 mm per year occurred over the period 1990 to 2000, giving 4 cm for the period 1990 to 2000 (Ref. NOAA-NESDIS-STAR).

The real rise of 70 cm thus becomes 87 cm (70 cm + 13 cm = 87 cm) counting in DVR90 and with a rise over the period 1990-2100, as is done in climate adaptation for Copenhagen. The difference in real terms is therefore 13 cm in 2100.

It may be mentioned for comparison that the most recent estimates, based on updating of the IPCC calculations, show that a rise in sea level is now estimated for North America that is 12-16 cm higher than the expected rise stated in the most recent IPCC report from 2013 (Ref. NOAA Technical Report NOS 083, 'Global and Regional Sea Level Rise Scenarios For the United States', U.S. Department Of Commerce, National Ocean Services). The trend in the rise in sea level is assumed to be identical in the two cases.

MORE THAN A CHALLENGE FOR COPENHAGEN

There are regional interests in protecting Copenhagen against storm surges, as storm surges do not respect municipal boundaries. Citizens, businesses and other municipalities in the Capital Region will notice the consequences of a large storm surge affecting Copenhagen. If Copenhagen is to be protected optimally against storm surges, the closest municipalities south of Copenhagen should be involved in joint solutions for storm surge protection.

The effects of a storm surge in a metropolitan region with a complex composition cannot be stated in monetary terms for properties with flooded basements. The impact of the damage is far broader, affects common systems and can make Denmark vulnerable.

Copenhagen is part of the Capital Region, with a population of 1.8 million. Copenhagen and the region are intertwined in a number of areas, particularly in transport, the common labour market and energy supply.

A storm surge may thus affect large parts of the infrastructure in Copenhagen and surroundings, resulting in large losses. The Øresund Bridge, the railways, the Metro, power and water supplies, etc. are some of the assets that may be affected, resulting in prolonged breakdown of service.

The labour market in the capital area is closely integrated. Sixty-eight percent of people in employment living in the municipalities around Copenhagen work in Copenhagen and not in their municipality of residence. The high level of commuting means that Copenhagen businesses annually pay DKK 77 billion in wages and salaries that is taxed in other municipalities.

Economic activity in Copenhagen therefore makes a large contribution to the taxation base in municipalities in the Capital Region.

COOPERATION WITH OTHER MUNICIPALITIES

Protection of Copenhagen against storm surges has to be coordinated with the efforts of other municipalities. It is particularly the case for storm surges from the south that protection schemes in the municipalities of Brøndby, Hvidovre, Dragør and Tårnby to differing degrees are significant for the protection of Copenhagen. Copenhagen should maintain a dialogue with these municipalities to ensure the best solution for protection against storm surges to the benefit of all the municipalities.

MAIN APPROACH AND LEVEL OF PROTECTION

MAIN APPROACH: AN OUTER SOLUTION

Copenhagen is vulnerable to storm surges and to rises in sea level in general. A main approach and a level of protection have to be dimensioned based on consideration of storm surge risks, rising sea level and waves. It is essential to find out how much the city has to be protected, what can pay for itself, and where the storm surge protection schemes can be located.

Copenhagen can be protected against storm surges using an inner solution or an outer solution.

An ***outer*** solution can protect the harbour and the outer coastline with barriers, dikes and floodgates across the harbour at Trekroner in the northern approach to Copenhagen and just south of the motorway bridge at Kalveboderne. Similar solutions will have to be established at Nordhavn, Svanemøllen and the east coast of Amager.

An ***inner*** solution can safeguard the harbour with protection along all the quaysides in the inner harbour of Copenhagen and at Nordhavn, Svanemøllen and the east coast of Amager. The greatest difference compared with the outer solution is the establishment of 56 km of raised quaysides and dikes along the harbour. The inner solution will to a significant extent lead to higher quay installations with diminished urban space and access to the water.

The outer solution with barriers, dikes and floodgates is judged overall to be the better solution of the two. The reason for this is that the outer solution is considered to be more flexible in terms of future urban development and rising sea level, to have lower construction costs and a shorter construction time and to result in the least encroachment on the city and harbour. It is also considered to provide an opportunity to use the existing harbour front for recreational purposes. The main approach to storm surge protection in the City of Copenhagen is marked out in yellow on the page opposite.

WHEN IS TO THE CITY TO BE PROTECTED?

It is recommended that Copenhagen is protected against storm surges from the south now. This means that a protection scheme should be constructed in the form of floodgates and a barrier at Kalveboderne just south of the motorway bridge, and part of the east coast of Amager is also to be protected against storm surges from the south. This can be done in several ways, and in further detailing activity it will be necessary to work out which solutions overall are best suited to the area.

The combined protection against storm surges from the north is not as urgently needed as protection against storm surges from the south. But there may be benefits in coordinating with the city's other needs, such as the deposition of excess soil. This may mean that parts of a protection scheme against storm surges from the north should begin early. This is discussed in the chapter on 'Potentials' (see page 29).

FIGURE 2: MAIN APPROACH TO STORM SURGE PROTECTION IN COPENHAGEN

LEVEL OF PROTECTION

When indicating the level of protection for storm surge protection, how often a storm surge of a given height is experienced is stated. We therefore talk of 100-year, 500-year and 1000-year events, for example. This does not mean that a 1000-year event happens only once every 1000 years. There may well be three different 1000-year events in the course of 10 years, for example, although this is not particularly likely.

PROTECTION AGAINST 1000-YEAR STORM SURGES IN 2100

The optimum level of protection has emerged by first calculating the combined damage caused by flooding from the sea between now and 2117 that it is estimated would be inflicted on Copenhagen if the city is not protected against future storm surges. The outcome of this is then compared with the estimated costs of different levels of protection. It is recommended on this basis that Copenhagen should be protected to a level equivalent to a 1000-year storm surge in 2100.

In some areas it may be appropriate to protect to a higher level than a 1000-year storm surge, see section on relations with the Vestamager dike and the Metro.

ASSESSMENT OF HEIGHT OF PROTECTION

The magnitude of storm surges and flood statistics, the rise in sea level over 100 years and wave height are included in assessment of the height of protection schemes. Figure 3 illustrates this in simplified form.

DAMAGE AND ECONOMIC LOSSES

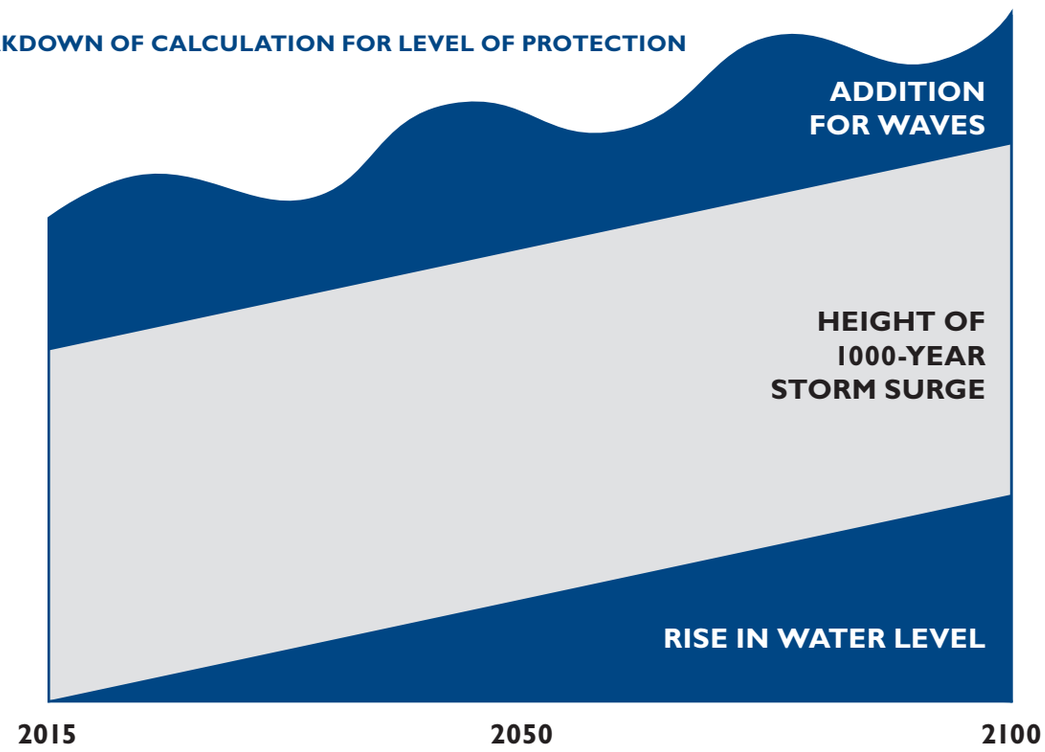
The calculated losses concern damage to buildings, transport disruption, loss of production, power failures, damage to and loss of operation of major transport infrastructure such as the Metro and railways, etc. The damage has only been calculated for the City of Copenhagen and therefore does not include losses in other municipalities. Nor do the loss calculations include indirect losses. There may, for example, be losses due to spread of pollution from old industrial sites or damage to building foundations as a result of a sudden rise in groundwater level close to the coast.

The actual combined losses may therefore be greater. Further light can be shed on this in a detailing phase, if the storm surge plan is adopted (read more on page 31). Figure 4 shows examples of possible consequences of a major storm surge.

DIFFERENCE IN SEA LEVEL IN A STORM SURGE

The extent of storm surges differs from one geographical place to another. As a result, future heights of protection schemes will also vary, from a high level for a barrier with floodgates between Nordhavn and Refshaleøen and at Kalvebodbro bridge to lower levels for example at Svanemøllen Bay and the east coast of Amager.

FIGURE 3: BREAKDOWN OF CALCULATION FOR LEVEL OF PROTECTION



IMPACT ON THE CITY'S INFRASTRUCTURE

As can be seen in Figure 4, there may be great consequences for Copenhagen's infrastructure if the city is affected by storm surges. The figure shows the consequences of a 1000-year storm surge from the south. It can be seen here how parts of HOFOR, BIOFOS and Metro facilities may be put out of action for a prolonged period of time. An example of the consequences of this is the interruption of district heating from the Amagerværket plant for up to three months. In addition, two out of the three sewage treatment plants (BIOFOS) serving Copenhagen may be put out of action for up to two months, and certain sections of the Metro may be forced to close for up to two years. The safeguarding against sea level rises and storm surges in the storm surge plan is therefore protection of vital parts of Copenhagen's infrastructure, parts that make it possible for the city to function. Amagerværket supplies heating to the municipalities of Copenhagen, Gentofte, Gladsaxe, Tårnby and Frederiksberg, and BIOFOS sewage treatment plants receive wastewater from 15 municipalities in the Capital Region. The Metro is an integral part of the Capital Region's public transport network. Breakdowns in HOFOR, BIOFOS and the Metro would therefore be noticeable across a large part of the Capital Region.

COORDINATION WITH THE VESTAMAGER DIKE, ETC.

There will be sections where it will be appropriate to protect to a higher level than 1000-year storm surges. The dike already established in Vestamager is intended to protect Ørestad and the Metro. The dike was planned was planned to provide a very high level of protection, and the actual dike is up to 5.8 metres high close to the point at Kalvedbod and the motorway bridge where it is recommended that floodgates should be built.

The aim should be to coordinate the level of protection for Copenhagen with the level of protection that actors with assets of great value work with.

UNCERTAINTY IN THE STATISTICS

There are several uncertainties in the use of statistics that should be taken into account. How the risk of storm surges is assessed depends on how far the water rises in the future, and what historical observations have been made of water levels during storm surges. Both projections and observations are subject to uncertainty, which affects the assessment of the future risk of storm surges.

It is difficult to predict the water levels of the future, as they depend on a large number of factors on which there is great uncertainty, for example the level of greenhouse gas emissions and their impact on the trend in global temperature, and therefore sea levels, in the long term.

The systematic collection of observations of sea levels did not begin in Denmark until 1874. Observations predating 1874 are consequently subject to greater uncertainty, but can be verified by several contemporary reports, for example several observations of the same storm surge event.

RISK

Risk is defined as the product of the probability of something happening (*the danger*) and the consequence of it (*the effect*). This means, for example, that an area with great assets (e.g. a town or city) is at greater risk than an agricultural area, if both places are exposed to the same danger.

Source: Danish Coastal Authority, Kystanalyse (Coastal Analysis), 2016

THE PHYSICAL BOUNDARY OF A STORM SURGE

As part of a qualification of the knowledge base for the flood statistics, the City of Copenhagen asked the Danish Meteorological Institute (DMI) to comment on COWI's study from June 2016, 'Designgrundlag for beskyttelse mod oversvømmelse af København' ('Design basis for protection of Copenhagen against flooding'). It was this study that led to the preparation of a storm surge plan, see Copenhagen City Council decision of 10 November 2016.

FIGURE 4: SYSTEMS PUT OUT OF ACTION IN A 1000-YEAR STORM SURGE FROM THE SOUTH

DMI has judged that a storm surge above 3.5-4 m, in the present-day climate, is probably not ***physically*** possible. COWI's assessment is that storm surges from the ***statistical*** point of view may be higher. With a mean sea level rise of 1 metre, a 10,000-year storm surge is expected not to exceed 4.5-5.0 m in 100 years' time. The estimated design sea levels and wave heights are stated in the new report from April 2017, 'Opdateret overslag for sikring af København mod stormflod' ('Updated estimate for protecting Copenhagen against storm surges'). The combined elevation at Avedøre Holme for 1000-year floods in 2100 including wave height is calculated at 5 metres. Based on this and further assessments by COWI, it is not considered, with regard to the level of protection recommended for the City of Copenhagen, that this should be studied more closely in the work on this storm surge plan.

There may, however, be reason to re-examine the assessments later, particularly in light of the fact that there may a long time between implementation of the solutions against storm surges in the south and north. The City of Copenhagen will continue in years to come to monitor the assessments of climate trend provided regularly by recognised institutions, etc., and the City will update and, if necessary, revise the assessments in work on detailing the plan.

FIGURE 5: MEAN SEA LEVEL IN DENMARK, 1990-2100

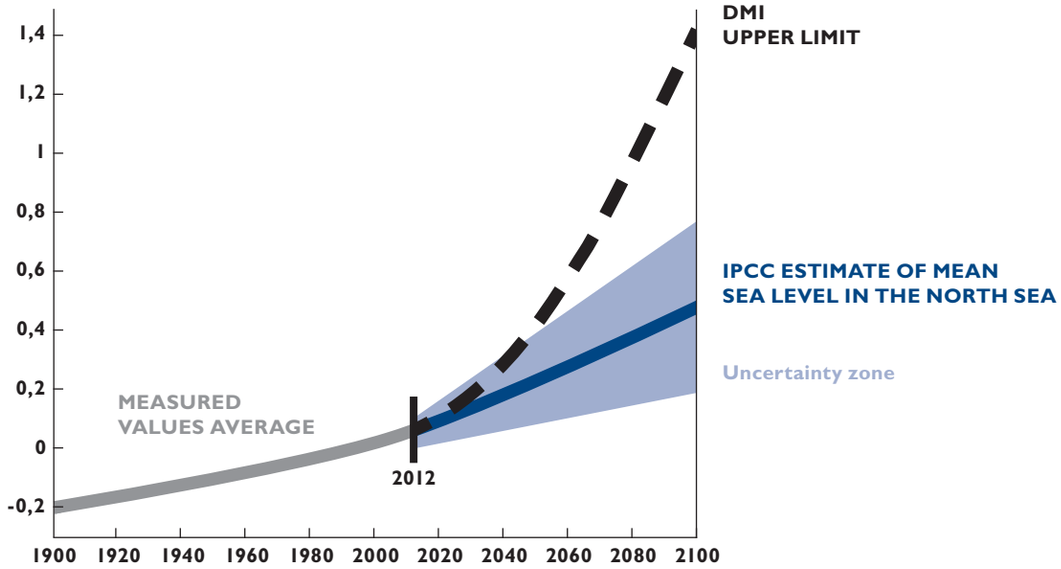
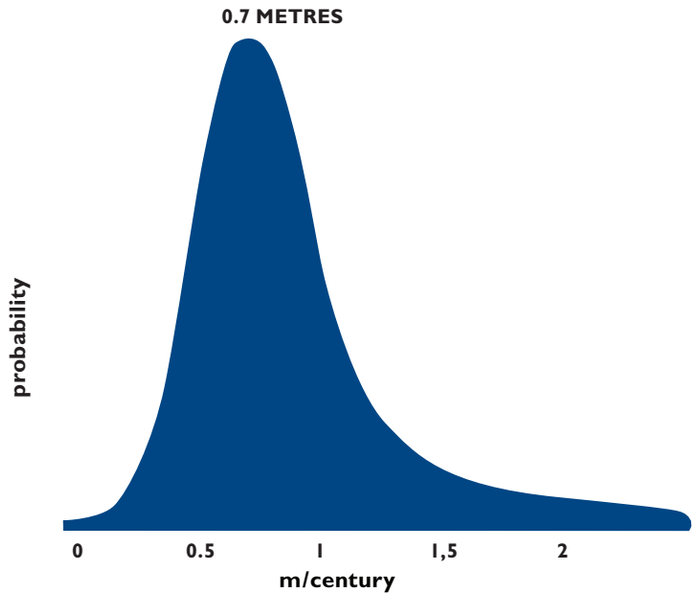


FIGURE 6: PROJECTED RELATIVE RISE IN SEA LEVEL OVER THE 21ST CENTURY



WATER LEVELS IN THE FUTURE

Projections of the trend in future sea levels are subject to great uncertainty, and new research results that improve understanding of the interaction between changes in the atmosphere and conditions in the oceans, including water levels, appear regularly.

The Fifth Assessment Report of the UN Intergovernmental Panel on Climate Change (IPCC) from 2013 assesses the uncertainties regarding rising sea levels. It is found that the observed rise in global mean sea level over the period 1993-2010 is consistent with, and with a high degree of assurance is due to, thermal expansion and melting of the glaciers, the Greenland ice cap and the Antarctic. In brief, it can be said with a high degree of assurance that the warmer it becomes, the higher sea levels in the oceans will rise.

In response to the IPCC report, DMI has estimated future possible changes in water level in Denmark. Figure 5 shows DMI's estimation of possible future water levels and the uncertainty associated with the trend. It can be seen that there is a high degree of uncertainty regarding long-term future water levels. However, all the projections point in the same direction: water levels will rise. DMI's calculation of likely future water levels for Copenhagen can be seen in Figure 6.

The calculation shows that the likely increase in daily sea level around Copenhagen in 100 years' time is around 70 cm. Lower or higher sea levels cannot be ruled out, but a sea level more than 70 cm higher is more likely than smaller rises in sea level.

OBSERVATIONS

The Danish Coastal Authority prepares flood statistics based on observations going back around 130 years. The validity of these observations is regarded as very high. Data for sea levels for the time before systematic observations were carried out are based on historical reports. They are generally more uncertain, but during powerful storm surges reports have often been written recording how high the water rose and left marks on buildings that can verify the reports.

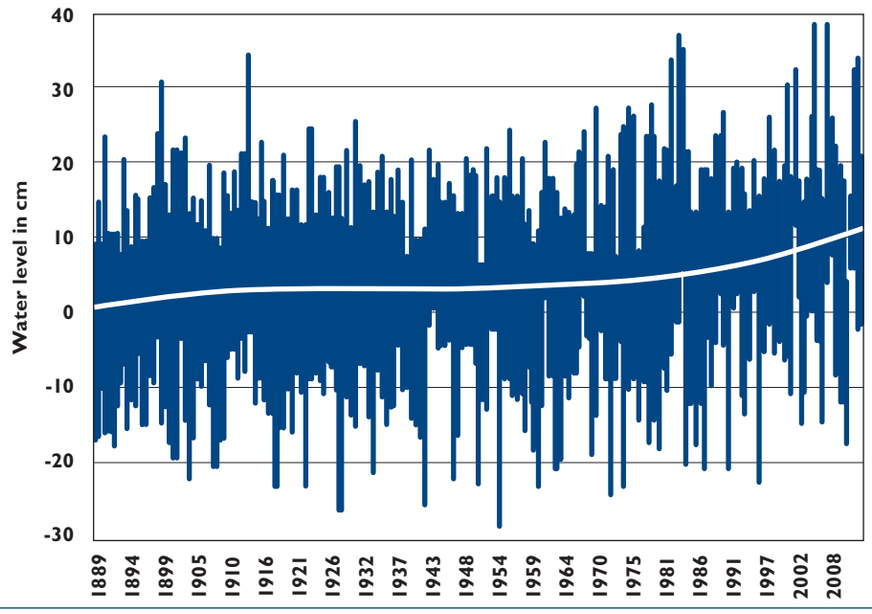
After the storm surge in 1872, for example, water marks were left on buildings in Køge Harbour, indicating how high the water had risen. Such marks, together with reports from other places in Denmark and Germany also affected by the storm surge give the magnitude of the storm surge event of 1872 a high degree of validity.

An anticipated rise in sea level of 100 centimetres by 2110 was adopted in preparing the Climate Adaptation Plan in 2010-2011. This is slightly more than is estimated on the basis of data from the IPCC Fifth Assessment Report from 2013, but still a likely trend within the uncertainty that very long-term projections work with.

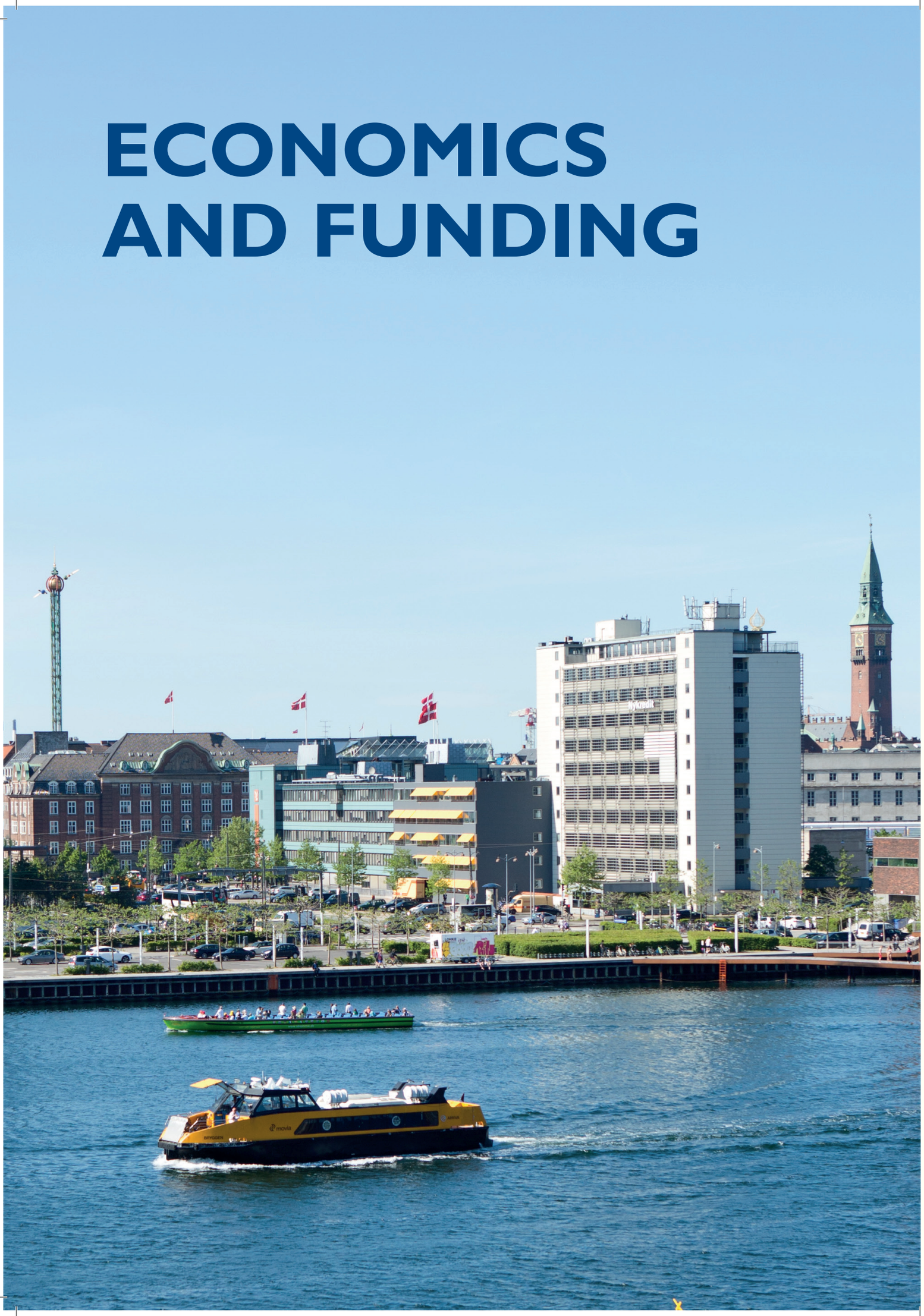
SEA LEVEL HAS RISEN

It can be noted that mean sea level around Copenhagen is rising. Over the past decade rises have been around 3 mm per year. Figure 1 shows observations from DMI's measurement of water level in Copenhagen Harbour.

FIGURE 7: OBSERVED MEAN WATER LEVELS IN COPENHAGEN HARBOUR



ECONOMICS AND FUNDING



ECONOMICS

If the recommended level of protection is chosen, equivalent to a 1000-year storm surge in 2100, estimates can be made of what the construction costs will be. The constructions works need not be carried out simultaneously, but it is recommended that protection against storm surges from the south should be carried out now. Expenditure on protection against storm surges from the south accounts for around one-fifth of the total construction costs.

STORM SURGE PROTECTION CAN PAY FOR ITSELF

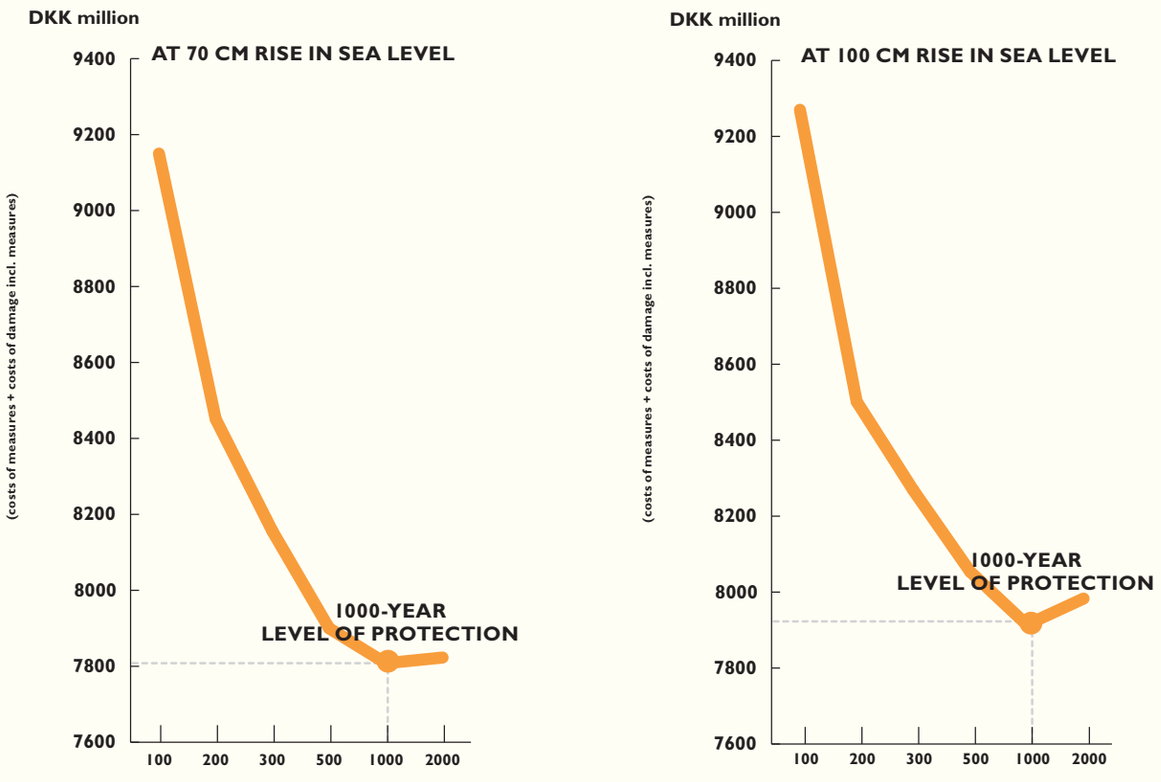
It will cost around DKK 3.5 billion in construction costs to protect the stretches of coastline along the Øresund coast of the City of Copenhagen at the motorway bridge across Kalveboderne (the Kalvebodbro bridge). In addition, there are operating costs of around DKK 70 million per year, equivalent to 2% annually of the construction cost. Construction and operating costs are jointly referred to as costs of measures. The costs of measures over 100 years, in the case of 1000-year protection, are DKK 7.5 – 7.6 billion (depending on whether 70 or 100 cm sea level rises are concerned), excluding the remaining risk, which cannot be prevented by these measures.

The protection scheme costs roughly the same, regardless of whether a decision is made to protect to a lower level than a 1000-year storm surge. If Copenhagen is not protected, it is estimated that the city is at risk of incurring losses of between DKK 7.3 and 11.8 billion over the next 100 years.

The calculated losses over 100 years depend in particular on the magnitude of sea level rises. There is an estimated loss of DKK 11.8 billion and a net gain from protection of around DKK 2.9 billion, if sea levels rise by 100 cm, and losses of around DKK 7.3 billion and a net gain of around DKK 0.5 billion if the sea rises by 70 cm. The net gain takes account of the inclusion of both construction and operating costs over 100 years. See Figure 9.

The calculated losses are an expression of statistically calculated costs of damage. There will be considerable spread in the real world, with heavy damage in individual years, but there will be periods without damage. The possibility of individual events that may result in very large losses, including losses greater than DKK 7.3-11.8 billion, therefore cannot be ruled out.

FIGURE 8: CALCULATED ECONOMICALLY OPTIMUM LEVEL OF PROTECTION



Total costs (costs of measures + costs of damage incl. measures)
The reason why 'costs of damage incl. measures' is included is that even when protection measures are taken, damage could arise from a statistical point of view. The background to the economic results can be found, for instance on page 10 of the COWI report 'Opdateret overslag for sikring af København mod stormflod' ('Updated estimate for protection of Copenhagen against storm surges') (April 2017). Regarding uncertainties in economics, see page 20 of the present plan.

UNCERTAINTIES IN ECONOMICS

The economic assessment represents an estimate made in a screening phase. The figures are subject to uncertainty and require more detailed studies of geological conditions, final choices of solutions for protection, drainage conditions, pipes and installations, clarification of ownership of stretches of coastline where protection schemes are to be carried out, clarification of the need for acquisition of sites, and so on.

SMALL ADDITIONAL INVESTMENT FOR 2000-YEAR PROTECTION

Copenhagen can be protected for a 1000-year storm surge event with an investment of around DKK 3.5 billion. It has been mentioned above that there may be stretches of coastline where it may be appropriate to protect to a higher level than 1000-year storm surges, for example at Kalveboderne and the Vestamager dike. If a further investment of around DKK 0.1 billion is made, Copenhagen can be protected against a 2000-year storm surge.

As can be seen in Figures 10 and 11, the net gain is broken down differently depending on whether a protection scheme is established to the south or to the north.

A protection scheme to the south (Figure 10) will provide a net gain of DKK 391-564 million, depending on whether the rise in sea level is 70 or 100 cm. A protection scheme to the north (Figure 11) will not provide a net gain at a rise in sea level of 70 cm, but result in a negative net gain of DKK 861 million. On the other hand, it is estimated that a protection scheme to the north will yield a net gain of DKK 2296 million at a rise in sea level of 100 cm.

FIGURE 9: ESTIMATD ECONOMIC NET GAIN AT 70 AND 100 CM RISES IN SEA LEVEL

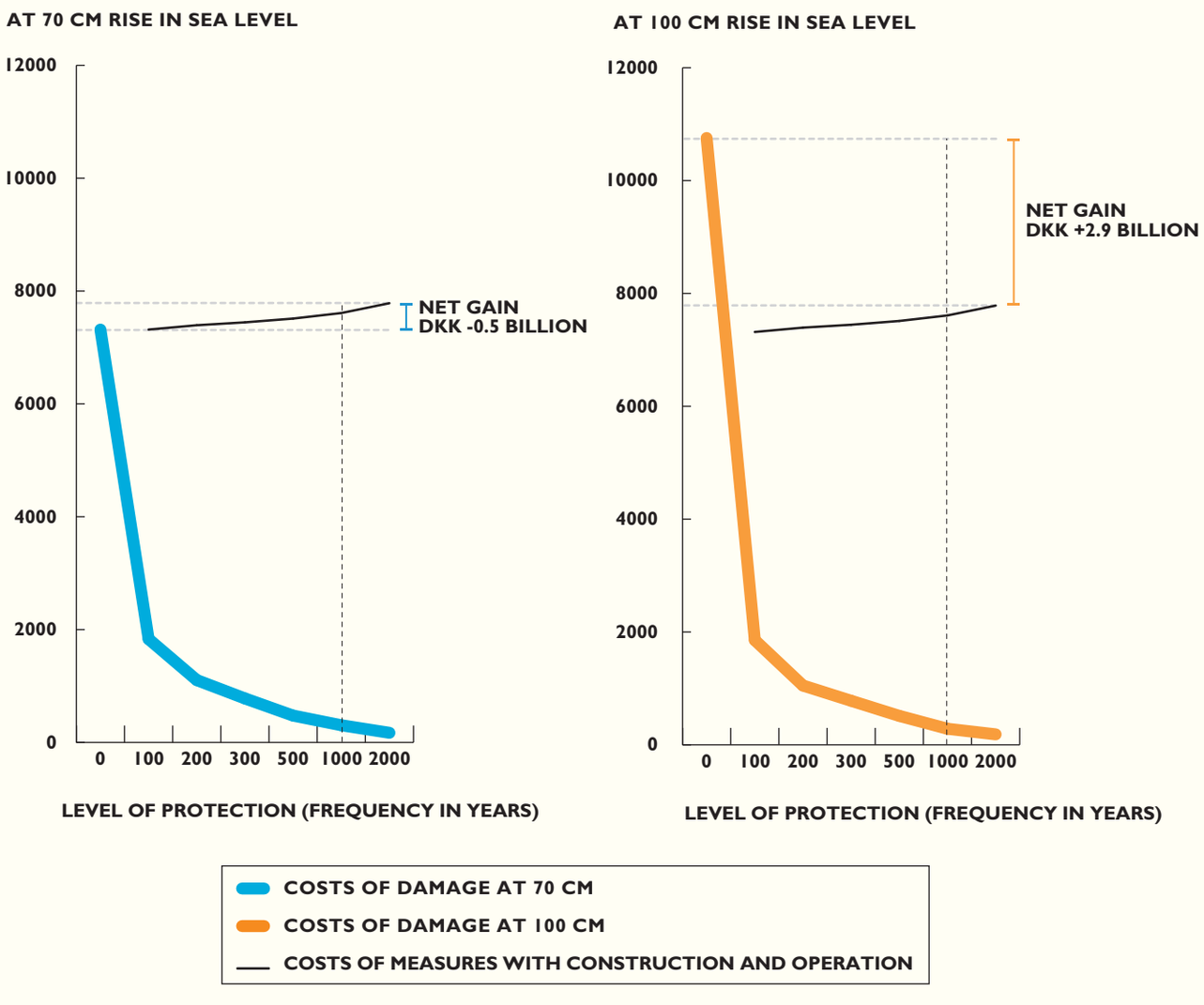


FIGURE 10: COSTS OF DAMAGE AND COMBINED COSTS, SOUTH

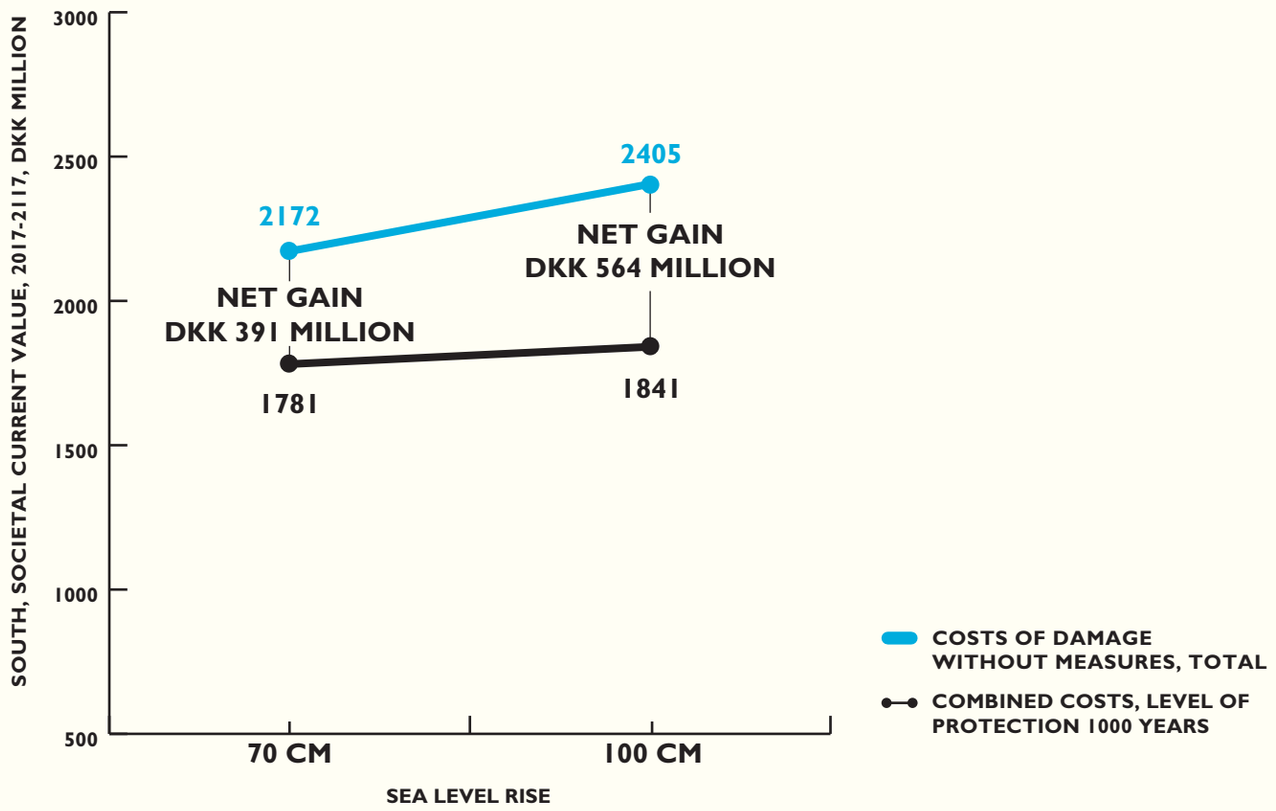
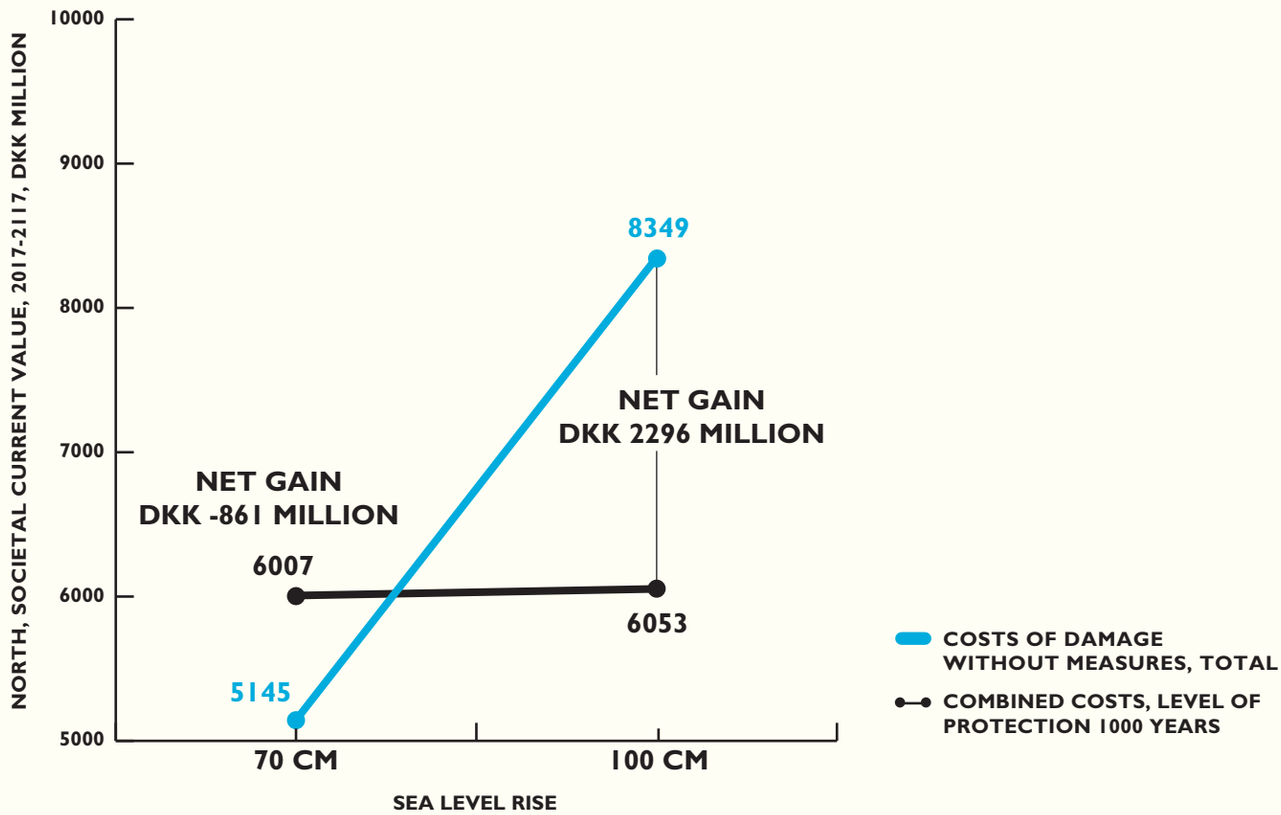


FIGURE 11: COSTS OF DAMAGE AND COMBINED COSTS, NORTH



FUNDING

A model must be created for funding construction and operating costs with contributions to funding from landowners or others who benefit from a protection scheme.

Under the Coastal Protection Act, coastal protection normally has to be paid for by all owners of properties that are directly protected or obtain another benefit from the construction works. When the municipality's decision on distribution of expenditure has been approved by the Danish Coastal Authority, it is binding on all parties covered. The municipality also decides whether it is to pay itself to fund expenditure until the contributions from the contributing parties are received or, where appropriate, guarantee loans raised by these private parties. When the construction works are in operation, the municipality or a grouping established for the purpose will collect contributions for maintenance, etc.

As well as contributing as the owner of its properties, the City of Copenhagen can contribute to the protection of public interests, for example for transport or recreational purposes, tourism, etc. If public interests in another municipality are protected, this municipality can also be required to contribute, but other public authorities cannot.

As a capital city and a node for both public and private activity, Copenhagen contains large societal interests that extend beyond municipal interests. If a reasonable distribution of expenditure is to be achieved, it is crucial that these interests can be involved in deciding which parties enjoy a benefit and therefore have to contribute.

The Danish Coastal Authority does not have any experience of implemented projects with so many parties and such significant derived benefits. The implementation of a protection scheme in Copenhagen therefore depends on a usable and transparent model being developed for the distribution of expenditure on the construction and operation of coastal protection structures. This task falls on the Danish Coastal Authority, as the authority responsible for approving the City of Copenhagen's funding solution and distribution of funding. The City of Copenhagen will endeavour to ensure that a simple and fair model is established that can be used in cases with many involved parties and large societal interests.

A FUNDING MODEL FOR COPENHAGEN

Protection of public facilities and assets such as roads and railways, public utilities, hospitals, banks and other important public and private services, etc. in Copenhagen will be very substantial in comparison with other areas, where it is private homes and summer houses in particular that have to be protected. The same applies to losses of operation, where a property (for example a large business or a transport facility) is not directly destroyed but does not function for a prolonged period after flooding has occurred.

If the storm surge plan is adopted, work should take place in a further initiative on a funding model that views the city as a whole. It may, for example, mean involving consideration of the protection of Copenhagen's public functions, so that these have a prominent input to a model for funding solutions. A model is to be created in discussion with a number of the city's actors, neighbouring municipalities and the Danish Coastal Authority that is regarded as fair, transparent and easy to use in calculating contributions.

LEGISLATION AND OTHER PLANNING

LEGISLATION

Storm surge protection affects many interests and installations along the coast. Several municipalities and authorities are involved, and many landowners will be included. Account has to be taken of environmental conditions, transport conditions, recreational interests and, in a few areas, also regulatory provisions on conservation. Level of protection, construction solutions and distribution of expenditure on storm surge protection are regulated by a number of laws, but have not previously been applied in a large city like Copenhagen.

The implementation of a municipally adopted project under the Coastal Protection Act requires a permit from the Danish Coastal Authority (except harbour sites). In issuing such permits, consideration is given to the effect of the construction works and at the same time to nature and environmental interests. There may also be a need for permits from other authorities.

The Coastal Protection Act lays down detailed rules and procedures for the implementation and funding of coastal protection projects. Under the Act, the municipality establishes both the level of protection and the model for how expenditure on coastal protection is to be distributed between the owners of real estate who obtain (direct) protection or other (derived) benefit from the action that is taken.

Both protection proposals and the distribution ratio have to be approved by the Danish Coastal Authority, but it has not yet been established in the Authority's practice to what other benefits of a coastal protection measure weight can be attached in the distribution of expenditure. Most experience of implementation of the Coastal Protection Act comes from open coasts with few affected properties and plenty of space for protection schemes. The Act has only been used to a very limited extent in urban contexts with many affected properties, complex and extensive infrastructure and limited space.

HOW IS COASTAL PROTECTION IMPLEMENTED?

When a municipality has received a request or has itself chosen to take an initiative for a coastal protection project, the project has to be submitted to the Danish Coastal Authority for a statement. Based on this statement, the municipality decides whether the case is to be pursued. If so, all owners of real estate who obtain protection or other benefit from the project are to be consulted on the project, alongside the public consultation process. The consultation process covers both the design and economics of the project, including the distribution of expenditure on construction and subsequent operation. In Copenhagen, the number of landowners will be very high.

After the consultation process, the municipality decides whether the project is to be put into practice, and whether minor amendments need to be made. The parties concerned can appeal against this decision to an appeals board. If the project goes ahead, an application is made to the Danish Coastal Authority for final approval. Decisions under the Coastal Protection Act are legally binding. On this basis, the municipality also makes a decision on who is to own and operate a coastal protection scheme, and whether land is to be compulsorily purchased to build it. The actual construction and later operation can be dealt with by a grouping established for the purpose (in which all the contributors are members) or by the municipality itself.

STORM SURGE PROTECTION AND OTHER PLANNING

The 2015 Copenhagen Municipal plan already takes account of the fact that planning has to be done with storm surge protection in mind. In continued planning, a flexible approach has to be adopted to protection and a number of analyses have to be performed.

Until such time as combined storm surge protection has been established in Copenhagen, there will be a need to assess what attitude the municipality should have towards new construction and new installations, etc. This means that an assessment is made of building elevations, requirements for the protection of building and construction and assessment of whether there are particularly vulnerable functions that should not be located in at-risk areas or that should be protected in a particular way. In drawing up new local plans close to the coast, the City of Copenhagen at present recommends that buildings and structures should be protected against a 100-year storm surge of 2.63 metres. This is based on a recommendation in the Climate Adaptation Plan. Consideration is to be given to whether this recommendation should be revised, and an impact assessment should be made of new recommendations or requirements.

The analytical activity should be viewed in conjunction with other steps in a detailing phase. Read more on page 31.

Groundwater

The groundwater level in the City of Copenhagen will rise firstly due to the general rise in sea level and secondly in situations in which there are floods for a short period following storm surges. Screening has been carried out and, depending on what situations are concerned, rises in groundwater level of 0.25-2.5 metres are seen 1-2 kilometres inland.

The calculated rises in groundwater level will be critical for buildings and sewer pipes, etc. in several places in the calculated storm surge situations, which will occur very rarely. There is a need for analyses on this topic in continued work.

Soil pollution

There may be a soil pollution impact when a storm surge occurs. Installations with polluting activities may be destroyed, leading to a release of pollutants. It is the responsibility of the individual installations to be protected against a storm surge, but installations must be identified and it must be ensured, where appropriate, that no unnecessary risks arise.

MUNICIPAL PLAN 2015

The Municipal Plan 2015 states that Copenhagen must be protected against storm surges by an outer protection scheme, which is to be planned as a combined solution, taking account of needs for coordination with neighbouring municipalities. An objective for the level of safety against flooding is to be established over the next few years which includes a safety elevation for the whole city as well as establishing an actual site reservation for the route of an outer protection scheme. The storm surge plan forms part of this initiative.

It is also to be examined whether an investment in storm surge protection can and should be linked to other development and infrastructure projects or is primarily to be managed as an independent installation for storm surge protection. The planning of the coastal parts of the municipality has to take account of a future rise in sea level with a consequent risk of flooding and a rising level of groundwater. The need for local site levelling and other adaptation must be assessed in practical terms.

LEGISLATIVE FRAMEWORKS FOR CLIMATE CHANGE ADAPTATION IN LOCAL PLANS

In the amendment of the Planning Act of 1 July 2012, climate change adaptation was inserted as a basis of planning in Section 15(1). Consideration of climate change adaptation can therefore independently form the basis for local planning regulation. Local plans, in contrast to the other types of plan, have a direct legal impact on citizens, but cannot in themselves force through changes to the existing, statutory use of a property, as local plans cannot impose a duty to act on landowners.
As any local plan provision necessitates a specific and objective planning basis, the implementation of a combined storm surge protection scheme for Copenhagen, at local plan level, takes the form of individualised solutions in the individual local planning areas. The local plan provisions have to be reasoned in each individual local plan on the basis of the specific needs for climate change adaptation that arise in the individual local planning area.
The aspects that can be statutorily regulated in a local plan are itemised exhaustively in Section 15(2) of the Planning Act. Section 15(2) of the Planning Act makes provision for the establishment of various storm surge solutions at local level, solutions that are relevant both to the outer protection scheme and to initiatives in the period before the outer protection scheme is in place. The Danish Nature Agency guidance on 'Climate adaptation plans and climate local plans'[2] indicates a number of climate adaptation solutions that can be accommodated in the local planning catalogue in Section 15(2) of the Planning Act.
The following storm surge solutions can be mentioned by way of example:

- **Designation of sites for construction of dikes, which can protect against storm surges**
- **Keeping areas threatened with flooding free of buildings and structures**
- **Designation of sites for storage of water**
- **Locating of buildings on sites at high elevations or raised sites to provide protection against flooding**
- **Requirements for minimum basement height to avoid flooding**

It must be clarified in the detailing phase whether requirements are to be set for elevations in the local plans for solutions in the period before the outer protection scheme is established. A distinction is made in this connection between site elevation requirements and floor elevation requirements. There is no doubt that site elevations can be set in local plans pursuant to Section 15(2)(6) of the Planning Act; on the other hand it is uncertain whether there is statutory authority under Section 15(2) to lay down local planning provisions on floor elevations.

As local plans, in contrast to national plans, regional plans, sector plans and municipal plans, for example, only regulate site arrangements within locally defined areas, the criterion for success for a combined storm surge protection scheme from the local planning point of view will probably be that the individual local plans follow an overall planning strategy that ensures that there is agreement over the way in which local planning is done in the areas threatened by flooding. As local plans, as mentioned above, cannot impose a duty to act on landowners, it will not be possible to ensure that structures for local storm surge protection can be brought about directly, as the structures will not have to be established until planning takes place in the local planning area. Combined storm surge protection of Copenhagen therefore probably necessitates the protection being rooted at several levels in the planning hierarchy and compulsory purchase being considered as one of the tools to be used in achieving combined protection.

[2] I Danish Nature Agency guidance 2013:02 'Klimatilpasningsplaner og klimalokalplaner': http: www.klimatilpasning.dk/media/598918/klimatilpasningsvejledning_web.pdf

PREPAREDNESS PLAN

Before storm surge protection is established for Copenhagen, a storm surge preparedness plan must be drawn up in cooperation between the Technical and Environmental Administration of the City of Copenhagen and the Greater Copenhagen Fire Department (Hovedstadens Beredskab). Knowledge has come about in this provisional work that can be incorporated into a municipal emergency response plan to avoid losses of life, breakdown of the city's vital functions and trade. Risks in relation to individual topics such as soil pollution must also be assessed in this preparedness work.
An action plan must form part of the combined planning complex for the City of Copenhagen and for the whole of the Greater Copenhagen Fire Department, and must describe the Administration's preparedness organisation and management in the event of storm surges.

RECOMMENDATIONS, URBAN DEVELOPMENT AND NEXT STEPS

RECOMMENDATIONS

Copenhagen must be protected against storm surges, and the storm surge plan must ensure that political decisions regarding how this is to be done can be made on a justified basis. The storm surge plan must form part of the city's other planning and form the basis for the implementation of specific protection solutions.

It is recommended that

1. Copenhagen is protected with an outer protection scheme, which is integrated with future plans and options for urban development.

2. Copenhagen is protected at least to a level equivalent to 1000-year floods in 2100, however with the possibility of protection to a higher level on individual stretches of coast.

3. priority is given to the initiative in which protection is first provided against storm surges from the south. This will mean protection at the Kalvebodbroen bridge and parts of the east coast of Amager.

4. in a detailing phase after the storm surge plan has been adopted, analyses, specific solution proposals, proposals for funding models, timetable for roll-out of solutions, etc. are prepared.

5. the City of Copenhagen should work during a detailing phase towards a funding model in which the general and derived benefits of protection are weighted in accordance with their true significance.

POTENTIALS

In continued work on detailing proposals for solutions, consideration must be given to how the storm surge protection can advantageously interact with other future projects of the city or the qualities that already exist in the city. The solutions must support the overall and local features of local urban planning.

COORDINATION WITH SOIL DISPOSAL

The Municipal Plan 2015 states that it must be examined whether an investment in storm surge protection can and should be linked to other development and infrastructure projects or is primarily to be managed as an independent scheme for storm surge protection. The Municipal Plan 2015 also mentions that excess soil as far as possible is to be managed locally, for example by making use of it for climate-proofing, noise barriers, recreational landscapes, etc. The area at Trekroner, between Lynetten and Nordhavn, is one of the areas to be protected by a barrier across the harbour entrance, which is to protect Copenhagen against storm surges from the north.

Based on current estimates, protection against storm surges from the north will cost more than protection to the south, and the risk of storm surges from the north is very limited for many years to come. Protection against storm surges from the north is therefore not as urgent as protection from the south. There may, however, be significant economic and planning benefits in coordinating part of the construction of the protection system in the north with the needs to dispose of soil from building and construction works in Copenhagen over coming decades.

Savings can be made by coordinating storm surge protection and deposition of soil in the north at Trekroner. A detailing phase for storm surge projection must include consideration of coordination with soil disposal. It has also been pointed out in earlier studies on soil disposal that a large disposal site could be established off Amager Strandspark. It is not considered that this disposal site could offer the same benefits, including coordination economies, as a disposal site at Trekroner.

THE CITY AND THE NEEDS OF ITS CITIZENS

The storm surge protection will affect large parts of the Copenhagen waterfront. To ensure that interaction with the city's qualities is possible and to exploit the potential to create a better city, it is important to adapt the individual stretches. The starting point must be the city and the significance of the individual areas in the city. In addition, the specific storm surge solutions should be linked to the local area and the needs of citizens. Great account should be taken of nature, the environment and particular local features.

THE CITY AT THE WATER'S EDGE

Copenhagen is closely associated with the harbour and the coast. Proximity and linkage between city and harbour are key factors. Water quality and access to the harbour and the coast are of great value and are regarded as common property. Many ships call at the port that in various ways contribute to the city by carrying cargo and passengers and providing tourist revenue and experiences for citizens. The entry to the harbour and the harbour itself are notable architectural features of the city and are supported by harbour life and harbour activities. Sailing and a wealth of cultural activities are vital to the significance of the harbour in the city. The harbour and the coast are the everyday recreational space for the population of Copenhagen and an essential element in the attraction of the capital. Priority is given here to availability and public access for everyone.

Solutions in the north can be linked to the development and investments of the city, and be integrated with the city's architectural and historical assets, the attachment of the city and its relationship with the harbour and coast. It is crucial here that storm surge protection as far as possible is linked to the city's needs, from disposal of soil to long-term considerations of new housing, institutional needs and the needs of the people of Copenhagen for recreation and nature experiences.

Solutions in the south are linked to the high landscape assets, existing coastal protection and infrastructural facilities. The solutions here are expected to be linked to expansion and continuation of existing dikes and the establishment of protection in the form of a barrier and floodgate next to the existing Vestamager dike. Here too, account has to be taken of landscape assets and the great nature interests must be protected.

NORDHAVN, SVANEMØLLE BAY AND TREKRONER

It must be ensured that further development of Nordhavn contributes to future protection against storm surges, and that the district at the same time gains good access to water and coastal recreational activities.

Storm surge protection at Trekroner should be created in conjunction with possible urban development, culture and recreation. It is an area of the city with great cultural and historical, architectural and landscape assets.

New solutions can contribute to creating new attractions in the city and improving access to water for the population of Copenhagen. The city's harbour profile must be supported and enhanced, including the visual relationships.

The potential for joint funding of soil deposition and possibly other urban development measures can be illustrated in connection with the detailing phase for storm surge protection.

EAST COAST OF AMAGER

The storm surge protection of the east coast of Amager must be linked to the existing planning and urban development in the area, including cloudburst planning, with several cloudburst roads ending at or around Amager Strandpark. The green line along parts of the east coast of Amager, the value of views, relationship with green spaces, beach, park and sea are key aspects.

COPENHAGEN SOUTH

Along the Copenhagen part of Kalveboderne there is at present a dike up to 5.8 metres high (the Vestamager dike). Protection can be provided at Kalveborderne with a barrier and floodgates just south of the motorway bridge. It can be ensured here that the protection solution responds to local recreational needs. This is an area where consideration must be given to nature and the environment, conditions relating to current and sediment, water quality and sailing, and other recreational interests must be involved.

NEXT PHASE

If the storm surge plan is adopted, a detailing phase should be launched in which protection against storm surges from the south is started first. The following actions should be identified (the list below is not exhaustive):

- Preparation of a more detailed project for protection against storm surges from the south
- Examination of whether it is economically appropriate to establish protection schemes that can be carried out in a short time and avert damage if smaller storm surges occur – the 'low-hanging fruit'
- Planning of protection against storm surges from the south coordinated with the municipalities of Brøndby, Hvidovre, Dragør and Tårnby
- Qualification of the provisional economic and technical calculations from the screening phase
- Identification of contributors and preparation of a funding model
- Clarification of impacts of the storm surge plan on the environment and nature
- Analyses of rises in groundwater level as a result of storm surges and rising sea level
- Analyses of the soil pollution impact of storm surges and rising sea level
- Drawing- up of a preparedness plan
- The options for integrating consideration of storm surge protection with the city's other future projects and the quantities already present in the city
- The options for adapting the solutions and placing in the local context and, if possible, offering new qualities for the whole city. The formulation of solutions must broadly involve specialists with the right skills
- Preparation of a long-term perspective project for protection against storm surges from the north with examination of the potential for coordination between storm surge protection and use of excess soil.

PROPOSAL FOR A PROCESS PLAN FOR PROTECTION AGAINST STORM SURGES FROM THE SOUTH

2021-2024
Authority consideration of storm surge protection and project planning

2024-2028
Construction of storm surge protection scheme

2028-2030
Commissioning of storm surge protection scheme

Detailing process with analyses, involvement process and proposal for solution

2017-2020 | **2021-2030**

2017
The storm sure plan is submitted for political discussion

START OF 2020
Submission of implementation plan for political discussion

2020
Proposal to the Danish Coastal Authority for storm surge protection is submitted for political discussion

Note: The process for storm surge protection in the north will not be fixed until later.

City of Copenhagen
Storm Surge Plan 2017

Technical and Environmental Administration
Finance Administration

Photographs: City of Copenhagen and Ursula Bach
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