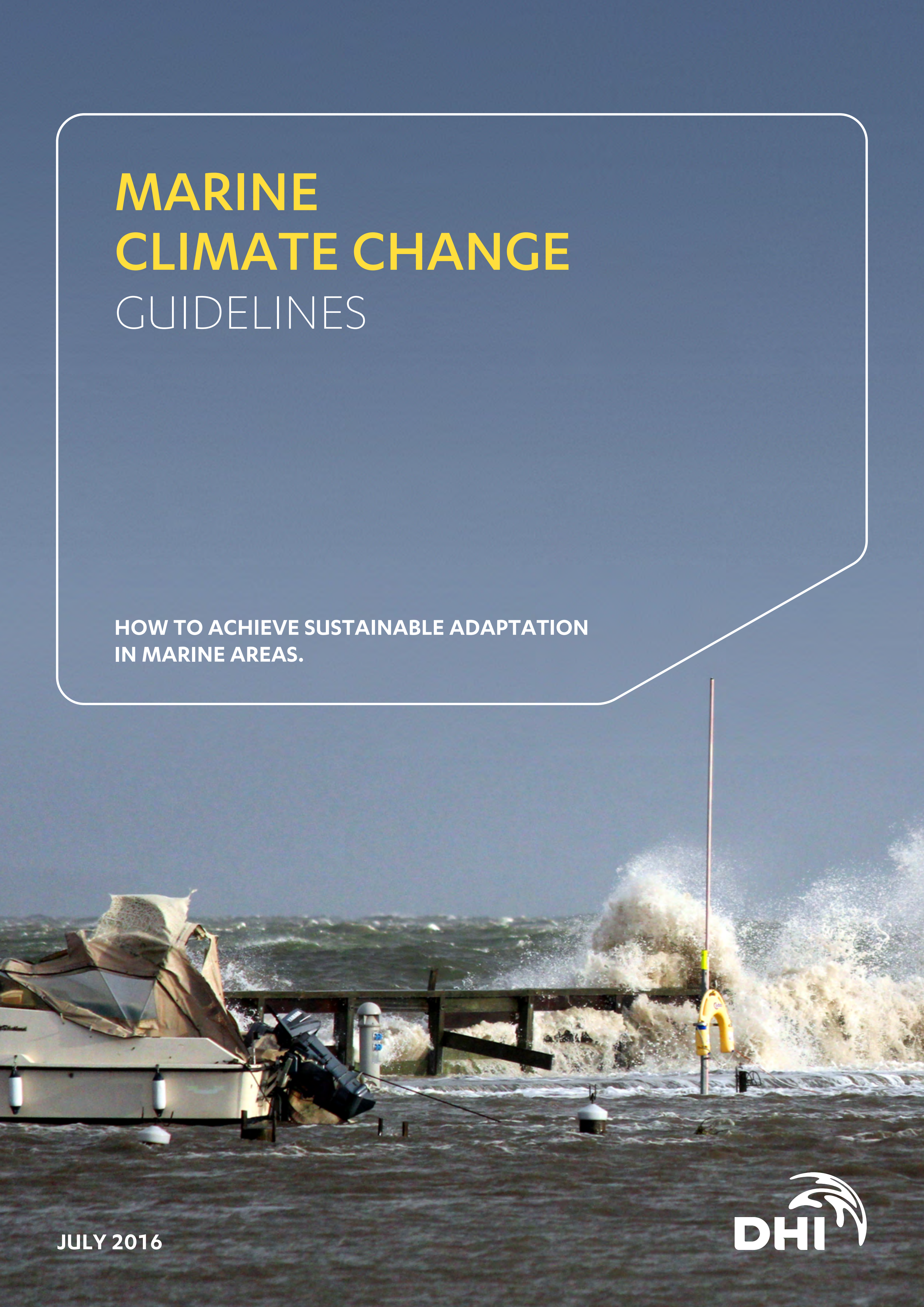

MARINE
CLIMATE CHANGE
GUIDELINES

HOW TO ACHIEVE SUSTAINABLE ADAPTATION IN MARINE AREAS.

JULY 2016

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Prologue

This document provides guidelines for analysis of climate change effects on marine infrastructures, coastal areas and the marine environment as well as adaptation to the climate changes. It is a document that will help guide you through some of the important climate change issues including life-time, design parameters, climate scenario and/or climate models.

By reading this document you will be guided through some of the different issues related to climate adaptation that you will need to address: This ranges from an overview of legislation, climate change projections, climate models, climate change scenarios to expected climate change effects due to sea level rise, temperature increases etc.

Adapting to climate change involves a wide range of stakeholders, and it also has a very strong scientific and technical focus. However, this document only relates to the more specific issues related to engineering and technical adaptation. Stakeholder involvement is also a very important aspect, but it is not addressed in detail in this document.

The last section describes work flow and how to address specific problems. In Appendices A to E examples on how different countries handle sea level rise are given, as well as a few practical examples on climate change adaptation. Adapting to climate change is becoming increasingly important with the more firm evidence of climate change from recent research. The IPCC Fifth Assessment Report emphasises the views on the problem with increasing Green House Gasses (GHG) in the atmosphere and related climate changes and stresses that climate changes will occur over the coming decades.

Over the last couple of decades climate adaptation is already taken into consideration in coastal engineering projects. Consequently, several examples are available with respect to adaptation to increasing coastal erosion and increasing risk of coastal flooding caused by sea level rise as well as changes in wind and storm patterns. However, to the knowledge of the authors no examples exist within the environment and ecosystem adaptation.

The first version of this document was published in 2011 based on the IPCC Fourth Assessment Report. This current version of the report has been updated according to the IPCC Fifth Assessment Reports from 2013/2014.

This document is one of three DHI documents related to climate change adaptation. The other two documents are: Water Resources Climate Change Guidelines: How to achieve sustainable adaptation, and Urban Climate Change Guidelines: How to achieve sustainable adaptation in urban areas.

1 Introduction

1.1 Background

Continuous scientific climate research and observations of global climatic conditions have made it clear that many future climate conditions will differ from historic and current trends. In general, the change in climate conditions, and, in particular, sea level rise, changes in storm patterns, sea temperature and ocean acidification, will most likely present the largest planning and engineering challenges in the future within coastal and offshore areas.

Over the last few decades, there has been increasing global awareness of the effects of anthropogenic climate changes. Not a day goes by when the public is not being warned that the continuation of our fossil-fuel powered lifestyles will lead to increasing global temperatures, increasing sea level, decreasing ocean pH levels, and changes in precipitation and storm patterns. This will have consequences for all humans – and animals, ecosystems, etc. – and impose challenges throughout the world adapting to new climate conditions.

Global climate models (GCMs) show positive links between increasing atmospheric concentrations of carbon dioxide (CO_2) and increasing global temperature. Scientists are increasingly convinced that human activities have influenced these changes and will continue to do so. As an increasing number of research work identifies harbingers of change – from early blooming of springtime plants to sea ice-free summers in the arctic, scientists and the public are increasingly concerned about the consequences of climate change.

The Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC)[1] Fifth Assessment Report (AR5), (IPCC, 2014), states:

> *"Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent climate changes have had widespread impacts on human and natural systems."*

It is important to reduce the use of fossil fuels. The fact that the CO_2 emissions are still increasing will make it even harder to reach the goal agreed by the UN member states to limit global warming to 2°C – but if we succeed, even a 2°C temperature increase will impose global, regional and local changes to which we need to adapt.

> ***Climate change*** *is any long-term change in the patterns of average weather of a specific region or the Earth as a whole. Climate change re-flects abnormal variations to the Earth's climate and subsequent effects on other parts of the Earth, such as in the ice caps over durations ranging from decades to millions of years (Source Wikipedia).*

During recent years, much work has been done regarding global climate change and the likely impacts that may arise from this change. Research results have been collected and compiled by IPCC and presented in their assessment reports from 1990 (First Assessment Report, AR1), 1996 (AR2), 2001 (AR3), 2007 (AR4) and 2013 (AR5).

[1] The "Intergovernmental Panel on Climate Change" (IPCC) is the leading international organization for the assessment of climate change. The IPCC was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to provide a worldwide scientific basis on current and projected climate changes and their potential technical, environmental and socio-economic impacts.

These reports document state-of-the-art, but there is a fast growing amount of literature on climate change and its impacts, adaptation analysis etc. that continuously provide new results and new knowledge, and which also need to be considered. The studies and reports detail the predicted environmental, social and economic consequences from a range of possible CO_2 emission scenarios. The 'greenhouse effect' and the effects of this phenomenon on increased temperatures, changes in ocean circulation, sea ice and glacial melt, species extinction, sea level rise and changing weather patterns have been widely studied. While the vast majority of this work has been based on the 'data rich' developed countries, recent satellite advances have helped to provide better global data.

Climate change is already occurring and will continue throughout the coming decades. However, difference of opinion exists between scientists when they predict the absolute future changes, but this is merely a question of the magnitude of the change of different variables and not a question whether climate change will occur. In IPCC AR5 (IPCC, 2013) levels of confidence and likelihood are included in their assessment of observed and projected changes.

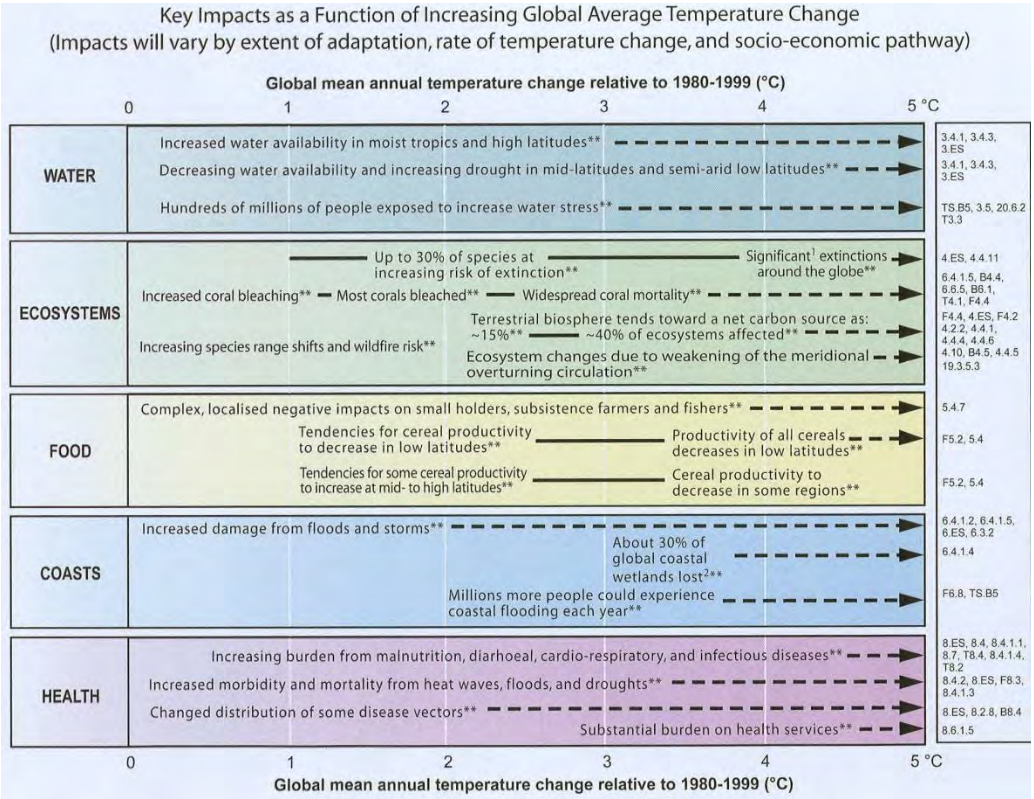

Figure 1.1 Predicted impacts from different temperature increases (IPCC, 2007)

The effects on the Earth's climate are expected to vary between different regions of the world; however, scientists are predicting increasing temperatures globally. Increasing global temperatures will have consequences that ripple through many sectors, as outlined by IPCC, see Figure 1.1. The changes affect the amounts and spatial variability of rainfall, which will cause droughts in some areas and floods in others. This change will lead to changed crop yield (crop stresses, reduced/increased yield, crop failures) and issues relating to food security. Biodiversity challenges will arise as native flora and fauna are stressed by changing temperature and precipitation and competition by alien invasive species moving into new areas that may push many indigenous species towards extinction. The spatial distribution of vector-carrying fauna, such as malaria-carrying mosquitoes, will be able to move into areas previously too cold for them to survive. The raised temperature will cause reduction in the coverage of sea ice in the arctic, will cause the arctic ice cover as well as other ice cover and glaciers to start melting and thus heat up the oceans causing thermal expansion of the seawater. These phenomena will directly or indirectly lead to rising sea levels. And, marine flora and fauna will be stressed by the increase in sea temperature and the decreased ocean pH (ocean acidification), which is a result of increased absorption of CO_2 by ocean water as the atmospheric CO_2 and the ocean water temperature increase.

However, it is important to remember that all predictions are uncertain. The Danish writer Storm P. claimed: *It is difficult to make predictions, especially about the future* - and as we move ahead new knowledge will change our prediction of what the future will bring. For example, IPCC AR4 predicted a global sea level rise between 0.18 m to 0.59 m[2] in 2100, whereas IPCC AR5 now predicts an increase between 0.26 m to 0.82 m. This is, however, still in the lower range compared to a number of other reports such as e.g. a report from the Arctic Monitoring and Assessment Programme (AMAP, 2011) which indicates that we are facing a global sea level rise of 0.9 m to 1.6 m in 2100. Especially the sea level rise has been subject to discussions and the IPCC AR5 has put more focus on the sea level rise. However, the point is that if and when adapting to climate change the preferable solutions must be flexible, as adaptation schemes are bound to change in the years to come.

1.2 Headline statements from the Summary for Policymakers in IPCC AR5

Based on IPCC AR5 a number of short headlines have been produced with respect to observations until today (copied from IPCC, 2013):

- Warming of the climate system is unequivocal, and since the 1950s many of the observed changes are unprecedented over decades to millennia. The atmosphere and oceans have warmed, the amounts of snow and ice have diminished, the sea level has risen, and the concentrations of greenhouse gases have increased.
- Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, 1983–2012 was probably the warmest 30-year period of the last 1400 years.
- Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (high confidence). It is virtually certain that the upper ocean (0−700 m) warmed from 1971 to 2010, and it is likely to have warmed between the 1870s and 1971.
- Over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (high confidence).
- The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (high confidence). Over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m.
- The atmospheric concentrations of carbon dioxide (CO_2), methane, and nitrous oxide have increased to levels unprecedented during at least the last 800,000 years. CO_2 concentrations have increased by 40% since pre-industrial times, primarily from

[2] In IPCC 2007 you are advised to increase the predicted sea level rise by 0.2 m due to uncertainties.

fossil fuel emissions and secondarily from net land use change emissions. The ocean has absorbed about 30% of the emitted anthropogenic carbon dioxide, causing ocean acidification.

- Total radiative forcing is positive, and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO_2 since 1750.
- Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system.
- Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (very high confidence).
- Observational and model studies of temperature change, climate feedbacks and changes in the Earth's energy budget together provide confidence in the magnitude of global warming in response to past and future forcing.
- Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. This evidence of human influence has grown since AR4. It is extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century.

1.3 Purpose

The climate changes predicted today will impose a number of new challenges to coastal societies. Most evident, the climate changes will cause increased risk of flooding, coastal erosion, saltwater intrusion, changes in marine environment etc., and great concern is related to these impacts. This is due to the fact that the coastal zone is heavily occupied by human activities, such as coastal towns, ports, infrastructure, industry, public utilities, recreational and tourist developments and fishing communities, etc.

The most severe and direct impact is probably the increased risk of flooding, especially in the world's densely populated major deltas and low-lying island communities, such as atoll islands. Many mega-cities are located in low-lying areas, and already today flooding is a recurrent problem, which will be further aggravated with a rising sea level.

In some cases present day planning is already including a sea level rise for new developments in coastal areas, but how are we protecting the already developed low-lying areas against flooding caused by the rising sea level? Examples of handling this can be seen in the Netherlands, Venice, Hamburg, London and St. Petersburg, etc. where major barrages have been constructed to protect entire low-lying cities.

In some situations adaptation to sea level rise is no longer about avoiding the water but 'Living with Water', and as examples the climate adaptation plan from the Netherlands (Delta Committee, 2008) includes abandoning land which cannot be protected and includes this land as a flood relief zone.

More extreme examples can be found in some of the low-lying Asia-Pacific island communities that face total flooding with sea level rise, such as the Maldives, parts of Papua New Guinea and Tuvalu. For instance, the Maldives are now starting to look for 'new' land for future generations.

Many coastal communities in developing countries have built a lifestyle in symbiosis with the coast, and many people have their dwellings immediately behind the coastline and they use the beach for boat landing and for beach seine fishing. Their lives are directly related to beach and sea activities and they rely on the sea and the beach for income and for providing food for their families. At these locations, coastal protection needs to respect their use of the beach. Another important beach activity is international beach tourism. Global international tourism expenditures were estimated at about US$ 1200 billion in 2012 (UNWTO 2016) with a significant portion of this on beach tourism. Rising sea levels will lead to reduced beach widths, damage tourism infrastructure, and may be the single biggest factor in the shrinkage and/or collapse of the beach tourism industry in particularly fragile areas. Again, possible protection in beach tourism areas needs to be designed in such a way that the attractiveness of the beach is not lost but rather enhanced. In such areas the need is for integrated shoreline management schemes in contrast to traditional coast protection.

Ports and harbours have long been part of the preferred logistical transport network for nations to trade. The majority of international imports and exports are moved by sea transport because this method of transport is by far the cheapest compared to road, rail and air transport. This makes the long-term viability of ports and harbours a key element in a country's economic survival into the next century. Port and harbour development is very expensive and has design lifetimes of up to centuries. Therefore, a rising sea level is a potential threat to the viability of world ports, and therefore in the development phase we need to plan them carefully, and be fully informed about potential impacts from sea level rise.

From a biological and ecosystem point of view, we are strongly depending on the sea as a food reservoir, especially as the pressure on land-use and agriculture increases with the increasing world population. However, climate changes are likely to change the world's ecosystems alone caused by increasing water temperatures and acidification. As an example, NOAA reports (NOAA 2016) that today acidification is affecting the oyster industry negatively. The industry is depending on oyster seeds from hatcheries but during recent years occasions of massive larvae die off have been reported as the larvae cannot produce shells due to acidification. This affects the industry negatively with economic losses. This is of course not only the case for the hatcheries and oyster farms, but similar problems exist for natural ecosystems.

Some ecosystems will adapt, but changes will happen over time and we do not know if ecosystems will be able to change with the same speed as the climate changes. Hence, we might need to discuss the possibilities of eco-engineering[3], helping new species to adapt or migrate into new areas.

The purpose of this guide is to raise and discuss some of the issues needed for quantifying the impacts of climate change on marine infrastructures, coastal areas and the marine environment, allowing the readers to address and work through the different aspects of climate adaptation.

Furthermore, this guide provides an overview of the climate change information currently available, and it provides tools for and knowledge about how to address climate adaptation and climate proofing with respect to marine infrastructures, coastal areas and the marine environment. Wherever possible examples will be provided, but for some topics like the marine environment, climate proofing is just about to become an issue. Hence, this report will also provide an overview of some of the pitfalls and try to qualify the problems we face in the coming decades.

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[3] Eco-engineering we define as a tool to intervene with ecosystems by introducing new flora and fauna or similar flora and fauna that match changed water temperatures, salinities, etc. or by excluding flora and fauna close to critical threshold temperatures, salinities etc. and deciding not to work for their survival.

When designing installations and infrastructure focus is already on climate change. As an example, the new link between Denmark and Germany (The Fehmarn Belt Link) includes climate change in storm patterns, sea level rise and changes in sea ice during winter as parameters in the construction design. Hence, when designing installations and infrastructure, knowledge and understanding about limitations and suitability of the different climate models on a global, regional and local scale are required.

Furthermore, in-depth understanding of key design parameters for the installation or infrastructure in question at a specific geographical location is required: An understanding that needs to be linked to climate data through statistical and/or dynamic methods for downscaling.

This guide will provide detailed descriptions and methods for analysis of some topics, like coastal flooding, and more general thoughts to be considered for other topics, like the marine environment.

This guide is one of three DHI guidelines on climate adaptation and climate proofing. The other two guidelines are: Water Resources Climate Change Guidelines: How to achieve sustainable adaptation, and Urban Climate Change Guidelines: How to achieve sustainable adaptation in urban areas.

1.4 Who should use this guide?

Quantifying climate change effects is challenging. It requires handling a large amount of factors with large uncertainties both with respect to understanding complex physical phenomena, developing mathematical models and the fact that the drivers to climate change to a very large extent depend on political decisions.

Nevertheless, investment decisions have to be made to meet the future changes and assure sufficiently safe structures within a design life that will be impacted by a changing climate.

This calls for decisions on investing, designing and managing at different levels, but for all stakeholders involved this document provides ideas and guides on how to approach the problems and/or challenges and how to understand and address uncertainties. Hence, this guide is considered useful for all of the following groups;

- authorities,
- developers,
- utility companies and
- consultants.

1.5 The interdisciplinary aspect and definition of problem

When addressing climate adaptations separately, they become a matter of numbers, design parameters, uncertainness, natural science, decision-making and good practices. However, in most cases climate adaptation involves a number of different disciplines. In some cases, like designing offshore structures, climate adaptation solutions can be regarded separately, but as we move towards land the coastal issues and potential conflicts between: living at the coast, risks, legislation, perception, knowledge etc. become increasingly more important, hence requiring an interdisciplinary approach.

When discussing adaptation of ecosystems and potential eco-engineering we move towards more ethical considerations – both if deciding to intervene through eco-engineering and also when deciding not to intervene. Especially, as most ecosystems are complex and we seldom know the exact effects of introducing new species (flora or fauna).

In Figure 1.2 some of the disciplines, which besides natural science are involved in climate adaptation, are highlighted. It clearly shows some of the potential conflicts arising throughout the process. However, it is beyond the scope of this guide to further develop these interdisciplinary interactions, but it is merely mentioned that there are multiple aspects to consider when planning climate adaptation – particularly when working in areas with multiple interests and environment/ecosystems.

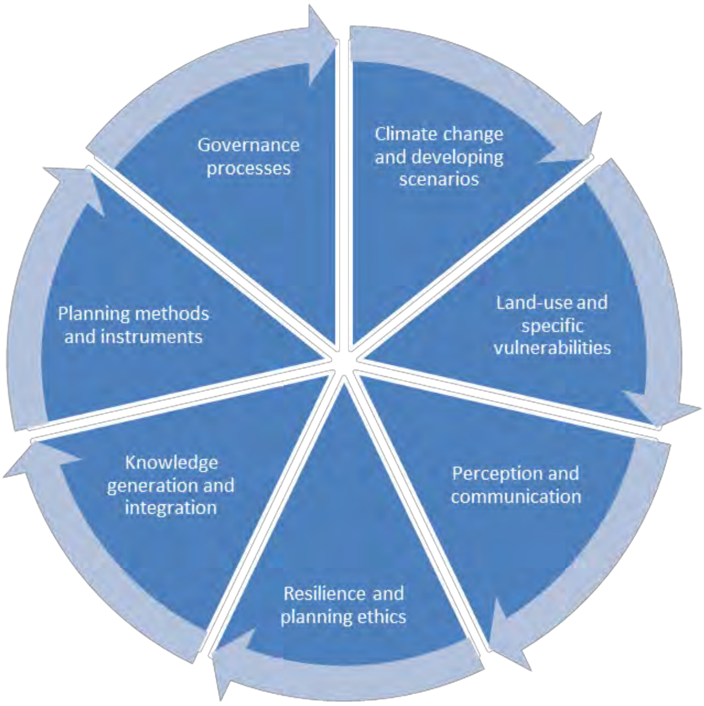

Figure 1.2 Adapting to climate changes requires multiple disciplines, especially close to the coast as many interests potentially conflict in these areas (re-drawn from the project Plan B:altic (Plan Baltic 2009)).

As indicated in Figure 1.2, a holistic approach is required, and a solution for adapting to climate change in one place may be causing problems elsewhere.

1.6 Drivers of 'action'

Today, a number of climate drivers of action are present or emerging. Especially in Europe the Flood Directive is a key driver of action when looking at flooding and hence potential sea level rise. Also, when designing large infrastructures with a design life exceeding 50 years, effects from climate change are found to be important, and many projects now include climate changes in their design.

However, there are still large parts of today's legislation which do not fully incorporate the effects from a changing climate. Examples here are the European directives: The Water Framework Directive, The Marine Strategy, The Habitat Directive, and others. This is so, despite the fact that investments made today to meet these directives may be impacted by climate change effects. However, this is changing, and the focus on climate change effects is now touched upon in some of the directives.

Furthermore, large differences in handling climate changes exist between new (urban and infrastructure) developments and existing developments. For new developments climate adaptation is increasingly being included as part of the planning and management as it makes sense to include this at an early stage when different possibilities of handling sea level rise, increased precipitation etc. still exist. In existing developments, the possibilities are limited, and even though most people will be affected by climate changes in these areas, only limited effort has been put into existing developments. One example though, is the Climate Adaptation Plan for the City of Copenhagen (Copenhagen Climate Adaptation Plan 2011). This plan includes a number of measures, and during the coming years different adaptation strategies will be tested in an existing part of the city.

When involved in climate adaptation, legislation and authoritative planning at different levels should be included and evaluated with respect to the potential implementation of any adaptation solution. These are discussed in the following sub-sections.

Transnational legislation

In Europe a number of transnational legislations imply national action – some related to climate change adaptation, but most related to issues other than climate change and climate change adaptation:

1. EU Flood Directive
2. EU White Paper Adapting to Climate Change
3. Water Framework Directive
4. Marine Strategy
5. Habitat Directive

Some of these directives do not deal with climate adaptation and climate change as such. However, climate change adaption should comply with the above directives, but in some cases the directives may to some degree act as a barrier.

National legislation

Examples are:

1. Sewage plan
2. Sewer renewal plan
3. Contingency plan

Municipal planning and planning at other levels

Climate effects may also affect other planning processes, particularly municipal planning, plans for water quality, etc. In many countries the central government requires that the municipalities shall undertake climate adaptation plans that contain mapping of risk for flooding and prioritisation of the actions, which again fit into municipality plans.

Examples are:

1. Local climate adaptation plans as e.g. the Climate Adaptation Plan for the City of Copenhagen.

Certifying agencies and insurance companies

A number of private companies also need to include climate change in their risk assessment. Examples are certifying agencies (like DNV GL) and insurance companies. Their core business is accurate risk assessment, and it is therefore vital for them to consider the changing climate.

2 Projections of future climate change

Projections of future climate changes are based on the application of climate models together with emission scenarios (or representative concentration pathways) that have been developed based on assumptions of different kinds of future human behaviour. Thus, estimating climate changes resulting from anthropogenic changes in the atmospheric composition strongly depends on accurate climate models and scenarios of political decisions on emissions.

Climate models are based on mathematical equations that describe the physical behaviour and evolution of the atmosphere and the ocean. The future climate can be projected, and the past climate can be hindcasted to a certain precision using these models. In addition to the internal processes of the models themselves, external factors influence the results of the model simulations. These include both natural (e.g., changes in incident solar radiation due to variations in the activity of the sun and volcanic eruptions) and anthropogenic forcing factors. Anthropogenic external forcings are unknown for the future, but they can be assessed using assumptions of different kinds of future human behaviour. IPCC has developed qualitative assumptions for the future and deduced several quantitative future scenarios. For the IPCC AR5 these scenarios are named "Representative Concentration Pathways" (RCP). Detlef *et al.* (2011) summarise the development process and main characteristics of the RCP. Earlier IPCC assessment reports used another set of emission scenarios, the SRES (Special Report on Emission Scenarios) (IPCC, 2000). The first set of scenarios IS92 was published in 1992.

Emission scenarios are plausible representations of the future development of emissions of greenhouse gases and aerosol precursors, based on coherent and internally consistent sets of assumptions about demographic, socio-economic, and technological changes in the future. As their predecessors, RCPs are a set of standards used primarily by climate modellers. Research takes place in many countries, and RCPs provide a common, agreed foundation for modelling climate change. The RCPs are used to initialise models so that everyone starts from a place everyone understands, using values everyone is familiar with, and they provide a way to compare results and communicate findings easily across a broad spectrum of interests.

The RCPs complement and, for some purposes, are meant to replace earlier scenario-based projections of atmospheric composition, such as the SRES scenarios. The new set of scenarios are developed by combining a suite of atmospheric concentration observations and emission estimates for greenhouse gases (GHGs) through the historical period (1750–2005) with harmonised emissions projected by four different Integrated Assessment Models for 2005–2100, see Meinshausen *et al.* (2011) for further details.

By combining the Meinshausen *et al.* (2011) with the earlier SRES scenarios (IPCC, 2000) the two sets of emission scenarios can be compared, see Figure 2.1. The RCP scenarios cover a wider range of future CO_2 concentrations in the atmosphere than the most widely applied SRES scenarios: B1, A1B and A2.

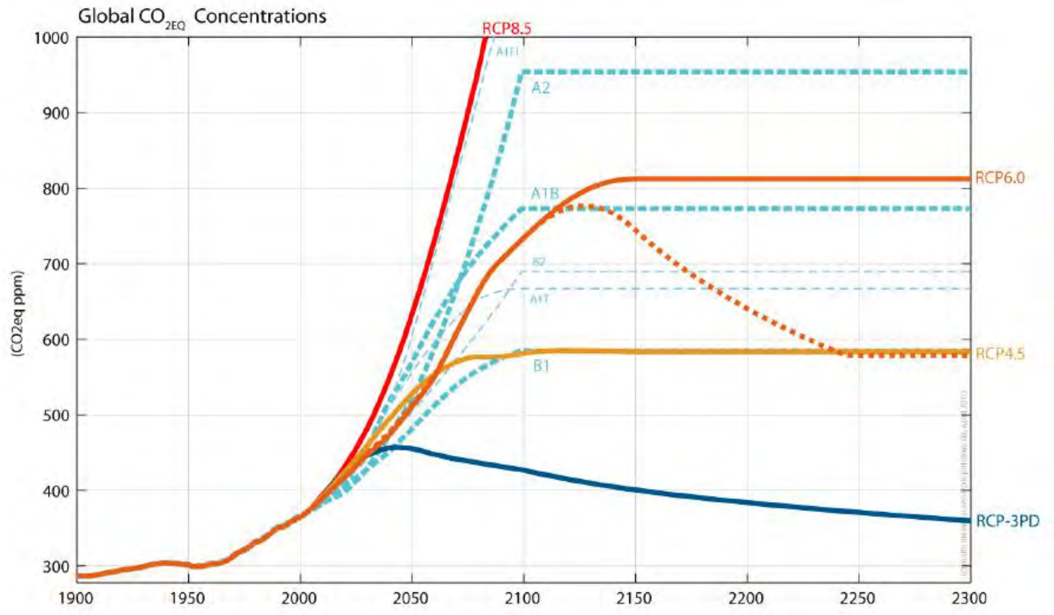

Figure 2.1 Development in global CO_2 concentrations according to the RCP and SRES emission scenarios[4], respectively. Note that the time continues to year 2300, and hence illustrates that climate change is not something we need to consider for the next 100 years alone

2.1 Introduction to climate modelling

The climate is a highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land/ocean surface and the biosphere, and the interactions between them. It evolves in time under the influence of its own internal dynamics, but also due to external forcing such as volcanic eruptions, solar activity variations and anthropogenic forcing such as the changing composition of the atmosphere (e.g. through emissions of carbon dioxide, methane, and other greenhouse gases) and land-use change. Through large scale Global Circulation Models (GCMs) and/or Regional Climate Models (RCM) the scientific community tries to combine the main physical climate characteristics and the input from the emission scenarios (RCPs) to describe future projections for temperature, precipitation, etc.

However, before assessing any climate change effects and potential climate adaptation a few terms need to be described: Climate variability, natural variability and climate change.

Climate variability

Climate variability refers to variations in the mean state and other statistical parameters (such as standard deviations, the occurrence of extremes, etc.) of the climate on temporal scales in the order of several decades, which is well beyond that of individual weather events forecasted on a scale of days. Climate variability may be due to natural internal processes within the climate system (internal variability), or due to variations in natural or anthropogenic external forcing (external variability).

[4] Copied from a presentation by Jean-Pascal van Ypersele, Vice-chair of the IPCC, Cancún. December 2010: *Update on Scenario Development: from SRES to RCPs*.

Natural variability (patterns of climate variability)

Natural variability of the climate system, in particular on the seasonal and longer time scales, predominantly occurs with preferred spatial patterns and time scales, through the dynamical characteristics of the atmospheric circulation and through interactions with the land and ocean surfaces. Such patterns are often called regimes, modes or tele-connections. Examples of such tele-connections are the North Atlantic Oscillation (NAO), the Pacific-North American pattern (PNA), the El Niño-Southern Oscillation (ENSO), the Arctic Oscillation (AO) and the Antarctic Oscillation (AAO).

Climate change

Climate is defined as the statistics (mean, standard deviation, etc.) over a certain period of time (typically 20-30 years) of the different climate variables. Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability or other statistical properties, and which persists for an extended period, typically in the order of decades or longer. Climate change may be due to natural internal processes or natural external forcing (e.g. volcanic activities), or due to persistent anthropogenic contribution to changes in the composition of the atmosphere or in land use.

For further details, see IPCC (2007).

2.2 Scenarios for future climate change

The climate changes presented in this guide are based on the IPCC AR3, AR4 and AR5 reports from 2001, 2007 and 2013, respectively (see IPCC, 2001; IPCC, 2007; IPCC, 2013). As described above, these reports are based on different emission scenarios. In this regard, it is important to remember that the different emission scenarios are to be interpreted as narrative descriptions of the future. We do not know what the world will look like in 100 years from now. Just imagine if someone in 1910 had tried to describe the world as it looks today – most likely it would not have been anything close to what we know today.

The RCP scenarios used in IPCC AR5 are a set of standards used primarily by climate modellers. They include four scenarios: RCP8.5, RCP6, RCP4.5, and RCP2.6 (the latter also referred to as RCP3PD, where 'PD' stands for Peak and Decline). The numbers of the RCP refer to radiative forcings (global energy imbalances), measured in watts per square metre, by the year 2100.

Forcing is one key metric of the RCPs. Another is emission rates - how fast we put more greenhouse gases into the atmosphere. The third metric is emission concentrations, measured in parts per million for each of the greenhouse gases, e.g. CO_2, methane, nitrous oxide, etc.

Each pathway 'fixes' two values in the year 2100; how much the planet has heated up, and the concentration of greenhouse gases. Each RCP differs substantially regarding the rate of forcing and emissions. These different rates, or trajectories, form the 'pathways'.

Each of the four RCP was developed independently by a modelling team whose previous work was a close match to the starting requirements for the new scenarios. To determine the trajectories of emissions and forcings for each RCP, the team reviewed the existing literature and synthesised values for a wide range of scientific and socioeconomic data, like population growth, GDP, air pollution, land use and energy sources.

The development in GHG concentrations due to GHG emissions is shown in Figure 2.2.

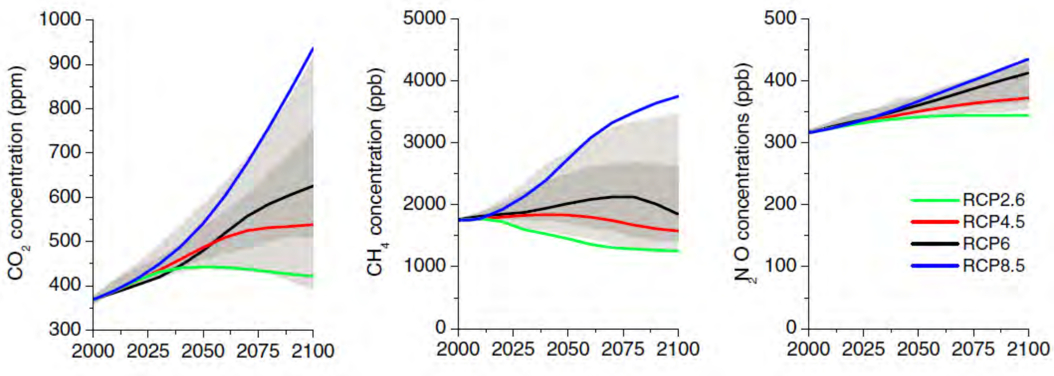

Figure 2.2 Trends in concentrations of greenhouse gases. Grey area indicates the 98th and 90th percentiles (light/dark grey) (Copy from Detlef *et al*. 2011.

In Figure 2.3 different evolutions in global temperatures based on the RCP scenarios are shown. It should be noted that the different climate scenarios are fairly similar within the first 30-50 years, after which the differences between the scenarios increase.

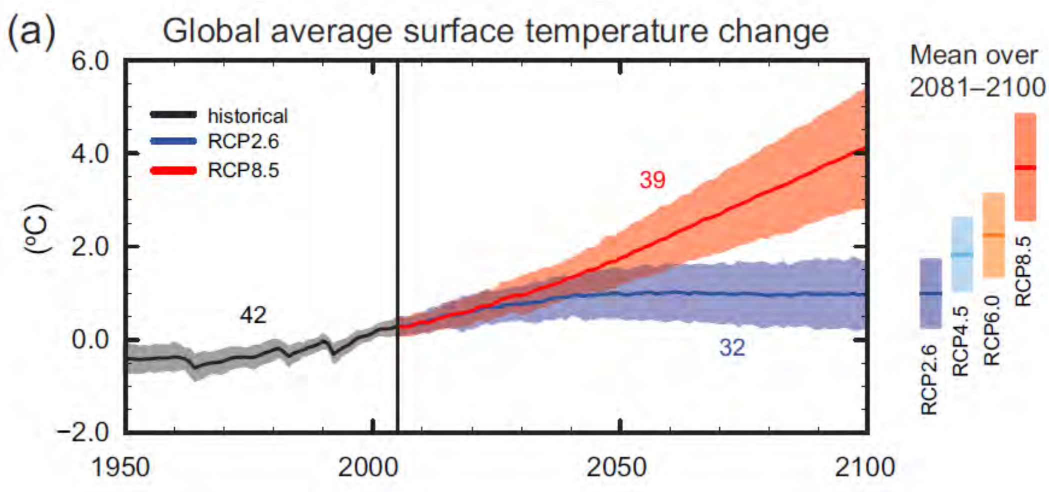

Figure 2.3 Global average surface temperature change (IPCC, 2013)

In addition to the official RCPs the EU2C scenario is often referred to in Europe. This is, however, not an emission scenario but corresponds to an emission that will not allow the global temperature to rise to more than 2°C above pre-industrial levels, and hence it is more a target than a scenario. This target describes a world where the international community and the individual countries enter into agreements to develop technological solutions and changes in behaviour in order to decrease anthropogenic influences on the Earth's climate leading to global temperature increases not exceeding 2°C above pre-industrial levels. The target corresponds to the EU's objective, as expressed by the European Council in 2005.

2.3 Intercomparisons of climate change model results

Results from the many different climate model simulations made by institutions worldwide have been and are being compiled in order to support assessments of future climate change. Examples of such model intercomparison projects are:

- Phase 3 of the Coupled Model Intercomparison Project (CMIP3) providing global climate model projections for the 4th Assessment Report
- ENSEMBLES project providing downscaled regional climate projections for the European area
- Phase 5 of the Coupled Model Intercomparison Project (CMIP5) providing global climate model projections for the 5th Assessment Report
- CORDEX which is providing global coordination of Regional Climate Modelling for improved regional climate change adaptation and impact assessment based on CMIP5 models (on-going)

3 Climate-related changes

IPCC's latest report was released in 2013 (see IPCC, 2013). Since the previous assessment report (IPCC 2007), several international reports on climate change have been released (see e.g. IARU, 2009; AMAP, 2011) of which most reports suggested that the sea level rise was underestimated in IPCC AR4. Hence, IPCC AR5 has focused on sea level rise and today there is a closer consensus between IPCC and the scientific community on sea level rise.

In the following sections we mainly refer to the IPCC AR5. However, new research is emerging all the time, and projections of the future climate change are updated continuously, so that everyone dealing with climate adaptation needs to stay well informed on the growing amount of literature. It should be taken into account that adaptation is in progress already, but preferably in flexible ways that will allow for modifications in the future.

Global climate change will have the following consequences, which are very important for the marine infrastructures, coastal areas and the marine environment:

- Increasing air and sea water temperature
- Sea level rise (rise in mean sea level)
- Changing storm surge conditions due to potential wind changes and sea level rise
- Potential changing wave conditions both in terms of intensity and direction due to changing wind conditions
- Changes in precipitation, which will affect (increase/decrease) runoff to the sea
- Increased acidity in the water due to increased CO_2 in the atmosphere

Most of the global climate changes will be directly reflected on a regional and local scale, whereas some variables, such as wind and precipitation, will potentially have strong local bias, and hence should be addressed with care.

In the scientific community there is agreement that climate changes will accelerate in the future, but there is obviously great uncertainty about the rate of these changes and hence, about how the climate will be for example in 2020, 2050 and 2100. Most predictions of climate change look at predictions up to year 2100, but it is important to stress that the changes are likely to continue for several centuries after year 2100.

3.1 Headline statements from the Summary for Policymakers in IPCC AR5

Based on IPCC (2013) a number of short headlines have been produced with respect to what we expect will happen over the coming decades (copied from IPCC, 2013):

- Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system.
- Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions.

- Global surface temperature change by the end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900 for all RCP scenarios except RCP2.6. It is likely to exceed 2°C for RCP6.0 and RCP8.5, and more likely than not to exceed 2°C for RCP4.5.
- Warming will continue beyond 2100 under all RCP scenarios except RCP2.6. Warming will continue to exhibit inter-annual to decadal variability and will not be regionally uniform.
- Changes in the global water cycle in response to the warming in the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase, although there may be regional exceptions.
- The global ocean will continue to warm during the 21st century. Heat will penetrate from the surface to the deep ocean and affect ocean circulation.
- It is very likely that the Arctic sea ice cover will continue to shrink and thin and that the Northern Hemisphere spring snow cover will decrease during the 21st century as global mean surface temperature rises. Global glacier volume will further decrease.
- Global mean sea level will continue to rise during the 21st century. Under all RCP scenarios the rate of the sea level rise will very probably exceed that observed during 1971–2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets.
- Climate change will affect carbon cycle processes in a way that will exacerbate the increase of CO_2 in the atmosphere (high confidence). Further uptake of carbon by the ocean will increase ocean acidification.
- Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. Most aspects of climate change will persist for many centuries even if emissions of CO_2 are stopped. This represents a substantial multi-century climate change commitment created by past, present and future emissions of CO_2.

3.2 Increasing temperature

There is clear evidence that the average global air and sea temperatures have been rising since temperatures were recorded systematically, starting around 1850, see Figure 3.1. The trend in surface temperature based on the period 1906 – 2005 is approximately 0.7 degrees per 100 years and the trend is increasing. Increases in global temperatures are not evenly distributed: Temperature increases are higher at higher latitudes than the average global change, and land areas have experienced a more rapid warming than the oceans.

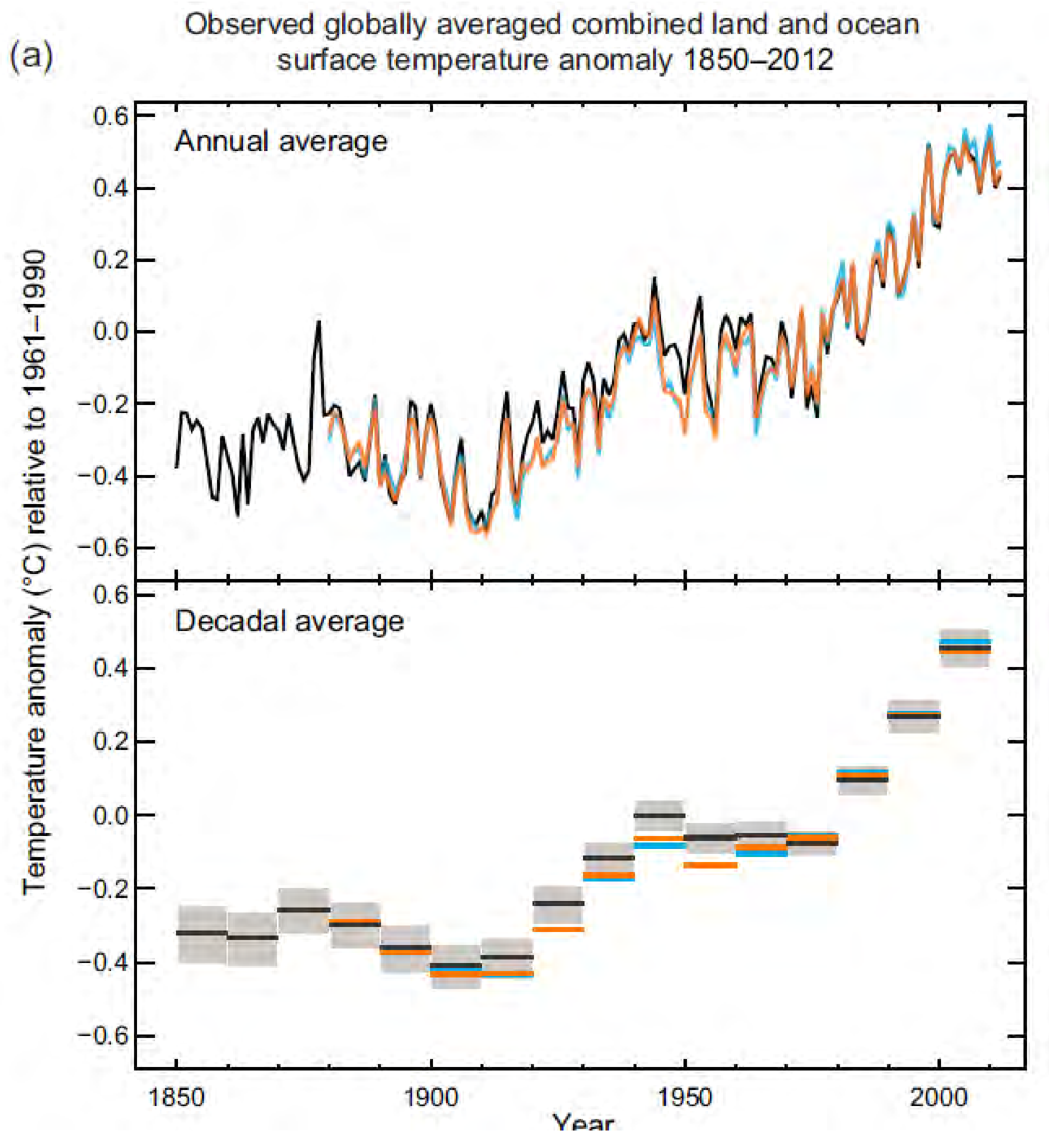

Figure 3.1 Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012 from three data sets. Top panel: annual mean values. Bottom panel: decadal mean values including the estimate of uncertainty for one dataset (black). Anomalies are relative to the mean of 1961−1990. (Copy from IPCC, 2013)

It is extremely likely that most of this observed increase in global averaged temperatures since the middle of the 20th century is caused by the parallel increase in the concentrations of anthropogenic greenhouse gases. In addition, there is a widespread agreement that even with the agreed measures to limit the climate change, global emissions of greenhouse gases will continue to grow for at least the next 20 to 30 years.

This will probably lead to additional warming in the future, even faster than observed over the past 100 years. A central estimate of temperature increase between the late 20th-century and the late 21st-century is approx. 2°C, but with variations in the central estimate of the various RCP scenarios between 1.0°C and 3.7°C. In addition, uncertainties lead to a likely range of between 0.3°C and 4.8°C for temperature increases in 2100. On top of that is the already observed temperature increase of approx. 0.8°C between the beginning of the 20th-century and today.

3.3 Sea level rise

Sea level rise is one of the most direct links to global temperature. Geological evidence of past sea level stands has been used to reconstruct conditions during previous inter-glacial periods. Sea level is driven by many different factors, as listed below:

- Increasing sea temperature which causes thermal expansion of the oceans
- Melting of the Arctic/Antarctic ice caps and glaciers worldwide
- Rapid reduction in areas of Arctic sea ice during the summer, which causes increased absorption of heat in the ocean

Many factors affect the local sea level along the coasts. These factors can be difficult to project individually and can be even more difficult to project in combination. IPCC has highlighted research and policy insight at the sub-national (regional) scale as an important and unexplored geographic and political arena for analysing the impacts of, and responses to sea-level rise. Historical trends in temperature, sea-level and snow cover have been widely documented for many areas, see Figure 3.2 - Figure 3.3, but the predictions of the rate of sea-level rise in the future and the use of local historic trends in predicting future conditions have remained a contentious and debatable issue.

Projected sea-level rise resulting from simulations of different scenarios in IPCC AR4 yields a range of projected increases from 1980 - 1999 to 2090 - 2099 in the range of +0.18 to +0.59 m (IPCC, 2007). However, in IPCC AR5 the range of projected increases from 1986 - 2005 to 2081 – 2100 was increased to the range of +0.26 to +0.82 m.

The main results of the simulations related to surface warming and sea level rise in IPCC AR5 are presented in Table 3.1.

There is some variation in the projections for the various RCPs. A sea level rise in the order of 0.50 m in 2100 is expected as an average of all the modelling results reported in IPCC AR5.

The IPCC AR5 projections referred to above do include the possible acceleration of ice melting from the Arctic ice sheets; however, this was not the case with the IPCC AR4 projections. The IPCC AR5 projections are therefore considered to be more reliable than the previous estimates.

At present there are two major techniques to project future sea level rise. A hierarchy of climate models (simple to comprehensive climate models, IPCC, 2013) and semi-empirical models. The IPCC AR5 climate model simulations use the RCPs for the projections of sea level rise. Semi-empirical models, the most discussed being the work by Rahmstorf (2007), developed a relationship between historic temperature and sea level rise to project the future sea level rise based upon the GCM temperature projections. Since Rahmstorf's initial study, several other semi-empirical projections have been developed, as shown in Figure 3.4. The likely ranges of sea level rise from these studies generally exceed the IPCC AR4 and AR5 projections. In IPCC AR5 it is stated that 'despite the successful calibration and evaluation of semi-empirical models against the observed 20th-century sea level record, there is no consensus in the scientific community about their reliability, and consequently low confidence in projections based on them'.

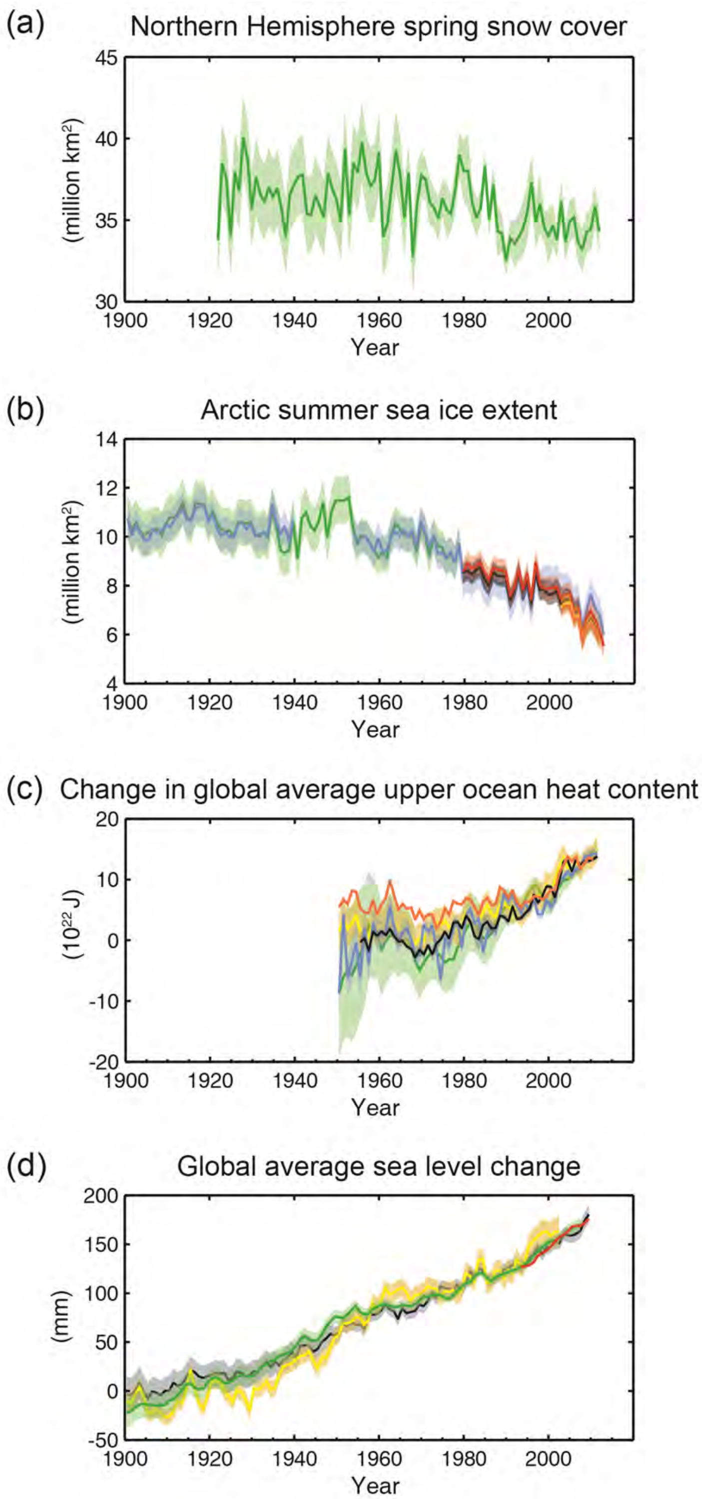

Figure 3.2 Multiple observed indicators of a changing global climate. (a) extent of Northern Hemisphere March-April average snow cover, (b) extent of Arctic summer average sea ice, (c) change in global mean upper ocean (0 – 700 m) heat content relative to mean of all datasets for 1971 and (d) global mean sea level relative to the 1900 – 1905 mean with all datasets aligned to have the same value (Copy of Figure SPM.3 from IPCC, 2013.)

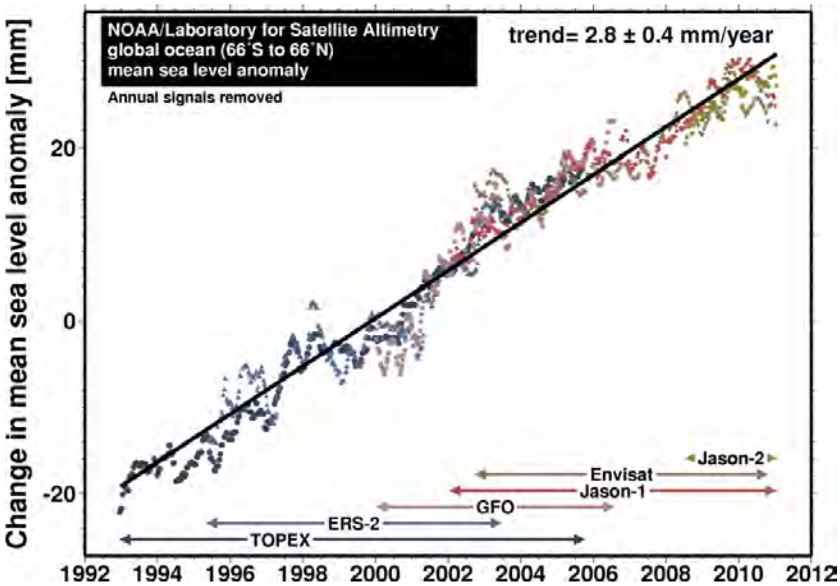

Figure 3.3 Sea level time series for the Global mean sea level (annual signals removed) measured by altimeter Satellite (NOAA Laboratory for Satellite Altimetry, Data for other areas can be found at http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_timeseries_regional.php)

Table 3.1 Projected change in global mean surface air temperature and sea level rise for the mid- and late 21st century relative to the reference period 1986 – 2005 (Copy of table SPM.2 from IPCC, 2013)

		2046–2065		2081–2100	
Variable	**Scenario**	mean	*likely* range [c]	mean	*likely* range [c]
Global Mean Surface Temperature Change (°C) [a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8
		mean	*likely* range [d]	mean	*likely* range [d]
Global Mean Sea Level Rise (m) [b]	RCP2.6	0.24	0.17 to 0.32	0.40	0.26 to 0.55
	RCP4.5	0.26	0.19 to 0.33	0.47	0.32 to 0.63
	RCP6.0	0.25	0.18 to 0.32	0.48	0.33 to 0.63
	RCP8.5	0.30	0.22 to 0.38	0.63	0.45 to 0.82

Notes:

[a] Based on the CMIP5 ensemble; anomalies calculated with respect to 1986–2005. Using HadCRUT4 and its uncertainty estimate (5–95% confidence interval), the observed warming to the reference period 1986–2005 is 0.61 [0.55 to 0.67] °C from 1850–1900, and 0.11 [0.09 to 0.13] °C from 1980–1999, the reference period for projections used in AR4. *Likely* ranges have not been assessed here with respect to earlier reference periods because methods are not generally available in the literature for combining the uncertainties in models and observations. Adding projected and observed changes does not account for potential effects of model biases compared to observations, and for natural internal variability during the observational reference period {2.4; 11.2; Tables 12.2 and 12.3}

[b] Based on 21 CMIP5 models; anomalies calculated with respect to 1986–2005. Where CMIP5 results were not available for a particular AOGCM and scenario, they were estimated as explained in Chapter 13, Table 13.5. The contributions from ice sheet rapid dynamical change and anthropogenic land water storage are treated as having uniform probability distributions, and as largely independent of scenario. This treatment does not imply that the contributions concerned will not depend on the scenario followed, only that the current state of knowledge does not permit a quantitative assessment of the dependence. Based on current understanding, only the collapse of marine-based sectors of the Antarctic ice sheet, if initiated, could cause global mean sea level to rise substantially above the *likely* range during the 21st century. There is *medium confidence* that this additional contribution would not exceed several tenths of a meter of sea level rise during the 21st century.

[c] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean surface temperature change in 2046–2065 *confidence* is *medium*, because the relative importance of natural internal variability, and uncertainty in non-greenhouse gas forcing and response, are larger than for 2081–2100. The *likely* ranges for 2046–2065 do not take into account the possible influence of factors that lead to the assessed range for near-term (2016–2035) global mean surface temperature change that is lower than the 5–95% model range, because the influence of these factors on longer term projections has not been quantified due to insufficient scientific understanding. {11.3}

[d] Calculated from projections as 5–95% model ranges. These ranges are then assessed to be *likely* ranges after accounting for additional uncertainties or different levels of confidence in models. For projections of global mean sea level rise *confidence* is *medium* for both time horizons.

Other research and international institutions have also published climate projections of sea level rise, which are higher than those proposed by IPCC. An example is the Synthesis Report, Climate Change, Global Risks, Challenges & Decisions University of Copenhagen, 2009). They state that it is most likely that the sea level rise in the year 2100 will be in the order of 1.0 m or even more, and that the sea level will continue to rise also after year 2100. In the report it is argued:

> "These revised estimates show that the ocean has warmed significantly in recent years. Current estimates indicate that ocean warming is about 50% higher than had been previously reported by the IPCC. The rate of sea level rise has increased in the period from 1993 to the present, largely due to the growing contribution of ice loss from Greenland. However, models of the behaviour of these polar ice sheets are still in their infancy, so projections of sea level rise to 2100 based on such "process models" are highly uncertain. An alternative approach is to base projections on the observed relationship between global average temperature rise and sea level rise over the past 120 years, assuming that this observed relationship will continue into the future. New estimates based on this approach suggest a sea level rise of around a metre or more by 2100. Sea level rise will not stop in 2100. Changes in ocean heat content will continue to affect sea level rise for several centuries at least. Melting and dynamic ice loss in Antarctica and Greenland will also continue for centuries into the future. Thus, the changes current generations initiate in the climate will directly influence our descendants long into the future. In fact, global average surface temperature will hardly drop in the first thousand years after greenhouse gas emissions are cut to zero."

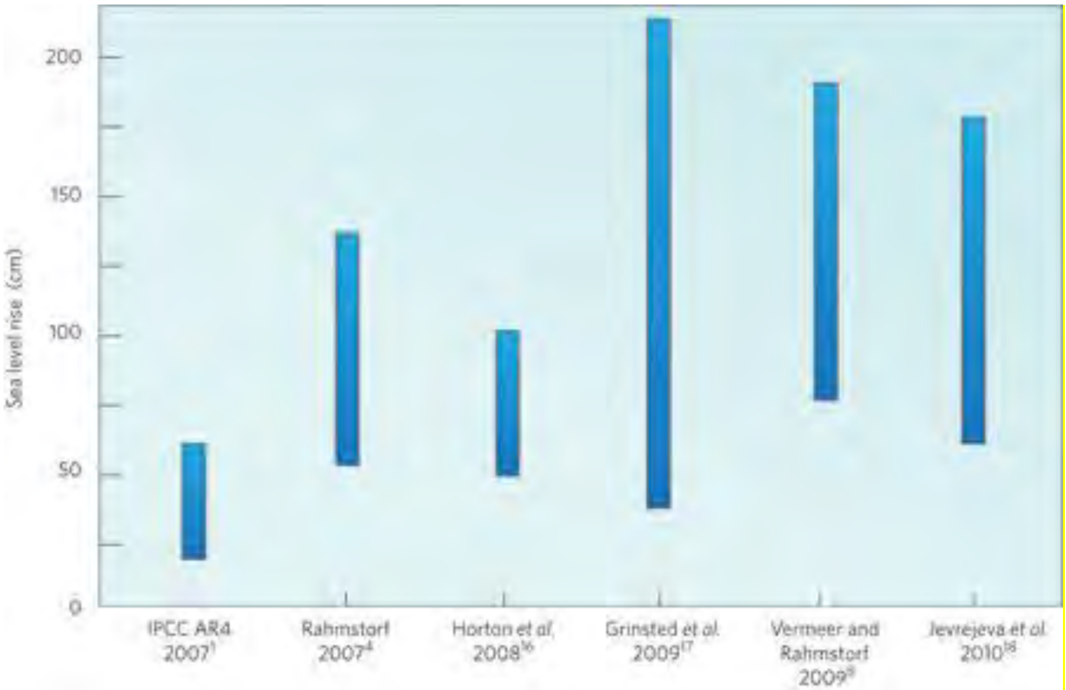

Figure 3.4 Estimates for twenty-first century sea level rise from semi-empirical models as compared to the IPCC AR4. For exact definitions of the time periods and emission scenarios considered, see the original references (IPCC 2007; Rahmstorf 2007; Horton *et al.* 2008; Grinsted *et al.* 2009; Vermeer and Rahmstorf 2010; Jevrejeva *et al.* 2006)

The report: Climate change, impacts and vulnerability in Europe 2012 by European Environmental Agency (EEA 2012), expresses the likelihood of reaching the high end of the projection area as follows:

> *"In summary, the highest projections available in the scientific literature should not be treated as likely increases in the 21st century sea level, but they are useful for vulnerability tests against flooding in regions where there is a large risk aversion to flooding, or the consequences of flooding are particularly catastrophic."*

Rising sea levels will have a direct impact on coastal cities, towns and subsistence communities mainly through coastal flooding and through shoreline retreat (coastal erosion). Both issues are exemplified in Appendix B. However, other effects are also expected as discussed above. Recommendations, guidelines or requirements used by different governments or agencies are provided in Appendix A as examples of the different approaches in use around the world.

Sea level changes are not uniform. Regional changes are caused by differences in the rates of oceanic thermal expansion, changes in wind and atmospheric pressure, and changes in ocean circulation (meteo-oceanographic factors) as well as changes in the gravity field of the Earth due to melting of ice. In addition, important non-climate processes may add to the relative change of the sea water level, such as glacial isostatic adjustments, tectonics, and subsidence (e.g. by overexploitation of groundwater). The regional variation in sea level from the global mean due to meteo-oceanographic factors is shown in Figure 3.5.

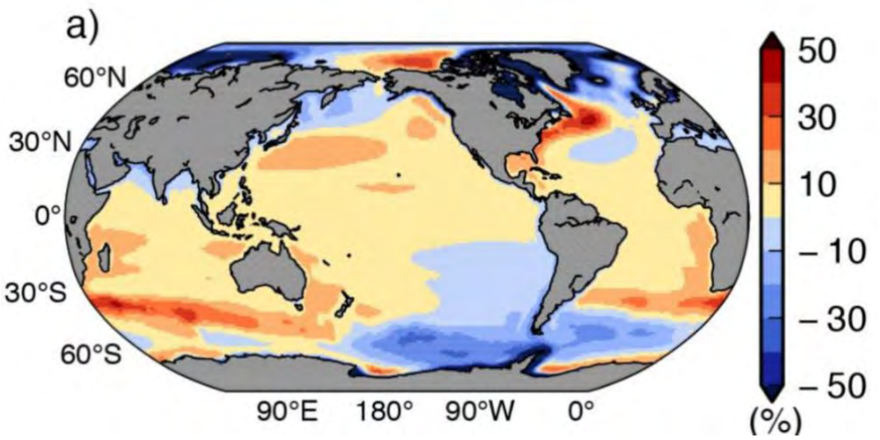

Figure 3.5 Relative deviation of the projected mean sea level change in 2081–2100 relative to 1986–2005 from the global mean. The results are based on an ensemble mean projection for the RCP4.5 scenario. The deviations are representative also for the other RCP scenarios. Reproduced from Church *et al.* (2013)

The global projections are usually given as sea level rise by 2100 relative to the sea level in 1986-2005. For estimation of the temporal evolution, a quadratic function can be used (Nicholls *et al.,* 2011).

3.4 Increased storminess

An increasing frequency of more extreme storms and cyclones is predicted for the 21th-century. The IPCC considers it likely that future cyclones will be strengthened by higher tropical sea surface temperatures resulting in more intense events with higher wind speeds and heavier rainfall, and maybe covering areas of higher latitudes (IPCC 2007). For example, storm tracks may shift north-eastwards in the North Atlantic. Some regions are likely to experience an increase in average wind speed throughout the year caused by stronger prevailing winds. The effect of just a 10% increase in wind speed on the coastal environment creates an order of magnitude increase of other coastal processes. A 10% increase in wind speed is predicted to result in a 26% increase in wave heights and potential increasing longshore transport rates by between 40% and 100% (Theron 2007). Actual changes will be co-determined by many other factors such as changes in wind directions, sediment availability, wave transformation, higher sea level, etc. These impacts are likely to affect coastal areas, particularly areas weakened by previous erosion or low-lying coastal areas.

In IPCC AR5 it is concluded that there is low confidence in region-specific projections of storminess and associated storm surges. Hence, any predictions on changes in storminess must be regarded as rather uncertain.

3.5 Change in wave conditions

Changing wind conditions will partly affect wave conditions and partly flooding conditions. Hence, some areas will experience more intensified wave conditions, whereas others may experience less intensified conditions. However, changes are most likely to happen including changes in the distribution of the waves. These changes could be significant enough to affect some coastal conditions, as for example transport and erosion/sedimentation conditions along the coasts, etc.

3.6 Changes in precipitation

In most parts of the world precipitation is expected to change. From a marine point of view this is important as river run-off is bound to change as well. In estuaries and coastal areas river run-off affects salinities, stratification and nutrients, which is why significant changes in river run-off will have a substantial impact on the biodiversity and ecosystem productivity, and vulnerability.

One additional factor that also needs to be taken into consideration when discussing nutrient loadings from river run-off and eutrophication in coastal areas is changes in agriculture. In many areas of the world, nutrient losses from agriculture is a result of the different crops and political control, which is why it is uncertain how climate changes in precipitation will affect nutrient loadings to coastal areas.

3.7 Ocean warming and acidification

Increasing water temperature and decreasing ocean pH (termed ocean acidification) are two other consequences of climate change. Both factors will affect the marine ecosystems and the environment. Most biological and chemical processes are linked to temperature, and increasing temperatures will – in most cases – imply accelerated processes. However, the different processes will not respond equally to temperature changes. For example, the heterotrophic community (bacteria and zooplankton) will respond stronger to temperature changes than the autotrophic community (primary producers like algae). Thus, even small temperature changes may push ecosystems to change dramatically from autotrophic communities towards heterotrophic communities – and potentially change ecosystems from benthic (at the sea bed) dominated communities to pelagic (in the water column) communities. The different ecosystems have some tolerance towards temperature changes and resilience towards changes. However, ecosystems in stress may respond strongly and irreversibly.

Furthermore, temperature affects oxygen saturation strongly and in areas where anoxic conditions are an increasing challenge, temperature increases will work against any improvements obtained with respect to oxygen.

Acidification is another important issue. While CO_2 increases in both atmosphere and oceans the entire ocean buffer system gets challenged and the pH decreases slowly. A number of living organisms depend on formations of different carbonated structures from clams, snails to crustaceans. In a worst case scenario the pH will at some stage not allow for these organisms and animals to reproduce and survive, thus entire food webs may collapse with unpredictable consequences for ecosystems around the world. Particularly the low saline areas, where calcium concentrations are low, are vulnerable. Enhanced nutrient reductions will accelerate this trend as algae uptake of CO_2 is reduced when the growth becomes nutrient limited.

In some areas of the world the first observation of acidification is evident: E.g. decreased coral calcification and decreased coral growth have already been observed on the Great Barrier Reef of Australia (Cooper *et al.* 2008; Hoegh-Guldberg *et al.* 2007) as a result of recorded temperature and dissolved CO_2 increases; increases which can be expected to continue (Anthony *et al.* 2008). At some point, the decrease in calcification may cause not only decreased coral growth but a decline in coral volume. Healthy coral reefs are of vital importance to the tropical habitats and also to the stability of tropical beaches. Most directly, the reefs buffer wave energy, protecting the inland beaches from direct wave attack. In addition, carbonate beaches get their sand from the erosion of the coral reefs. Decreased coral calcification, loss of reef volume and sea level rise will increase wave energy on the beach and result in a decrease in available beach sand – all of which will have an adverse effect on the stability of the carbonate beaches.

In addition to acidification corals are vulnerable to increasing temperature. Above a certain temperature corals simply die. This is called coral bleaching and is a rather abrupt and fast process, and can be seen at different levels in areas after natural phenomena like El Niño.

3.8 Summary

The direct or indirect impacts in the coastal zone caused by these climate changes are outlined in Table 3.2. Note that the climate changes have direct impacts on the coastal zone as well as impacts via secondary effects.

Table 3.2 Summary of climate changes impacting coastal areas, their secondary effects and their impacts

<table>
<tr><th colspan="2" rowspan="2">Climate changes impacting coastal area</th><th colspan="2" rowspan="2">Secondary effects</th><th colspan="2">Impacts</th></tr>
<tr><th>Type</th><th>Rate of change</th></tr>
<tr><td colspan="2" rowspan="2">Increase in sea water temperature</td><td colspan="2">Sea level rise</td><td>See ‘sea level rise’ below</td><td>See ‘sea level rise’ below</td></tr>
<tr><td colspan="2">Risk of coral bleaching
Ecosystem changes
Ice coverage</td><td>Coral reef degradation and coastal erosion
E.g. from autotrophic to heterotrophic ecosystems</td><td>Above thresholds – gradual to fast
Gradual
Gradual</td></tr>
<tr><td colspan="2" rowspan="5">Sea level rise</td><td colspan="2" rowspan="5">Landward movement of the water/land interface
Elevated coastal groundwater levels
Reduced gradient of coastal rivers and streams
Vertical and lateral expansion of the zone of tidal influence in coastal rivers and streams</td><td>Coastal flooding of protected low lying areas</td><td>Catastrophic, impacting large areas</td></tr>
<tr><td>Coastal flooding of low lying areas</td><td>Gradual</td></tr>
<tr><td>Change coastal wetlands</td><td>Gradual loss of existing wetlands and generation of new wetlands</td></tr>
<tr><td>Backwater problems, increased salinity and sluice practice</td><td>Gradual</td></tr>
<tr><td>Shoreline retreat (coastal erosion)</td><td>Gradual, along the shoreline</td></tr>
<tr><td colspan="2" rowspan="3">Changed wind pattern (increased storminess)</td><td>Higher storm surge</td><td></td><td>Coastal flooding of low-lying areas</td><td>Gradual</td></tr>
<tr><td>Higher waves</td><td>Higher littoral transport</td><td rowspan="2">Shoreline retreat
or
shoreline accretion</td><td rowspan="2">Gradual, along the coast</td></tr>
<tr><td>Changed directional characteristics of winds and waves</td><td>Changed littoral transport</td></tr>
<tr><td rowspan="4">Changed precipitation</td><td rowspan="3">Higher</td><td colspan="2">Increased supply of sediments to the coast</td><td>Shoreline accretion</td><td>Gradual</td></tr>
<tr><td colspan="2">Increased supply of nutrients to coastal waters</td><td>Eutrophication</td><td>Gradual</td></tr>
<tr><td colspan="2">Potential changes in salinity</td><td>Changes in ecosystems
Changes in stratification</td><td>Gradual
Gradual</td></tr>
<tr><td>Lower</td><td colspan="2">Decreased supply of sediments to the coast</td><td>Shoreline retreat</td><td>Gradual</td></tr>
<tr><td colspan="2">Increased acidification</td><td colspan="2">Stressing of marine flora and fauna</td><td>Changes in marine flora and fauna such as coral reefs</td><td>Gradual and abrupt</td></tr>
</table>

4 How to include climate changes and climate adaptation when planning coastal areas?

As stated earlier, climate change and climate change adaptation are interdisciplinary challenges. In most cases climate adaptation involves a number of different stakeholders and should be regarded as a strongly interdisciplinary exercise.

Hence, before addressing climate change adaptation searching for technical solutions and/or approaches, a number of key steps assessing vulnerability to climate change need to be evaluated.

4.1 Key steps for assessing vulnerability to climate change

Determine objectives and scope

- Identify audience, user requirements, and needed products
- Engage key internal and external stakeholders
- Establish and agree on goals and objectives
- Identify suitable assessment targets
- Determine appropriate spatial scales
- Determine planning horizon, the so-called life time of the intervention
- Select assessment approach based on targets, user needs, and available resources

Gather relevant data and expertise

- Review existing literature on assessment targets and climate impacts
- Reach out to subject experts on target species or systems
- Obtain or develop climate projections, focusing on physical and ecologically relevant variables and suitable spatial and temporal scales
- Obtain or develop physical and ecological response projections

Assess components of vulnerability

- Evaluate climate sensitivity of assessment targets
- Determine likely exposure of targets to climate/ecological change
- Consider adaptive capacity of targets that can moderate potential impact
- Estimate overall vulnerability of targets
- Document level of confidence or uncertainty in assessments

Apply assessment in adaptation planning

- Explore why specific targets are vulnerable to inform of possible adaptation responses
- Consider how targets might develop under various management and climate scenarios

- Share assessment results with stakeholders and decision-makers
- Use results to advance development of adaptation strategies and plans

The steps above are all important to ensure sustainable adaptation to climate change; however, a number of the above steps will not be described in more detail, but are merely mentioned to state that climate adaptation calls for interdisciplinary work and strong collaboration between science, authorities, local communities, private stakeholders, etc.

The following sections aim at highlighting practical tools and issues to collate the background material to address all climate relevant issues and stakeholders mentioned above.

4.2 Climate adaptation

An approach for addressing climate adaptation in practice is illustrated in Figure 4.1.

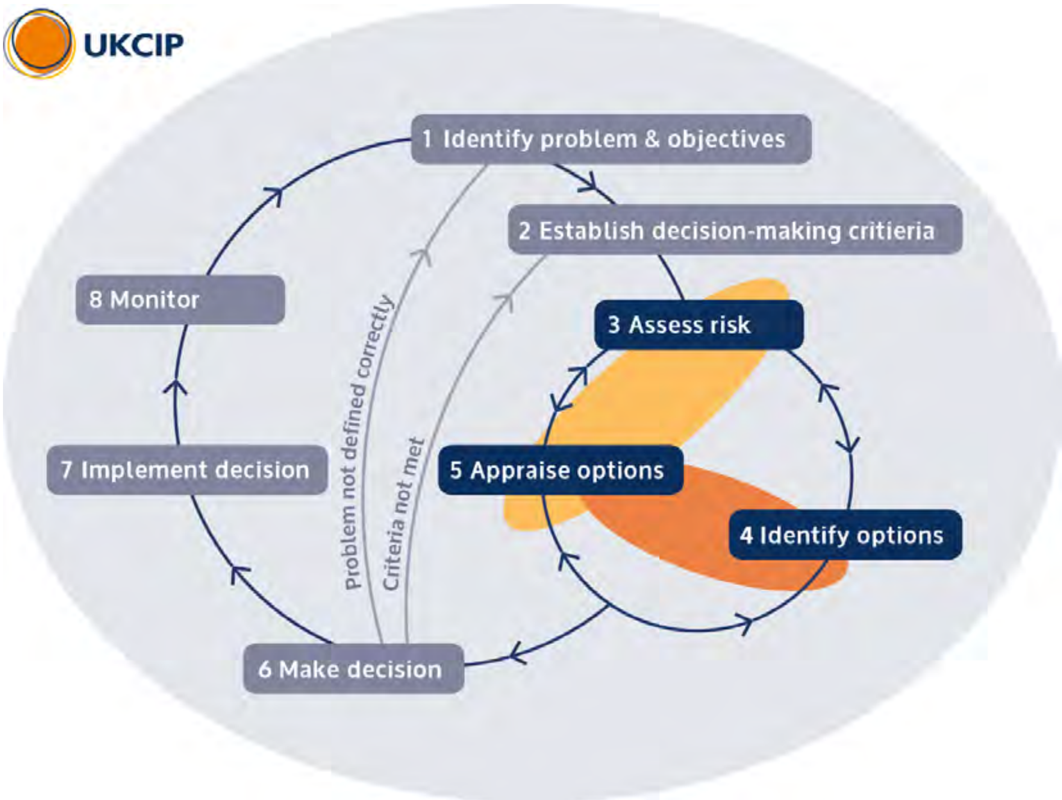

Figure 4.1 Risk, uncertainty and decision-making framework suggested by UKCIP (Brown *et al.* 2011)

The key stages of the process are:

Stage 1: Identify the problem and objectives, including:

- Location / climate region
- Likely climate change scenarios

Stage 2: Establish your risk tolerance level and decision-making criteria, including:

- Life-time / time horizon

Stage 3: Identify and assess your risks, including:

- Detailed environmental design parameters as expressed in relevant IPCC and local government publications, or assess risks by further analyses as listed below:
- Are the important design parameters covered by climate models or not
- Global climate models
- Regional climate models
- A combination of local and global models
- The way to handle effects not covered by climate models
  - Select downscaling method
  - Availability of measurements and observations
  - Model uncertainty
  - Statistical methods
  - Simplified approaches

Stage 4: Identify a range of adaptation options

Stage 5: Appraise your adaptation options

Stage 6: Make a decision

Stage 7: Implement the decision

Stage 8: Monitor the decision and evaluate new information

In the following sections some guidelines on stages 1-3 are provided.

4.2.1 Identify the problem and objectives (Stage 1)

As mentioned earlier, IPCC has created different emission scenarios – scenarios which are plausible representations of the future development of emissions of greenhouse gases and aerosol precursors, but effects differ significantly on a 100-year time scale and even more beyond year 2100. Furthermore, at present climate changes seem to appear faster than anticipated by IPCC, thus at best any climate adaptation solution needs to be flexible and adaptable to different climate outcome.

When addressing climate changes at project level, location and hence climate region are most likely known. However, issues on likely climate change scenarios are often much more difficult to address. In this case you will have to rely on the judgment of others depending on the problem at hand:

- For targets related to national or local authorities it will be national policymakers deciding on which scenarios are relevant. As an example, in Denmark previous governmental guidelines said that Danish authorities should adapt according to the SRES A1B scenario. The policy makers have not yet decided on any recommended scenarios related to the RCPs. This is most likely the case worldwide, hence any work related to climate adaptation may relate to potential older guidelines. In any case, it is recommended to apply different scenarios and projections to assess the uncertainty in the impact assessment.
- For other targets, insurance companies, certifying agencies or national/international research organisations may provide guidelines on which scenarios to follow.

However, every climate change adaptation starts with an estimate based on a climate scenario. This estimate can be either directly based on

- Existing scenarios/state of art scenarios, or
- Expert judgement on preferred scenarios.

As an example, the projections of sea level rise have large uncertainties. The choice of projections will be case-specific, depending on the vulnerability and associated risk of sea level rise for the region being considered. For instance, in UK a scenario of up to 2m sea level rise by 2100 has been developed (denoted the H++ scenario). The probability of this scenario is unknown but was found to be relevant due to large potential impacts of such a sea level rise (Nicholls, 2011).

In general, it is recommended to apply a range of sea level rises for the impact assessment, representing a lower, upper, and median change. For studies with large potential impacts, it is recommended to use a high-end scenario such as the UK H++ scenario.

4.2.2 Establish your risk tolerance level and decision-making criteria (Stage 2)

Looking at climate changes and potential climate change adaptation the life-time is an essential issue. As indicated in Table 4.1 and Table 4.2, life-times less than 10 years do not need to consider climate changes. For life-times of approximately 20 years, some areas and regions will potentially be affected by a climate change signal exceeding the natural variability that could be important. Targets with a life-time of more than 50 years should always include some evaluation and adaptation of climate changes and climate change effects.

Table 4.1 General impacts of climate change for different life-times/planning horizons

Life-time (years)	Climate change effect on climatic and oceanographic parameters
10	Dominated by natural variability, not climate change
20	The natural variability generally increases with increasing latitude. This implies that the natural variation at this time scale will dominate the climate change effect at mid and higher latitudes (above approximately 50 degrees). Hence, climate change will show limited effect at these latitudes. At lower latitudes the effect of climate change will be more pronounced, see text below.
50	Climate change will have an impact. Some difference between the different IPCC Scenarios.
100	Climate change will impact all parameters. Significant difference between the different IPCC Scenarios.

In the projections of climate change effects on climatic and oceanographic parameters uncertainties are unavoidable. However, the uncertainties change on different scales and for different areas. The main sources of uncertainties are:

- Internal variability (increases at short temporal and spatial scales)
- Climate model uncertainty
- Scenario uncertainty (increases over time)

Table 4.2 Impacts of climate change for different types of marine focus area for different life-times

	Life-time/planning horizon (years)			
Type of marine focus area	**10**	**20**	**50**	**100**
Offshore structures, including: • Offshore Wind Farms • Oil platforms • Etc.	None	Minor impact	Some impact on design	Significant impact on design
Pipelines and subsea systems	None	Minor impact	Some impact on design	Significant impact on design
Ships and ports	None	Minor impact	Some impact on design	Significant impact on design
Coastal erosion and coastal flooding issues: • Coastal erosion [5] • Shoreline retreat[6] • Retreat solutions[7] • Dune erosion • Coastal flooding[8] • Flooding of urban areas • Saltwater intrusion	None	Some impact	Significant impact	Significant impact
Aquaculture	None	None	Significant impact on species	Significant impact on species
Water quality for recreational purposes	None	Some impacts depending on storm water overflows	Some impacts depending on storm water overflows	Significant impacts depending on storm water overflows
Changing ecosystem, including: • Changing of habitats (loss of habitats) • Increasing eutrophication • Moving towards a pelagic system • Acidification • Ballast water • New species • Anoxia	None	Some impacts in some areas	Some impacts	Significant impacts and potential irreversible effects for some ecosystems

[5] An example of 'Impact assessment of climate change on coastal erosion and sediment transport' is available in Appendix B

[6] An example of 'Shoreline retreat' is available in Appendix B

[7] An example of 'Retreat solution (setback lines)' is available in Appendix B

[8] An example of 'Changes in flood conditions' is available in Appendix B

4.2.3 Identify and assess your risks (Stage 3)

4.2.3.1 Detailed environmental design parameters

Different targets will react differently to the different climate change parameters, and the decision as to which design parameters to include will vary between targets, see Table 4.3.

Table 4.3 Marine focus areas impacted by change in the different climatic and oceanographic parameters

Marine focus area	Wind	Air temp.		Sea temp.	Precipitation	Waves	Current	Storm surge and tide	Mean sea level	Sea ice
Offshore structures										
• Platforms, fixed	X	X		X *		X	X	X	X	X
• Platforms, floating	X	X		X *		X	X			X
• Pipelines and subsea systems				X **		X	X			
• Offshore wind farms	X	X		X*		X	X	X	X	X
Ports	X					X	X	X	X	X
Coastal protection	X					X		X	X	
Sea defence	X					X		X	X	X
Cooling water	X	X		X		X	X	X	X	
Aquaculture										
• The structure (floating)	X	X		X		X	X			X
• The fish				X			X			X
Water quality for recreational purposes				X	X		X			
Changing ecosystem										
• Habitats				X	X	X	X		X	X
• Eutrophication				X	X					
• Acidification				X						
• Anoxia				X	X				X	
• Invasive species	X			X	X		X			X
• Bio-manipulation				X	X		X			X

* Fouling
** Density

4.2.3.2 Are the important design parameters covered by climate models or not

National guidelines on e.g. sea level rise may already exist and can be used directly when taking climate change into account in a given case. In other cases it is necessary to look at results from GCMs and RCMs and detailed local environmental models.

Output variables from atmospheric GCMs and RCMs include surface wind, sea level pressure, temperatures, precipitation, etc., while output variables from oceanographic GCMs and RCMs include sea surface temperatures, ice, sea surface height, etc. In some cases a wave model is also included with a GCM and RCM. Output variables from wave models include wave heights, periods, direction, etc. In some cases, the GCMs and RCMs comprise all three types of models.

One of the main purposes of the oceanographic models is to describe the transfer and storage of heat and CO_2 in the ocean. Since oceanographic models in general are of the same order of complexity as atmospheric models and thus require large computational resources, they are often simplified as much as possible, while they still fulfil their purpose. Tides are often neglected as they are not important for the large-scale circulations. An oceanographic GCM and RCM (whether simplified or not) may be adequate for the interaction with the atmosphere, but these models are not yet detailed enough to describe phenomena such as storm surges and current patterns in coastal areas, estuaries and other shallow or enclosed areas.

Likewise, the wave models applied together with GCMs and RCMs are often suited for the open seas, but not for shallow water areas where varying water levels, refraction, shoaling etc. are important. One reason is that spectral wave models, which are normally applied, require considerable computational resources, especially when they include shallow water effects.

To have an accurate description of wave, water level and current conditions in coastal areas, estuaries and other shallow or enclosed areas, it is therefore recommended to apply regional wave and oceanographic/hydrodynamic/flow models which use output variables from detailed RCMs as input.

4.2.3.3 How to handle effects not covered by climate models

A number of climate change projections are needed on time scales and spatial scales much finer than climate model resolutions. Hence, projections from GCMs and even RCMs need to be regarded as guidelines or overall average future projections and should not be used for projections on local scales. For handling climate change effects and climate adaptation on local scales methods for downscaling need to be considered. This is especially important when looking at extreme values, which may have large biases. Furthermore, all climate models are simplifications of nature, and hence do not project all features equally well. To handle both downscaling and model biases a number of issues need to be considered:

- Availability of measurements and observations
- Climate model uncertainty
- Statistical downscaling and bias correction method
- Advanced local modelling
- Establishment of statistics for governing variables

The following downscaling methods should be considered for different assessments:

- Dynamical downscaling with local environmental models – often applied in marine applications. RCMs operate on a relatively coarse spatial resolution. Local (environmental) models with a finer spatial resolution and/or better variable description than what can be included in RCMs are required in many cases. Examples include:
  - Wind wave models
  - Coastal current and water level models (2D or 3D) including inland flooding from the sea and possibly combined with inland flooding models
  - Inland flooding models
  - Hydrological models

- Statistical downscaling – in many cases not adequate in marine applications: Climate projections from global circulation models (GCM) are biased and cannot adequately reproduce the variability in climate variables that are present at the local scale. Statistical downscaling relates the climate projections at a larger scale (from GCMs or RCMs) to climate variables at the local scale. Downscaling may be performed using probability functions of the climate variable considered or by statistical adjustments of climate time series that are subsequently used for deriving relevant statistics and/or used in local modelling from which other key variables are derived. In both cases local information about the variable being considered is required, either in terms of a probability distribution or as a time series.

Widely applied statistical downscaling procedures are based on a general change factor methodology. The basic concept in change factor methods is that climate model simulations are used to extract changes in different statistical characteristics of climate variables from the present to the future climate (denoted change factors). These changes are then superimposed on the statistical characteristics of the climate variable representing the local scale. Examples are:

- Mean correction (often referred to as the Delta Change Method)

- Mean and variance correction

- Stochastic weather generator

- Correction of probability density function (pdf)

5 More information

5.1 Resources summarising IPCC work and climate science

Intergovernmental Panel on Climate Change Fifth Assessment Report (https://www.ipcc.ch/report/ar5/)

IPCC Data Distribution Centre: Observed and projected climate data and supporting technical guidelines (http://www.ipcc-data.org/)

UNEP (2009): Climate in Peril – A popular guide to the latest IPCC reports (http://www.unep.org/pdf/0903ClimateInPerilfinaldraft.pdf)

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APPENDICES

APPENDIX A

Handling sea level rise around the world

A Handling sea level rise around the world

A.1 United Kingdom

The sea level projections developed by Defra for the coast of Great Britain are an example. The main tools used by the United Kingdom for coastal management are Shoreline Management Plans (SMP), revised Shoreline Management Plans (SMP2), Defra SMP, and a new Coastal Change Policy, Defra (2010).

The UK anticipates that with whatever policies are put into place now to address climate change, their country will experience at least 30 to 40 years of rising temperatures and 100 years of rising sea level. The UK coast has experienced an average historic sea level rise of 1 mm/year, or 0.1 metres per century. In anticipation of increased future sea level rise, new engineering projects with a 100-year design life are required to include up to 1 metre of sea level rise. The plan provides recommended rates of sea level rise for various time periods (Table A. 1), recognising that the rate of rise is expected to be larger at the end of the 21st century than at the beginning.

Table A. 1 UK Recommended Net Sea Level Rise rates and cumulative amounts, relative to 1990

Time Period	Low Rate (mm/year)/ cumulative SLR since 1990 (m) at end of period	Moderate Rate (mm/year)/ cumulative SLR since 1990 (m) at end of period	High Rate (mm/year)/ cumulative SLR since 1990 (m) at end of period
1990 – 2025	2.5/0.09	3.5/0.12	4.0/0.14
2025 – 2055	7.0/0.30	8.0/0.36	8.5/0.40
2055 – 2085	10.0/0.60	11.5/0.71	12/0.75
2085 – 2115	13.0/0.99	14.5/1.14	15/1.21

SOURCE: Defra 2010.

A.2 The Netherlands

The Netherlands has had a long tradition of reliance upon dykes and engineered structures for sea defence and had undertaken a very pro-active approach for national protection against coastal flooding. After the 1953 North Sea floods, the country initiated a major effort to upgrade its protective works, and most major urban areas now have sea defence designed for recurrence periods that range from 2,000 to 10,000 years for coastal flooding, and from 250 to 1,250 years for river flooding. Work by Stefan Rahmstorf (projecting up to a 1.4 metre rise in sea level from 1990 to 2100 through a semi-empirical method that correlates global sea level rise and global temperature) has formed the basis for much of the recent work by the Delta Committee, the advisory board for the Government. The assignment of the Delta Committee is “to come up with recommendations on how to protect the Dutch coast and the low-lying hinterland against the consequences of climate change. The issue is how the Netherlands can be made climate-proof over the very long term: safe against flooding, while still remaining an attractive place to live, to reside and work, for recreation and investment.

The task at hand then involved looking further than just flood protection. The Committee's vision therefore embraces interactions with life and work, agriculture, nature, recreation, landscape, infrastructure and energy. The strategy for future centuries rests on two pillars: flood protection and sustainability.

The Delta Committee has drafted the Delta Programme to implement its recommendations for a climate-proof Netherlands. The programme will be embedded, financially, politically and administratively, in a new *Delta Act (*Source: Delta Committee 2008).

A.3 South Africa

In South Africa, recommendations for sea level rise to use in projects are based on the project type and significance. Table A. 2 shows the breakdown of project types and recommended sea level amounts.

Table A. 2 Sea Level Rise Amounts for Different Types of Infrastructure, South Africa, from Dr. Andrew A. Mather (personnel communication)

Value of infrastructure	Life of infrastructure	Impacts of failure of the infrastructure	Planned amount of sea level rise
Low (Up to R2 million) I.e. Recreational facilities, car parks, board walks, temp beach facilities	Short term Less than 20 years	Low Minor inconvenience, alternative facilities in close proximity, short rebuild times	**0.3m**
Medium (R2 million to R20 million) Tidal pools, piers, recreational facilities, sewerage pump stations.	Short to Medium Term Between 20 and 50 years	Medium Local impacts, loss of infrastructure and property	**0.6m**
High (R20 million to R200 million) Beachfronts, small craft harbours, Residential homes, sewerage treatment works.	Medium to Long Term Between 50 and 100 years	High Regional impacts, loss of significant infrastructure and property	**1.0m**
Very high (higher than R200 million) Ports, desalination plants, nuclear power stations	Long term In excess of 100 years	Very High Major disruption to the regional and national economy, failure of key national infrastructure	**2.0m**

A.4 California, Oregon, and Washington

In 2012, The US National Academy of Science/National Research Council issued the following report, refer also to PIANC 2014:

"Sea-Level Rise for the Coasts of California, Oregon, and Washington:

Past, Present, and Future, NRC 2012"

The recommendations from this report are presented in Table A. 3.

Table A. 3 Regional Sea Level Rise projections (in cm) relative to year 2000 for Seattle, Newport, San Francisco and Los Angeles, Table 5.3 from NRC 2012

	2030		2050		2100	
Component	Projection	Range	Projection	Range	Projection	Range
Steric and dynamic ocean[a]	3.6 ± 2.5	0.0–9.3 (B1–A1FI)	7.8 ± 3.7	2.2–16.1 (B1–A1FI)	20.9 ± 7.7	9.9–37.1 (B1–A1FI)
Non-Alaska glaciers and ice caps[b]	2.4 ± 0.2		4.4 ± 0.3		11.4 ± 1.0	
Alaska, Greenland, and Antarctica with sea-level fingerprint effect[c]						
Seattle, WA	7.1	5.4–9.5	16.0	11.1–22.1	52.7	32.7–74.9
Newport, OR	7.4	5.6–9.5	16.6	11.7–22.2	54.5	34.1–75.3
San Francisco, CA	7.8	6.1–9.6	17.6	12.7–22.3	57.6	37.3–76.1
Los Angeles, CA	8.0	6.3–9.6	17.9	13.0–22.3	58.5	38.6–76.4
Vertical land motion[d]						
North of Cape Mendocino	-3.0	-7.5–1.5	-5.0	-12.5–2.5	-10.0	-25.0–5.0
South of Cape Mendocino	4.5	0.6–8.4	7.5	1.0–14.0	15.0	2.0–28.0
Sum of all contributions						
Seattle	6.6 ± 5.6	-3.7–22.5	16.6 ± 10.5	-2.5–47.8	61.8 ± 29.3	10.0–143.0
Newport	6.8 ± 5.6	-3.5–22.7	17.2 ± 10.3	-2.1–48.1	63.3 ± 28.3	11.7–142.4
San Francisco	14.4 ± 5.0	4.3–29.7	28.0 ± 9.2	12.3–60.8	91.9 ± 25.5	42.4–166.4
Los Angeles	14.7 ± 5.0	4.6–30.0	28.4 ± 9.0	12.7–60.8	93.1 ± 24.9	44.2–166.5

It is seen that average SLR projections for year 2100 range between 62 and 93 cm ±27 cm.

A.5 US Army Corps of Engineers

Funding and project development agencies too are setting standards for the sea level rise that must be considered in project planning and design. For example, the US Army Corps of Engineers (Corps) supports many of the coast protection projects in the United States; in 2009 the Corps issued Circular 1165, Water Resource Policies and Authorities Incorporating Sea-level Change Considerations in Civil Works Programmes. The purpose of this circular is to provide guidance for incorporating the direct and indirect physical effects of projected future sea-level change in managing, planning, engineering, designing, constructing, operating, and maintaining. The direction from this circular is that:

Planning, engineering, and designing for sea level change must consider how sensitive and adaptable 1) natural and managed ecosystems and 2) human systems are to climate change and other related global changes.

Corps planning studies and engineering designs will develop and assess alternatives, including structural solutions, non-structural solutions, or a combination of the two, for the entire range of possible future rates of sea-level change. The "low" rate of sea level rise uses the historic trend, the "intermediate" and "high" rates of local mean sea-level change using the modified NRC, see Figure A. 1. The Corps' "high" rate exceeds the upper bounds of IPCC estimates from both 2001 and 2007 to accommodate for the potential rapid loss of ice from Antarctica and Greenland. Evaluation of project alternatives considers the sensitivity to future sea level, how the sensitivity will affect project risk, and options to minimise adverse consequences from uncertain sea level rise conditions while maximising beneficial effects.

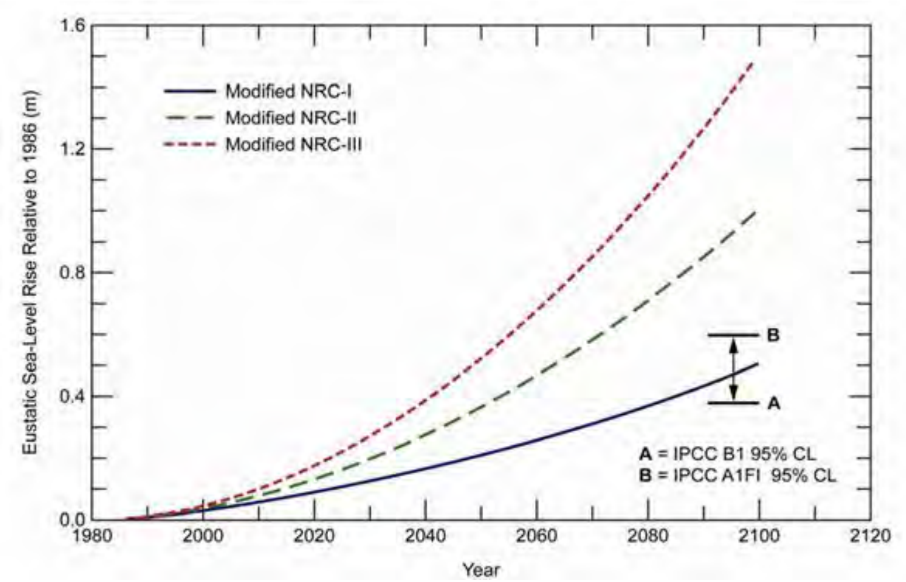


Figure A. 1 Modified NRC (1987) eustatic sea-level rise scenarios and the IPCC (2007) scenario estimates for use when predicting future sea-level change

The recommendations by the USACE in Figure A. 1 fits well with the recommended sea level rise values issued by Central Commission, 2012, see Figure A. 2.

NOAA water level station	State	Projected sea level rise (inches)			
		By 2030		By 2050	
		Best estimate	90% range	Best estimate	90% range
National average		5	2-9	12	6-22
Atlantic average		6	2-10	13	6-23
Gulf average		6	3-9	13	8-23
Pacific average		4	0-8	9	2-20

Figure A. 2 Projected sea level rise with 90% confidence intervals. From Surging Seas 2012

A.6 Danish Recommendations

The climate changes will cause a general rise of the mean sea level as well as a corresponding rise in the extreme water levels, which may be slightly higher than the general sea level rise due to increasing storminess. The following institutions in Denmark are analysing climate changes, publishing forecasts for climate changes and issuing guidelines for climate adaptation:

- The Danish Climate Centre at the Danish Meteorological Institute (DMI) under the Ministry for Climate, Energy and Buildings
- The Danish Coastal Authority (DCA) under the Ministry of Environment
- CRES. Centre for Regional Changes in the Earth system
- The Nature Agency under the Ministry of Environment

- The National Geological Surveys for Denmark and Greenland (GEUS)

Following the issue of the IPCC AR5 reports in 2013/2014 the following two reports have been issued in Denmark:

- Nature Agency 2014: Analysis of IPCC Working Group 2 report: Effects, climate adaptation and vulnerability – with special focus on Denmark.
- DMI 2014: Future climate changes in Denmark, Danish Climate Centre at DMI, Report no. 6, 2014, Oct. 2014.

The Nature Agency 2014 report presents the expected relative sea level changes for Denmark in 2100 as presented in Figure A. 3.

The highest uncertainties in the forecasted sea level rise are associated with the possible collapse (quick disintegration) along the edge of the ice sheets in the Antarctic area.

Figure A. 4 shows the probability of sea level rise at Copenhagen; the major uncertainty originates from the uncertainty related to the melting process in Antarctica. It is seen that the most probable sea level rise in Copenhagen in 2100 is around 0.7 m, but neither an SLR of 2.0 m nor an SLR of less than 0.7 m can be excluded.

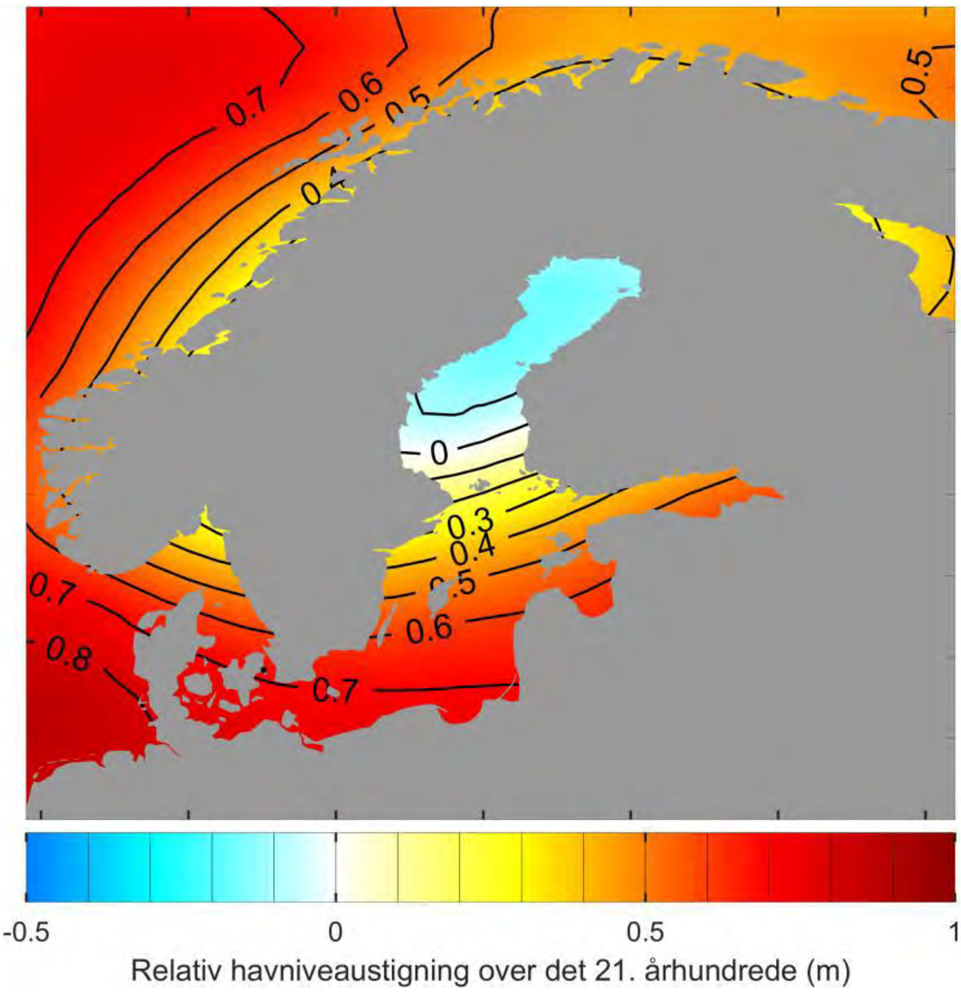


Figure A. 3 Relative sea level rise in Denmark in year 2100, including impacts of isostatic rebound movements

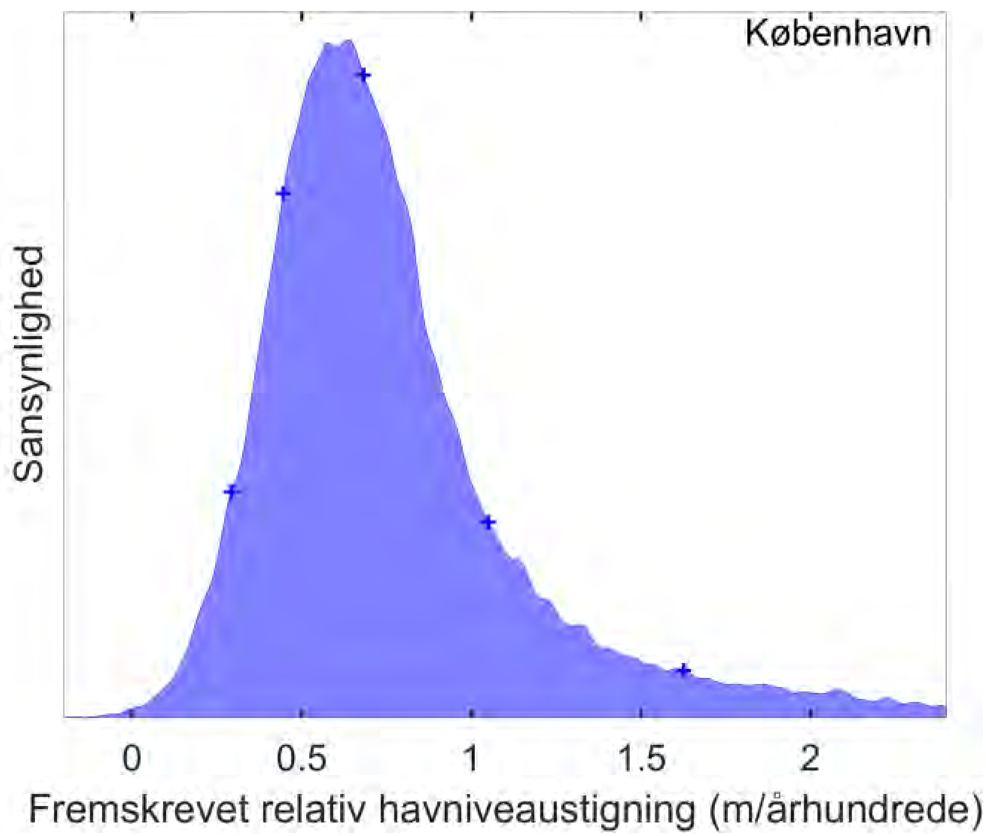


Figure A. 4 Distribution of possibility of Sea Level Rise in Copenhagen in year 2100 vs. Sea Level Rise in metres

APPENDIX B

Examples of climate change adaptation to sea level rise

B Sea level rise

B.1 Shoreline retreat

Sea level rise will introduce shoreline retreat. A sandy beach with a slope of the active coastal profile of s (typically s = 1/50 to 1/100) exposed to a sea level rise of h_{slr} will experience a shoreline retreat $R = h_{slr}/s$ (Bruun's rule, Bruun 1962). Thus, a coastal profile with a slope s = 1/100 exposed to a sea level rise h_{slr} = 1.0 m will experience a shoreline retreat of R = 1/(1/100) = 100 m.

Shoreline retreat, also referred to as coastal erosion, caused by sea level rise is a gradual process, and consequently it can be mitigated gradually as the sea level rises.

B.2 Changes in flood conditions

A sea level rise will increase the risk of coastal flooding of low-lying coastal areas through the rise of extreme storm surge levels. The sea level rise in itself will normally not cause flooding, but the raised sea level will increase the extreme water levels caused by storm surges, or in other words, the sea level rise will decrease the recurrence interval of storm surges over a certain level, see Figure B. 1. The examples show the impact of the forecasted SLR of 0.7 m for Copenhagen and of the SLR of 0.8 m for Esbjerg in year 2100.

It is seen that the SLR of 0.7 m in Copenhagen will shorten the recurrence period for the present 100-year storm surge level of 1.5 m from 100 years to 4 months. This is a very drastic relative impact of the SLR. The reason for this is the relatively low slope of the exceedance curve of 0.3 m per decade. This means that the SLR of 0.7 m corresponds to more than 2 decades.

The conditions in Esbjerg are different because the slope of the exceedance curve at this location is much higher, in the order of 0.6 m per decade. The forecasted SLR of 0.8 m in Esbjerg will shorten the recurrence period for the present 100-year storm surge level of 405 cm from 100 years to 7 years. This is a less drastic relative impact of the SLR compared to the situation in Copenhagen. This means that the relative impact of about the same SLR will be very different in these two parts of Denmark despite the fact that the two locations are only 270 km from each other.

Thus, it can be seen that the impact of the forecasted sea level rise has a major importance for the design of flooding levels. The exceedance of design conditions may lead to the breaching of sea defence structures (dikes), which is a catastrophic event as the protected low hinterland will be flooded. Consequently, proper adaptation measures must be implemented timely. Furthermore, the rise in sea level will increase the risk of coastal flooding in low-lying areas, which are not protected at present. Wetlands, dune systems and beaches will be drowned, and while new wetlands or dunes may eventually develop further inland, this will only be possible if the inland locations are not already covered with shore protection, roads, or other "permanent" infrastructures. The impacts of sea level rise will of course be most significant in low-lying areas, such as deltas, along barrier islands and at atoll islands. There are special challenges in planning for sea level rise in coastal towns as it is not straightforward to implement sea defence structures along a city frontage.

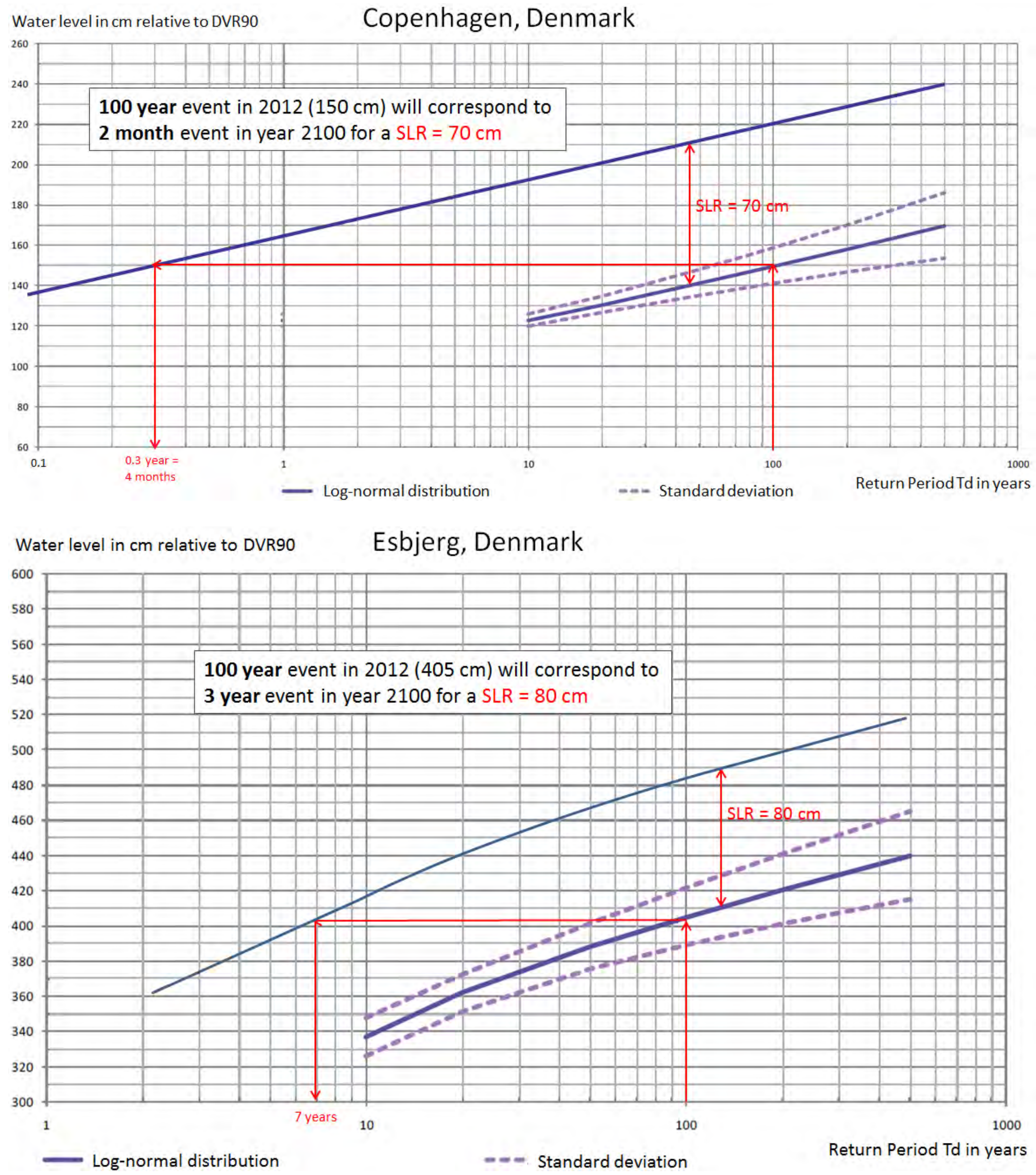


Figure B. 1 Example of extreme water level analysis, flooding levels vs. recurrence interval in years for the Inner Danish Waters represented by Copenhagen (upper) and for the Danish Wadden Sea represented by Esbjerg (lower). The influence of the forecasted sea level rises in year 2100 is shown

B.3 Design philosophy and risk assessment for adaptation to sea level rise

Many low-lying areas, which by nature are flooded regularly, have been protected by sea defence structures and are developed for agriculture, infrastructure and habitation. With the expected sea level rise caused by the climate changes there will be a need for strengthening of these defence structures. A design philosophy for determination of the relevant recurrence period to be applied relative to the life-time of the project and the associated acceptable probability for exceedance of the design event during the life-time is described in the following.

The following design parameters are used for design of sea defences:

- The acceptable probability of failure, P_f, that the sea defence/coastal project fails within the considered life-time *L*
- Life-time, L, of the sea defence/coastal project. The life-time is the number of years chosen as basis for design of a certain project.
- The design recurrence period, T_d, used for determining the design flood level.

The following sections discuss these design parameters and provide examples of possible values for both acceptable risk and life-time. Specific projects should determine these parameters, based upon national or regional directives, requirements from appropriate funding entities such as insurance companies, community standards and professional judgment. Since the assumptions for acceptable probability of failure and project life are integral to the project design, they need to be fully understood and agreed by project stakeholders; otherwise, serious conflicts of interest may occur if/when project design conditions are exceeded.

B.4 Acceptable probability of failure P_f

The acceptable probability for an area being flooded, or in general terms for a design event being exceeded, depends on the size of the protected area and the type/value of the protected facility. Acceptable probability of failure can vary due to differences in demographic conditions, availability of replacement facilities, economic conditions, community values and coastal culture; hence, what may be acceptable for one community may be unacceptable for another. Thus, failure consequences and acceptable probability of failure within the life-time of the project need to be carefully considered as one of the initial project steps.

B.5 Life-time *L* of sea defence/coastal project

The life-time of a sea defence structure or a coastal project is a concept used in the design of projects exposed to natural forces, which can be described by statistical models. Defining the life-time has taken on a new dimension with climate change because there is now a trend in the storm surge exceedance. This stresses the importance of deciding on the life time of a project at an early stage of the design process. It is necessary to define the life-time as part of the statistical design process and to define the acceptable probability of failure during the life-time. The design life-time of a project depends on the type of the project, the size of the protected area and the type of the protected facility.

B.6 Design recurrence period T_d

The recurrence period T_d to be used for the design of sea defence structures and other coastal structures, e.g. for determination of the relevant design storm surge level, is a function of the life-time L of the project and the acceptable probability of failure P_f during the life-time according to the equation for a parameter following a binominal distribution:

$$P_f = 1 - \left(\frac{1-1}{T_d}\right)^L$$

The correlation between P_f and T_d as a function of *L* is presented in Figure B. 1.

Table B. 1 The calculated acceptable probability of failure, P_f [in %] of a sea defence structure with a life-time, L [years], and design recurrence period, T_d, [years]. From Mangor 2004

Life-time, L (years)	Recurrence Period, Td (years)									
	5	10	20	30	50	100	500	1000	10,000	100,000
1	20	10	5	3	2	1	0.2	0.1	0.01	0.001
5	67	41	23	16	10	5	1	0.5	0.05	0.005
10	89	65	40	29	18	10	2	1	0.10	0.01
20	99	88	65	49	33	18	3	2	0.2	0.02
30	100	96	79	64	45	26	6	3	0.3	0.03
50	100	99	92	82	64	39	10	5	0.5	0.05
100	100	100	99	97	87	63	18	10	1	0.1
200	100	100	100	100	98	87	33	18	2	0.2
500	100	100	100	100	100	99	63	39	5	0.5

The procedure on how to utilise the correlation between life-time, recurrence period and acceptable risk for the combined effects of storm surges and sea level rise is discussed in the following with sample values provided to aid the discussion.

Step 1: Exceedance statistics for storm surges based on historical recordings

Many coastal authorities have typically recorded water levels for selected stations over decades. This data can be analysed for exceedance of certain water levels, which results in an exceedance curve for storm surge water levels, presenting the water levels exceeded as a function of the recurrence period. Such curves reflect an extrapolation of historical data and thus do not include climate change effects, at least only to a very limited extent.

An example of such a curve from Copenhagen in Denmark is presented in Figure B. 2. Such exceedance curves will typically be available at selected locations in most countries around the world.

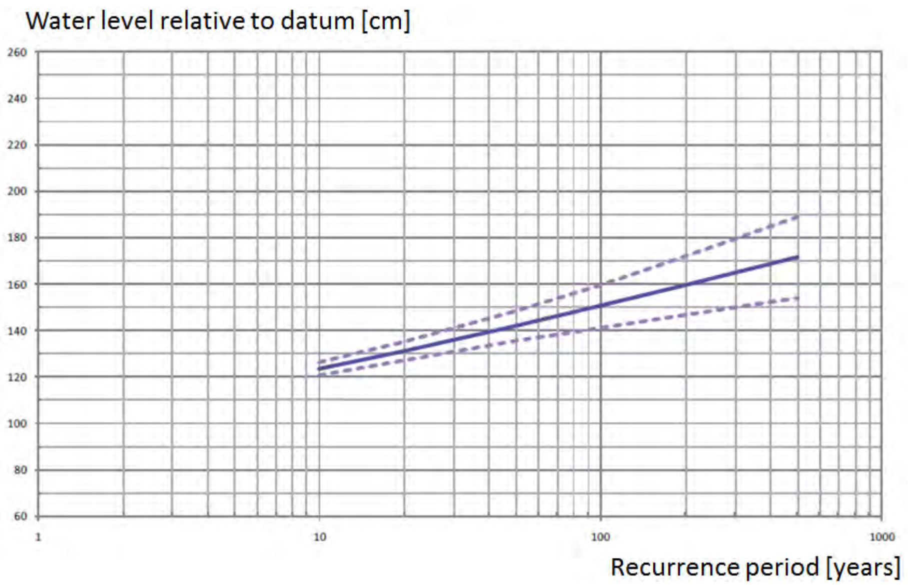


Figure B. 2 Storm surge water level in Copenhagen relative to MSL in 2012 as a function of the recurrence period, based on data from 124 years, from: http://borgere.kyst.dk/hoejvandsstatistikker.html

Step 2: Determination of project life-time L

The life-time of a project needs to be determined, using the recommendations in Table B. 2 as an example; however, specific countries, regions, communities and funding entities may have their own preferred methodologies. The life-time is used as a basis for determination of recurrence period, when the acceptable risk has been defined.

Table B. 2 An example of possible life-times L in years as function of, size of protected area/facility and type of the protected facility.

Size of area/facility	**Type of area/facility protected**		
	Farm land and recreational facilities	**Habitation and infrastructure**	**Public utility**
Small	20	50	100 - 200
Large	20 - 50	100	≥200

Step 3: Selection of scenario for sea level rise

The future rise in the sea level shall be taken into account when designing a project for a storm surge level. In principle there are two contributions:

1. The design water levels predicted on the basis of extrapolation of historical records of water levels, such as shown in Figure B. 2
2. The additional increase in the storm surge due to the climate changes (and increased storminess)

There are many approaches for determining an appropriate sea level rise scenario. The problem is that nobody can predict exactly how the future sea levels will develop, and consequently various authorities have developed different approaches. A common approach is that the relevant authorities describe different sea level rise scenarios and that the recommended sea level rise is selected as a function of the following criteria:

1. The life-time L of the project
2. The severity of impact of failure due to exceedance of the design water level

Re. 1: The life-time of the project is selected as described above. If the life-time is 50 years, the project shall be designed for the sea level rise, which is predicted 50 years from the time when the project can be completed. The design water level should be determined on the basis of exceedance curves (Figure B. 2 is an example of such data). The rise in sea level, plus a relevant contribution due to increased storminess, should be added to the design water level in order to develop the design conditions for the project.

Re. 2: The scenario for sea level rise shall be selected according to the severity of the impact of failure. See Table B. 3 for one set of sea level rise recommendations. For a specific project, the national, regional or funding entity recommendations should be consulted.

Table B. 3 Example of scenario for sea level rise as a function of the type of infrastructure impacted by the design event.

Type of infrastructure	Scenario	Typical sea level rise [m] in year			
		2030	2050	2100	Later than 2100
Farm land and recreational facilities	Low	0.1 – 0.2	0.2 -0.4	0.5 -1.0	Up to 1.2
Habitation and infrastructure	Medium	0.15 – 0.3	0.3 – 0.6	1.0 – 1.2	Up to 1.5
Major habitation, infrastructure and public utilities	High	0.2 – 0.4	0.4 – 0.8	1.1 – 1.5	Up to 2.0

Step 4: Determination of acceptable probability of failure P_f

The acceptable probability of failure for the size and type of project is determined on the basis of the national, regional, local or agency guidance. See example in Table B. 4.

Table B. 4 An example of the acceptable probability of failure P_f [%], i.e. risk of flooding, during life-time of a project as the function of size of the protected area and the type of protected facility

Size of protected area/facility	Type of facility protected	Acceptable risk of failure R [%] during project life-time
Small	Farm land and recreational facilities	50 - 80
	Habitation and infrastructure	10 - 20
	Public Utility	5 - 10
Large	Farm land and recreational facilities	25 - 40
	Habitation and infrastructure	5 - 10
	Public Utility	0.1 - 5

Step 5: Determine the recurrence period T_d

The recurrence period T_d is determined on the basis of the life-time L and the probability of failure P_f, based on national, regional, local or agency guidance for appropriate risk and life-time. See the values in Table B. 1.

Step 6: Determine the design water level

The design water level without the impact of climate changes is determined on the basis of a storm surge exceedance curve like the one presented in Figure B. 2 using the relevant recurrence period.

Step 7: Determine the future design water level including the impact of sea level rise

The future design water level including the impact of sea level rise is determined as the sum of the design water level obtained in Step 6 with the sea level rise decided in Step 3.

Two examples of how to decide the future design water level including the impact of sea level rise are presented in Table B. 5.

Table B. 5 Examples of how to determine the design water level including the impact of sea level rise for two projects in the Copenhagen area.

Steps	Type of project	
	Small recreational area	Large infrastructure
1. Exceedance curve	Exceedance curve	
2. Life-time *L*	20 years	100 years
3. SLR scenario and SLR value	Low, 0.15 m	Medium, 1.1 m
4. Acceptable risk *R* in %	65%	10%
5. Recurrence period T_d	20 years	1000 years
6. Design water level excl. SLR	1.3 m	1.8 m
7. Design water level incl. SLR	1.45 m	2.9 m

It is seen that there is a considerable difference in the final design water levels for the two different types of projects.

It is recommended to perform sensitivity analysis when designing actual projects where the influence of the following parameters is tested:

- Choice of life-time L
- Definition of type of project
- Choice of SLR scenario and selected SLR value
- Choice of acceptable probability of failure P_f

The following contributions have to be added to the future design water level in order to arrive at the habitable level for e.g. reclamation:

- The wave run-up can either be accommodated by introduction of a seawall, or the run-up contribution can be added to the level of the reclamation.
- A safety margin to take into account the uncertainty especially in the prediction of the sea level rise.

APPENDIX C

Examples of climate change adaptation: Coastal erosion and sediment transport

C Coastal erosion and sediment transport

C.1 Assessment of impact of climate change on coastal erosion and sediment transport

C.1.1 Introduction

Longshore sediment transport (littoral drift) is often found to be a very important factor in coastal morphology, and in many cases variation in the littoral drift along a coast will determine the accretion or erosion of a coastline. The longshore transport is driven by obliquely incident waves. When waves approach the coast at an angle, the breaking waves in the surf zone will exert a longshore driving force, which drives a current along the coast. On a sandy coast the combination of the current and the agitation by the waves will cause a transport of the sand along the coast. If the transport increases in the transport direction the shoreline will erode, and if it decreases the shoreline will accrete.

A changing climate can give changing wave conditions, which in turn change the sediment transport and therefore also the conditions for the shoreline evolution. The possible impact is illustrated by a model study carried out for locations at the Danish North Sea coast (Fuhrman *et al.* 2010).

C.1.2 Wave conditions

Nearshore wave data has been extracted from DHI's simulations of wave conditions, currents and water levels in The North Sea, The Inner Danish Waters and the Baltic Sea for the periods 1960-1990 and 2070-2100 under IPCC's scenario A1B. The simulations were made by the MIKE 21 SW model on the basis of DMI's regional model simulations with the HIRHAM model made under the ENSEMBLES project sponsored by the EU. The flow and water levels in the area were also modelled, using the model MIKE 21 HD.

Figure C. 1 The four locations at the Danish North Sea coast

Wave data was extracted at four locations as indicated in Figure C. 1. The sediment transport calculations were made for the two positions at Kryle and Hvide Sande. Wave data has also been extracted at Fjaltring and Nymindegab because wave buoy data is available here, which makes it possible to calibrate the calculations. The data extracted included results from the hydrodynamic model MIKE 21 DH, which provides water level variations due to forcing by tide and meteorology. In addition, a time variation in the sea level was introduced to represent a sea level rise of approximately 1 m over the next century. The water level variations are illustrated in Figure C. 2.

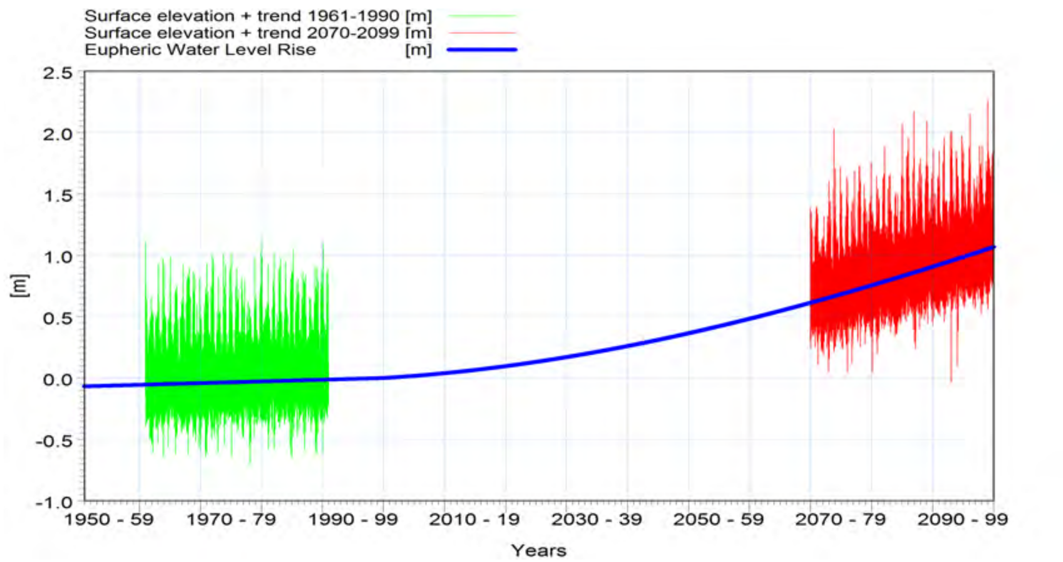


Figure C. 2 The water level variation in the two periods considered in the model. The blue curve shows the development in the mean sea level

Three wave data sets are thus available: historic wave measurements from the period 1992-2007, simulated wave data with a climatic forcing corresponding to the period 1960-1990 – in the following called hindcast data, and simulated wave data with a climatic forcing corresponding to the period 2070-2100 – in the following called forecast data. Before making the assessment there are some points to be aware of:

- The simulated wave data will be biased. Climate effects cannot be assessed by comparing predictions based on the forecast data and the measured historic data, because the bias of the simulated wave data may be larger than the climatic change found in the data.
- The hindcast wave data will be adjusted and calibrated to conform with the historic wave measurements and to reproduce the calculated littoral drift. Identical adjustments will then be made for the forecast data, which is obtained with the same model as the hindcast data and therefore presumably has a similar bias. In this way some errors are cancelled and the two simulated time series are expected to be consistent with the measured data and to reflect the effect of a changing climatic forcing in the regional meteorological model data used to drive the wave model.
- The hindcast and forecast time series for the two locations at Kryle and at Hvide Sande are giving adjustments derived from artificial 'measured' time series obtained by weighted averages of the recordings from the two measurement stations.
- Water levels need a special consideration in the analysis. The longshore transport depends on the water level, a change in water level will for example change the relative intensity of wave breaking occurring at a long shore bar and at the shoreline,

and therefore also the flow and transport. However, a change in the sea level over a century occurs so slowly that the characteristics of the coastal profile will adapt. This means that for example the mean water depth over the longshore bar is expected to be the same statistically, because of the natural adaptation to a slow sea water rise. Therefore short-term variations like tide and storm surge will be included, whereas the slow mean sea level rise is not taken into account with the littoral drift simulations.

Figure C. 3 shows near-shore wave roses for Fjaltring and Nymindegab. All wave roses show a dominant north-westerly component. The modelled results show a more smooth directional distribution.

(a) Fjaltring (b) Nymindegab

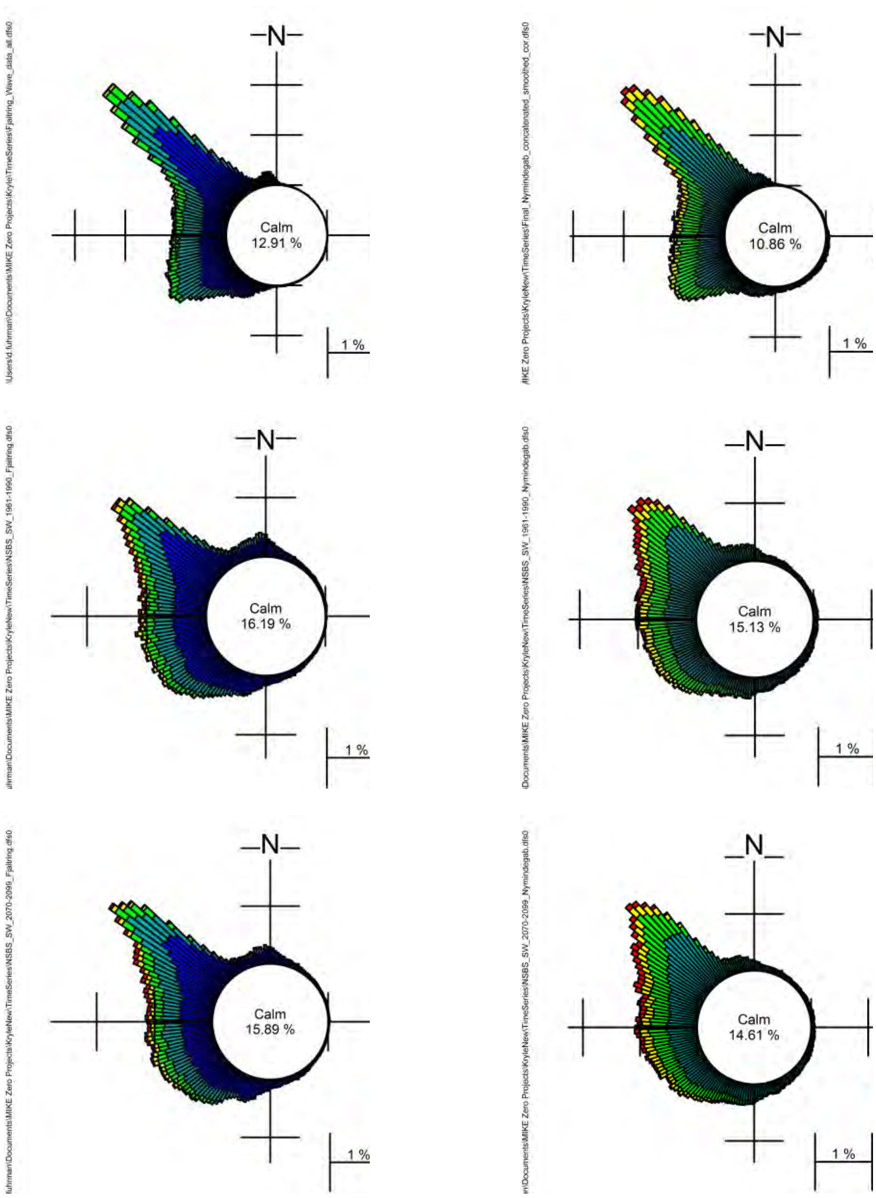


Figure C. 3 Wave roses: Top row: wave buoy measurements (1992—2007), Middle row: hindcast (1960—1990) and Bottom row: forecast (2070—2099). To the left: data for Fjaltring, to the right: data for Nymindegab

When comparing the measured wave data to the hindcast it is found that the mean energy flux in the modelled data is slightly larger (11% for Nymindegab and 20% for Fjaltring). There is also a difference in wave direction; the mean direction in the energy flux of the hindcast waves is turned slightly anti-clockwise relative to the measurements (4.4 degrees for Nymindegab and 3.5 degrees for Fjaltring).

The differences between the simulated wave roses for the periods 1960-1990 and 2070-2099 are not very pronounced. The mean wave energy flux is increased by approximately 10%, and the direction of the energy flux is changed by 1.7 degrees in the anti-clockwise direction.

C.1.3 Littoral drift

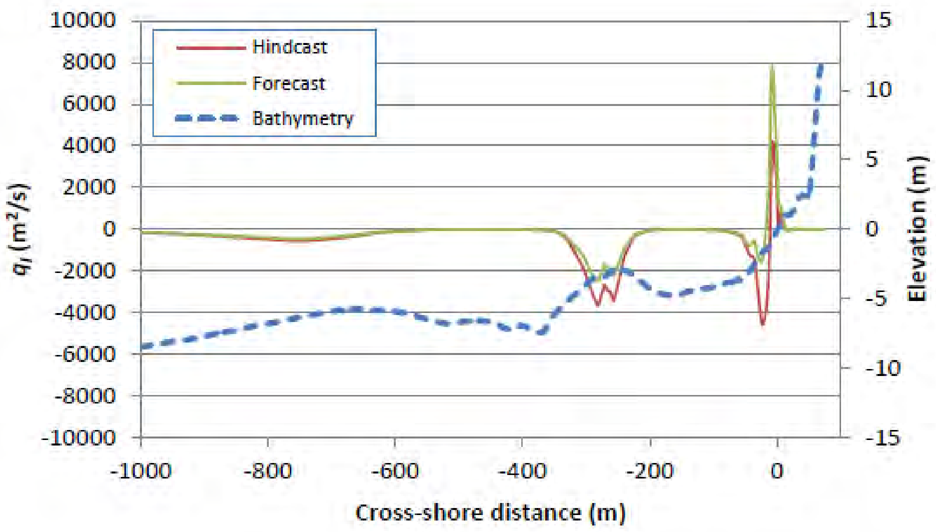
In order to compensate for the bias between measurements and hindcast the littoral drift calculations for Kryle and Hvide Sande were made with wave data extracted from the models at these locations, but adjusted in wave height so that the wave energy flux is reduced by 15% and in direction by 4 degrees.

The calculations were made by the LITPACK model for coastal profiles that were selected from the regular surveys performed by the Danish Coastal Authority. For both locations the grain size was set to be 0.2 mm. With these conditions the annual longshore transport rates were found to be for Kryle: 562,000 m^3/year (695,000 m^3/year) and for Hvide Sande: 1,582,000 m^3/year (1,107,000 m^3/year), where the numbers in parentheses are from calculations made from measured wave data interpolated between the measurements from Fjaltring and Nymindegab. All transport is in the southward direction. It is seen that the difference in transport calculations based on simulated and measured wave conditions is 20-40%, which in terms of sediment transport is not very large. However, the difference is not appearing in the same side and the deficit in sediment, found as the difference between what is coming in at Fjaltring and what is going out at Hvide Sande, is found to be 1,020,000 m^3/year (412,000 m^3/year). This is a measure of the erosion of the coastline and it is significantly larger for the simulated wave data than for the calculations based on the measurements.

With a distance of 17 km between the two locations and assuming an effective height of the eroding profile of 20 m an erosion rate of 1 m per year would correspond to a deficit of about 350,000 m^3/year.

It should be noted that the transport at Kryle is found to be much more sensitive to variations in the angle between the coastline and the mean wave direction than the transport at Hvide Sande. This is expected mainly to be because the littoral drift at Kryle is the result of contributions of transport going north as well as going south, with the latter being dominant, while the transport at Hvide Sande is practically only going south. Thus, the gross transport, which is affected by the change in direction is larger in the simulation for Kryle than for Hvide Sande. A steeper coastal profile at Kryle may also play a role.

The change in wave conditions from the hindcast to the forecast period has two different effects on the littoral drift. The slightly stronger waves (10% larger mean energy flux) will tend to increase the littoral transport while the anti-clockwise turn of the waves (by 1.8 degree) gives smaller driving forces in the southward direction and therefore tends to reduce the southward littoral transport.



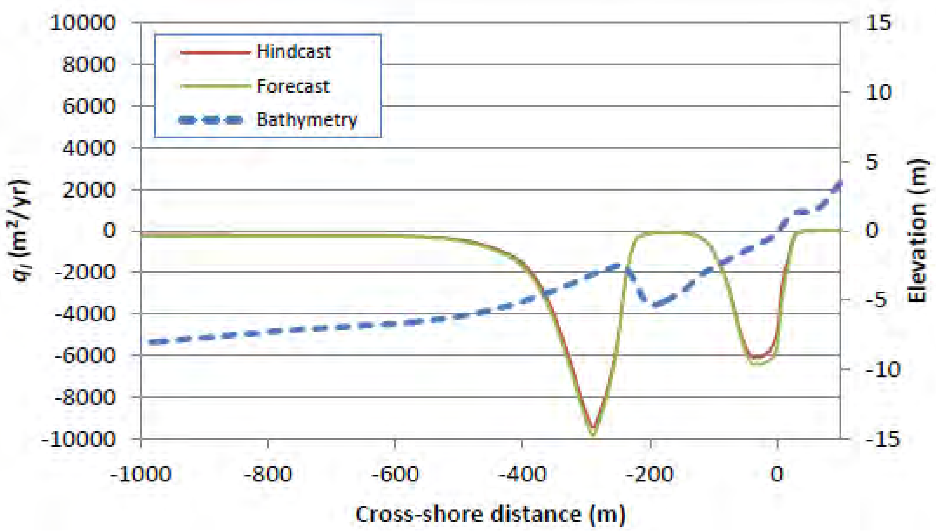


Figure C. 4 The distribution of the mean annual longshore transport across the coastal profiles. Top: Kryle, bottom: Hvide Sande

At Hvide Sande the combined effect is an increase in the calculated littoral drift from 1,582,000 m^3/year to 1,719,000 m^3/year. At Kryle the larger sensitivity to changes in the direction of the wave climate dominates and the calculated transport decreases from 562,000 m^3/year to 341,000 m^3/year. Figure C. 4 shows the distribution of the transport across the two coastal profiles used in the simulations. It is seen how the transport at Kryle is affected much more by the change in wave climate.

The result is that the sediment deficit increases by 360,000 m^3/year, which corresponds to an increase in the coastal erosion by approximately 1 m/year.

Figure C. 5 shows sediment transport roses for the Hvide Sande location. A transport rose illustrates the relative contribution of each wave condition (characterised by wave height and direction) to the littoral transport. The slight increase in wave energy and the anti-clockwise rotation of the wave climate from the hindcast to the forecast can be seen.

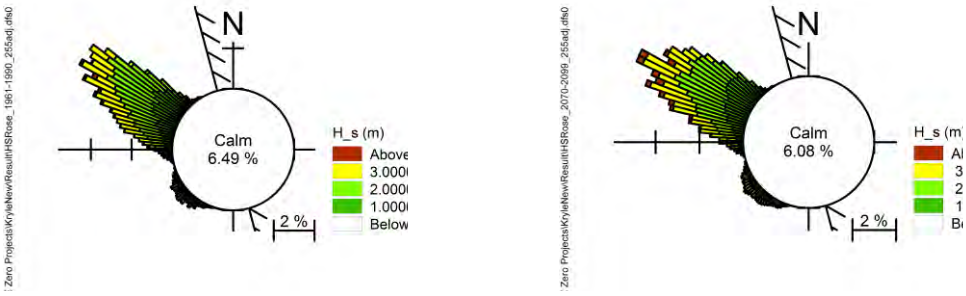


Figure C. 5 Sediment transport roses for Hvide Sande. Left: hindcast period (1960-1990). Right: forecast period, 2070-2100

At a given location the coastal profile will have a significant variability both in time and along the coast. The sensitivity of the present analysis was analysed by making simulations for a number of different profiles surveyed by the Danish Coastal Authority at both locations. While there was a considerable variability in the calculated transport rates, in particular at Kryle, the conclusion that the transport would decrease at Kryle and increase at Hvide Sande was robust.

C.1.4 Conclusions

- It is seen that simulations of the wave conditions can be used to assess the possible change in coastal erosion and sediment transport.
- Some of the challenges in compensating bias in the simulated results are illustrated.
- The sensitivity to variations in the coastal profile is investigated.
- It should be noted that the present analysis is only related to simulations of a single IPCC scenario (A1B) for the development in emissions and a single simulation by a regional climate model.
- It should be noted that the present calculated sediment transport rates and trends for coastal erosion have not been calibrated against measurements or observations. The study should therefore be taken as an illustration of possible effects of climate change rather than a specific coastal erosion study.

C.1.5 Acknowledgement

This work has partly been supported by the Danish Council for Strategic Research under the project COADAPT, Danish Coasts and Climate Adaptation – flooding risk and coastal protection, Project No. 09-066869.

APPENDIX D

Examples of climate change adaptation: Retreat solutions

D Retreat solutions (setback lines)

D.1 General discussions of setback lines

A setback line is a line on the seaside of which no construction or anthropogenic development activities must take place. The philosophy behind the concept of a setback line is to avoid conflicts between anthropogenic developments in the Coastal Zone and the active morphology of the coastal area within a certain agreed time horizon.

The general goals for introducing a setback line are the following:

1. To avoid conflicts between existing and new coastal developments and a receding shoreline. This is especially relevant for areas which will be exposed to erosion in the future for any reason, including the impact of sea level rise. It shall be mentioned that in many cases the setback line will only provide a partial security against damages caused by chronic coastal erosion, provided this erosion is allowed to take place. Furthermore, it is normally not feasible in the case of chronic erosion to introduce setback lines, which provide “full” security against coastal erosion especially in already developed areas where the space is limited

2. To allow for a certain natural variability of the shoreline due to seasonal longshore and cross-shore variations and extreme events

3. Allowance for a vacant backshore area as a buffer and to preserve a fringe of untouched coastal landscape, where natural backshore processes can take place, such as dune formation and where natural coastal flora and fauna can develop without restrictions

4. Allowance for changes caused by coastal development in adjacent area, such as the construction of ports or similar, which may be developed in future.

There is an inherent conflict involved in introducing a setback line in an area which in the future will be exposed to long term coastal erosion, as the eroding shoreline will eventually reach the setback line if this is defined as a static line. Consequently, two types of setback lines are defined:

- Dynamic setback line in an area with chronic erosion
- Static setback line in areas with only acute erosion

Of course, erosion problems can be mitigated by the construction of coast protection schemes. However, one of the intentions of introducing a setback line is to avoid reaching a situation where the construction of coast protection is required. This philosophy is related to the general development goal for the coastal area, i.e. that as much as possible of the coast shall be preserved as natural dynamic landscapes. Of course, the philosophy of how to protect the coastal area varies from country to country.

Sector regulations, such as setback lines, are often neither introduced nor adhered to in Countries in Transition (CIT), refer to PIANC 2014. This can be one of the main causes for the conflicts between shoreline development and building activities near the coast. It is therefore advisable for CIT to introduce setback regulations and to enforce adherence; however, this will only contribute to avoiding problems in the future.

Areas presently exposed to erosion have to be treated by introducing erosion mitigation measures.

D.1.1 Static setback lines for acute erosion

Static setback lines should only be used for areas with acute (reversible) erosion, whereas they are not applicable for areas with chronic erosion as explained above. There may be different setback lines for different activities. For example the setback line for housing can be 50 m away from the coastline, while the setback line for parking lots or food stalls may be less because such facilities have a temporary character and can easily be removed if required. The width of the setback zone can be calculated on the basis of the amount of acute erosion to be expected resulting from shoreline variations caused by longshore and cross-shore processes due to seasonal variation, owing to extreme events and due to the impact of climate changes. For temporary installations it can be based on events likely to occur once a year to once every 10 years, for houses for events likely to occur once in a hundred years and for public buildings and public utilities once in a thousand years. Using the method described in CUR (1989), it is possible to calculate the value of the acute erosion and thus determine the static setback line.

Allowance should also be provided for a fringe of natural coastal landscape.

Of course it is necessary to define the "coastline". But how this is done is not crucial, provided that the coastline is clearly and unambiguously defined so that everyone knows where it is. This should also be made clear in cases where the coastline is moving (see below).

D.1.2 Dynamic setback line for chronic erosion

In theory coasts with chronic erosion require a dynamic setback line, which is moved inland at intervals at the same average rate as the coastal retreat. The alternative is a “static” setback line with either a long time-period of effectiveness and a very long setback distance or a small setback distance with a short period of effectiveness.

In areas with chronic erosion it can be considered to associate a lifetime with the various types of setback lines and land uses. Consequently, it may not be advisable to define a setback line only in metres, because the speed of erosion has to be taken into account. For this reason, it could be considered to define the setback line as a function of the rate of coastal regression. For example: "It is forbidden to build houses in a zone likely to be threatened by the sea within the next 50 years". So in fact the width of the setback zone will be 50 times the annual erosion and there should be no problems with houses being threatened by erosion within the next 50 years.

The decision on the 50-year erosion rate to be used as basis for the computation of the setback line distance from the existing coastline can be based, for example, upon the lifetime of a house. The idea is that after 50 years the house will have to be rebuilt anyway. So if all houses are built at a distance of 50 erosion-years away from the coastline, it will never be necessary to remove a house because of coastal erosion. A condition to build “near” the setback line at any time shall be supplemented with the conditions that the house owner must accept that his house is to be abandoned when the erosion reaches the house and that he is not allowed to build a new house. However, this approach is probably not realistic and nor is it realistic that the house owner loses the entire value of his property after 50 years.

It is evident that the concept of a dynamic setback line is very difficult to maintain over the years and it might result in a lot of conflicts as described above. In practice the society will in many cases not allow the chronic erosion to take place, and in many cases the coastal authority will try to maintain the position of the coastline by protection of the coast by means of some of the applicable protection measures described in the preceding subsections. This means that eroding coastlines in developed areas, in areas with a certain population density and in areas with economic interests generated by beach tourism, will normally be stabilised, whereby the coastline becomes more or less static. A dynamic setback line thereby also becomes static. The present trend in many countries is to stabilise eroding coastlines by nourishment programmes, which secure a stable coastline at the same time as the nature of the coast is maintained as nearly natural, whereby the natural landscapes and processes are maintained with minimal interference.

Furthermore, it is not possible in practice to use varying setback distance dependent on the specific erosion rate in specific areas, and it will require major administrative efforts to shift the setback lines as future erosion progresses.

D.1.3 Recommended setback line policy

In practice it is not feasible to administrate dynamic setback lines. Consequently, in many countries there is a practice to protect the coastal landscape and the coastal facilities in a pragmatic and practical way, which uses static setback lines of various categories, such as:

- Use no setback line in ports and other industrial areas, where immediate proximity to the sea is a must
- Use the existing building line in cities and dwelling areas where the coastal area is already occupied with housing and infrastructure relatively close to the coastline. Allow protection of property and infrastructure following an application procedure. In this case emphasis is on protection of property rather than protection of the coastal landscape because the coastal landscape is already lost
- Use a sensible setback distance, e.g. 100 m, in areas laid out for recreational activities, such as summer houses and hotels. Use the existing building line in cases where it is too late to implement the 100 m setback line. Here the emphasis is mixed, partly to avoid conflicts with receding coastlines and partly to preserve the environmental and scenic values of the coastal landscape. Coastal protection is only permitted if fixed facilities are threatened by coastal erosion within a time horizon of several years, but coastal stabilisation via nourishment programmes are often used in these areas which secure a stable coastline at the same time as the nature of the coast is maintained as nearly natural
- Use a large setback distance, e.g. 300 m in open coastal areas, which are not occupied by any kind of fixed facilities, such as buildings and infrastructure. The purpose of this is to safeguard scenic, biological and recreational interests in the coastal hinterland. This strategy involves no effort to protect the land from erosion, which means that coastal areas subject to erosion are left for natural development and it is accepted that such areas are eventually eroded away as part of the natural development at the location. The philosophy is that nature shall not be protected against the forces of nature. Coastal protection will not be permitted in this category of area
- Introduce an e.g. 3 km wide coastal planning zone covering rural and recreational areas. Planning permission within this zone for new developments shall only be given if there is a specific planning or functional reason for location near the coast.

In principle, the setback lines are fixed but authorities may revise the setback lines if significant shoreline changes have occurred.

To maintain the setback lines requires an authority to control illegal building in the setback zone, to control illegal removal of sand from beaches or foreshore, to control removal of essential vegetation and disposal of waste and wastewater.

APPENDIX E

Modelling of coastal flooding

E Modelling of coastal flooding

Prediction of the conditions under a flooding event after breaching of protective dikes is complex and may require advanced modelling tools. It is important to know the distribution of the maximum water levels in the flooded area, but in order to plan and execute evacuations it can also be highly relevant to describe the path and the temporal development of a flood. In most cases a satisfactory description of a flooding event will require more than just knowledge of the location of the breach in a dike, the maximum storm surge level in the sea and the domain behind the dike which is below this level. Among the factors to be taken into account are:

- The time variation of the storm surge which determines the water level outside the dike
- The time and location for a breach of the dike and the time development of the breach
- The size and shape of the flood prone area, its topography and any barriers that can block or retard the development of the flooding
- The impact of freshwater from rivers or runoff which discharge into the area during the flooding.

Some of these effects and the implications of modelling them are outlined in the following, considering a specific location in the southern part of Jutland, Denmark, around the city of Ribe, Figure E. 1. The area is protected from storm floods in the Wadden Sea to the west by a dike. The water course Ribe Å runs through the area and crosses the dike through a lock. The flood condition where the dike is breached during a storm flood has been illustrated by numerical modelling, using the model MIKE 21. Some of the important aspects in setting up the model are described in the following.

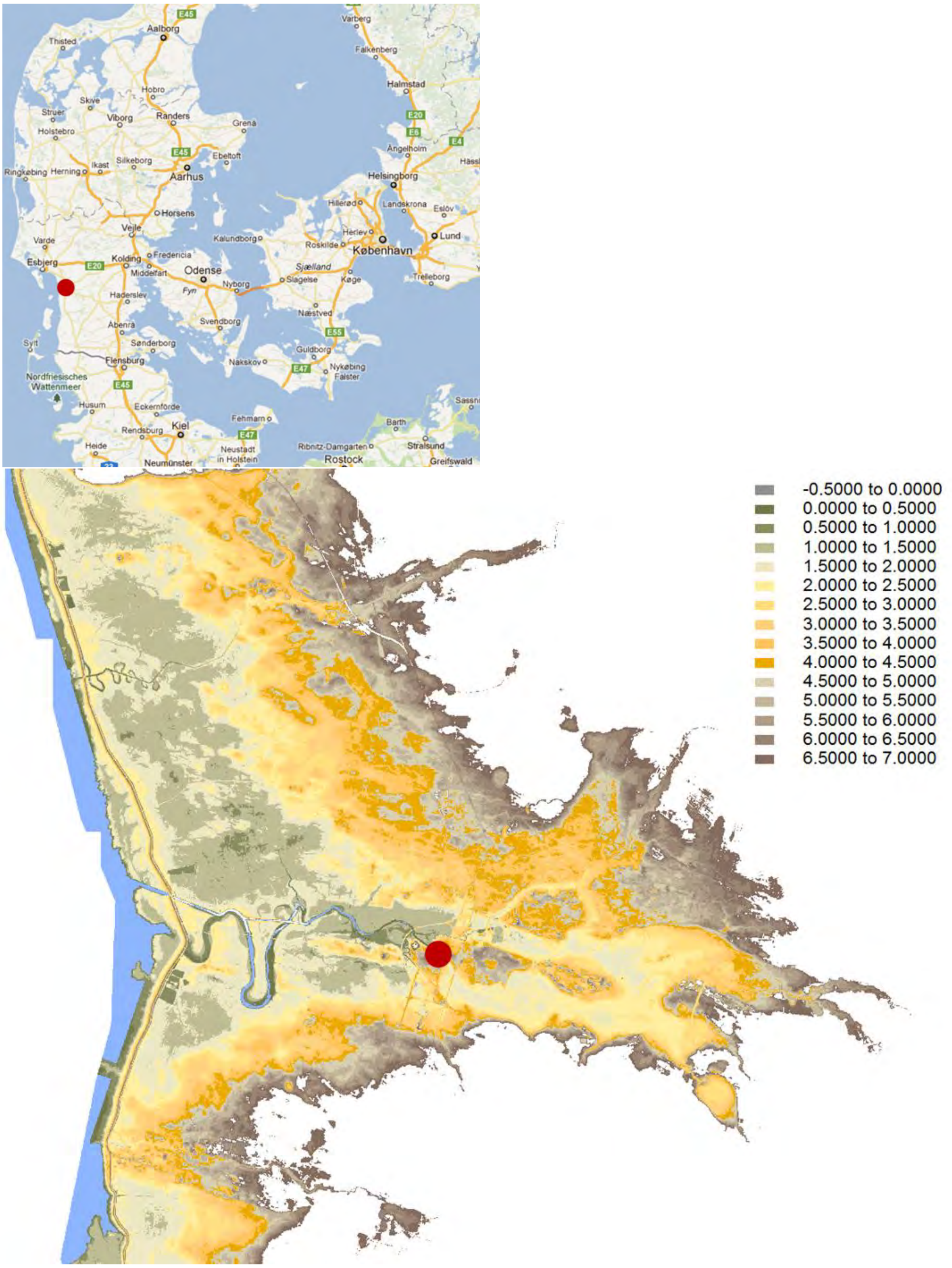


Figure E. 1 Top: the location of Ribe. Bottom: the topography of the area

E.1 The bathymetry

A good representation of the area topography is the crucial point in making a successful flood simulation. The basis can be a digital terrain model with a resolution of a few metres; for the present case at Ribe the resolution is 1.6 m. A significant data reduction is required in order to establish a manageable computational mesh. In this process it is important to maintain the topological properties, such as water courses and barriers for the propagation of floods as well as connections between low-lying areas through a barrier. A reduction of a number of tens of millions of data points by a factor of 200 can be made by eliminating neighbouring points within a certain distance provided that their levels differ by less than, say, 10 cm.

Figure E. 2 shows the model bathymetry. The levels are given as depth relative to the level zero, so that negative values characterise high-lying areas.

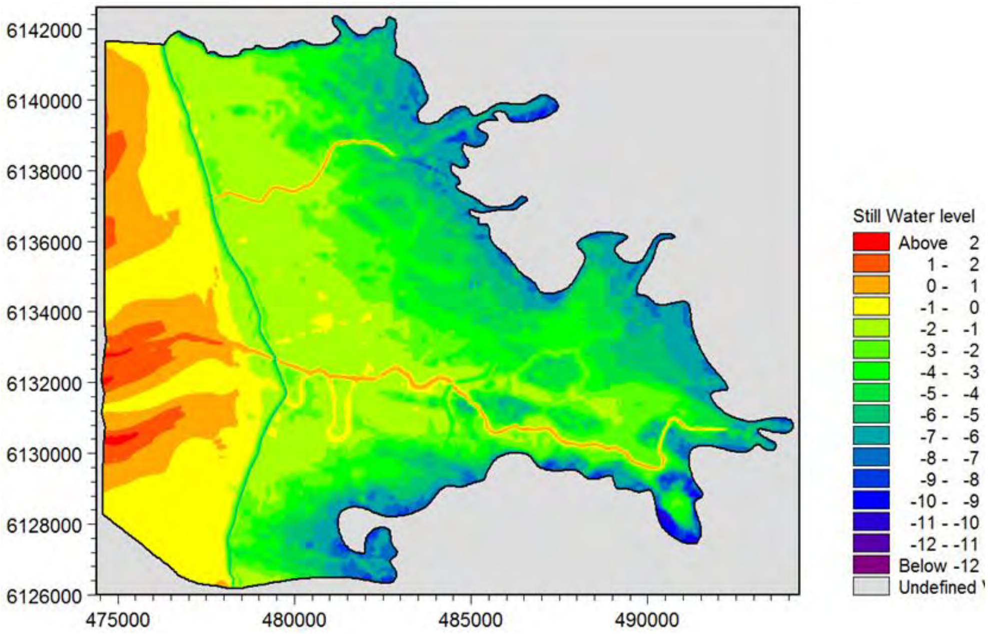


Figure E. 2 The bathymetry

Figure E. 3 shows the representation of Ribe Å flowing through the city and its crossing with a road, which is raised and acts as a flood barrier. It is important to represent the water course correctly in the model domain, as it is an important pathway for the propagation of the flood.

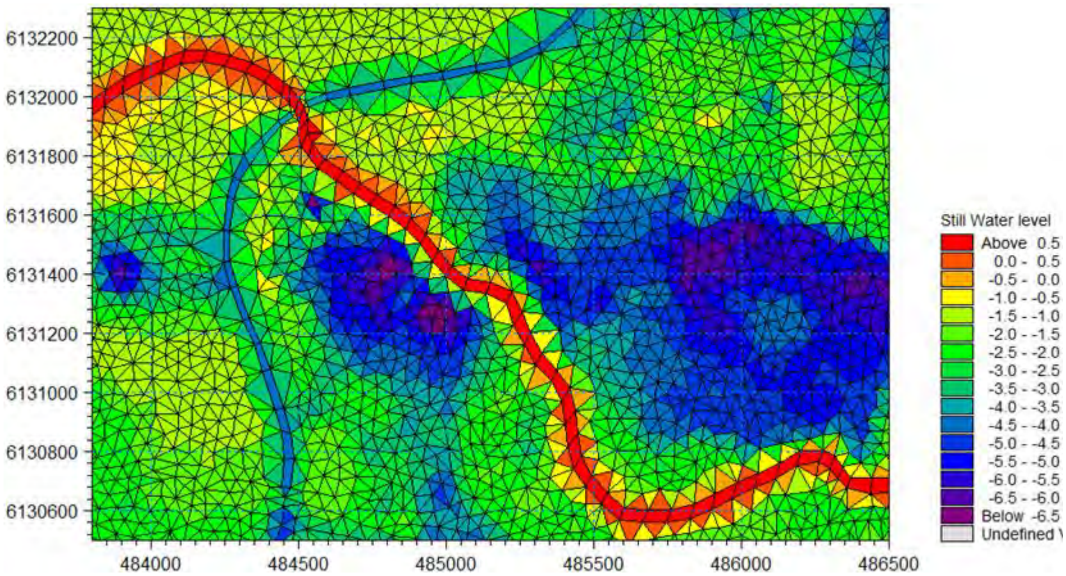


Figure E. 3 The representation of Ribe Å (red cells) flowing through the city and crossing the raised road (blue cells) in the upper left corner.

The crossing between the dike and Ribe Å is shown in Figure E. 4. The crossing is in the form of a navigational chamber lock. It is represented in the model bathymetry as a culvert that can be closed by a gate. The points defining the dike next to the creek are modified to have increased levels in order to ensure a well-defined bathymetry where flow only occurs through the cells defining the creek proper. The sluice is defined as a check valve allowing only flow towards the sea.

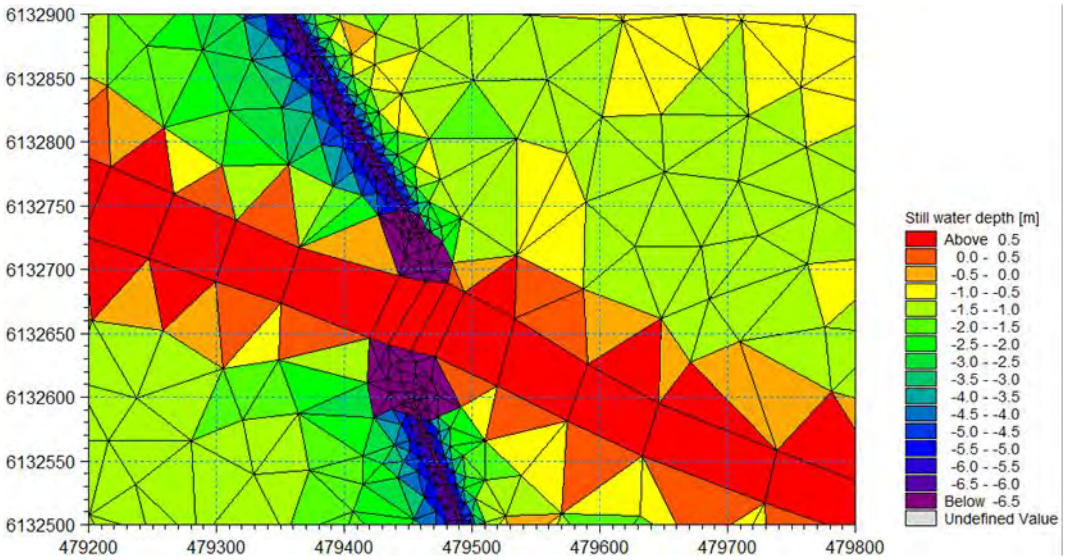


Figure E. 4 The crossing between the creek (red cells) and the dike (blue/purple cells). Note the modified elevation of the cells of the dike adjacent to the creek

E.2 Definition of the breach

The shape and the temporal development of the breach are defined as a time line series along the dike crest. It is further defined how far to the crest line the breach can normally be felt. Within this distance the bathymetry follows the level of the breach, and if the local level is lower than the breach level no changes are introduced. The area of influence of the breach will therefore increase with time.

A satisfactory resolution of the breach can be obtained by a fine mesh of structured triangles or rectangles, see Figure E. 5. The areas in- and offshore of the dike shall be defined by a relatively fine mesh to avoid instabilities due to humps or holes caused by large elements with centroids just outside the area of influence from the breach.

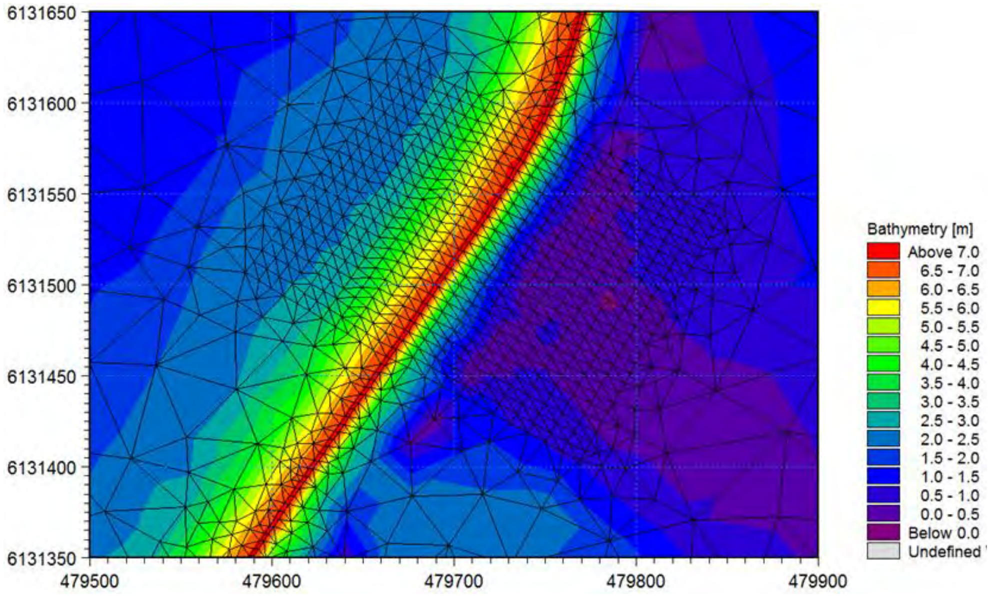


Figure E. 5 An optimal mesh for representation of an evolving dike breach

E.3 Model results

The water level in the Wadden Sea outside the dike during the storm flood has to be defined as a boundary condition. In many cases this will be associated with a relatively small uncertainty and may be obtained from historical data or simulations with a regional model driven by tide and meteorological forcing.

The location and time of a breach and its development also have to be given. This may be more uncertain, and often a sensitivity exercise is made. Potential locations of a breach may be assessed on the basis of the bathymetry of the foreland or from data on requirements for maintenance work at different sections of a dike.

An example of a breach development used in the simulations related to a 10,000 year event is shown in Figure E. 6 with profiles for every 15 minutes. It is seen that after a gradual evolution the breach suddenly grows drastically in width after having reached the base at a level of 1 m. The breach bathymetry is illustrated in Figure E. 7.

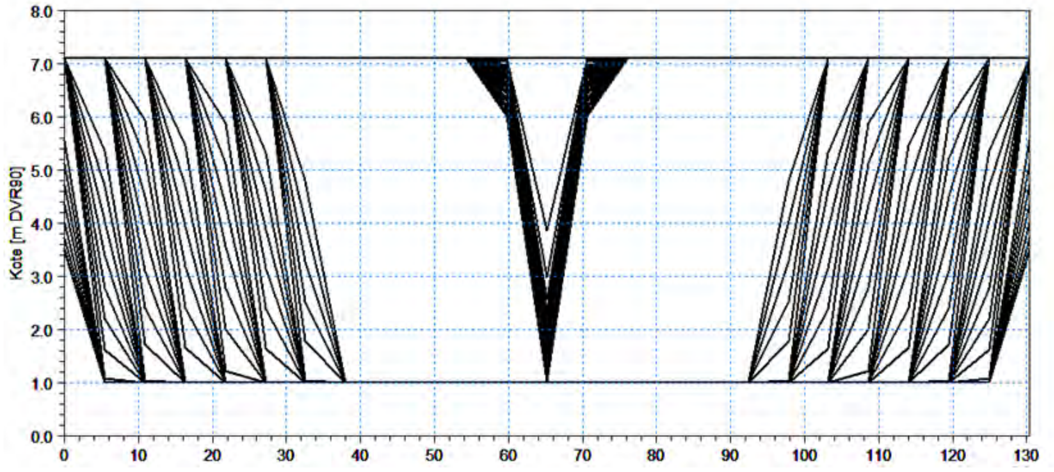


Figure E. 6 The temporal evolution of the breach

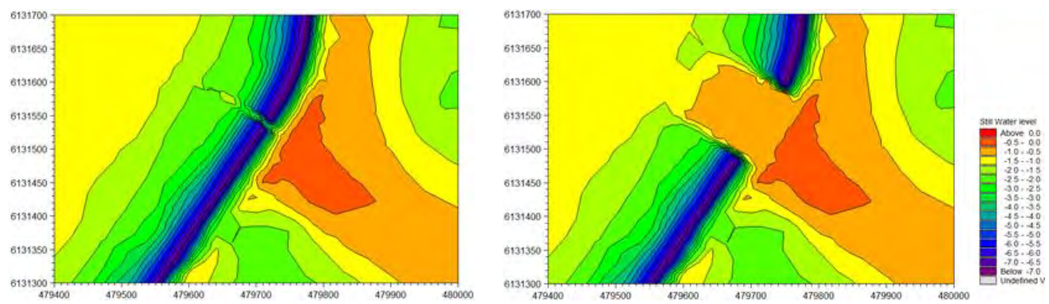


Figure E. 7 The evolving breach at two stages: initial and almost fully developed

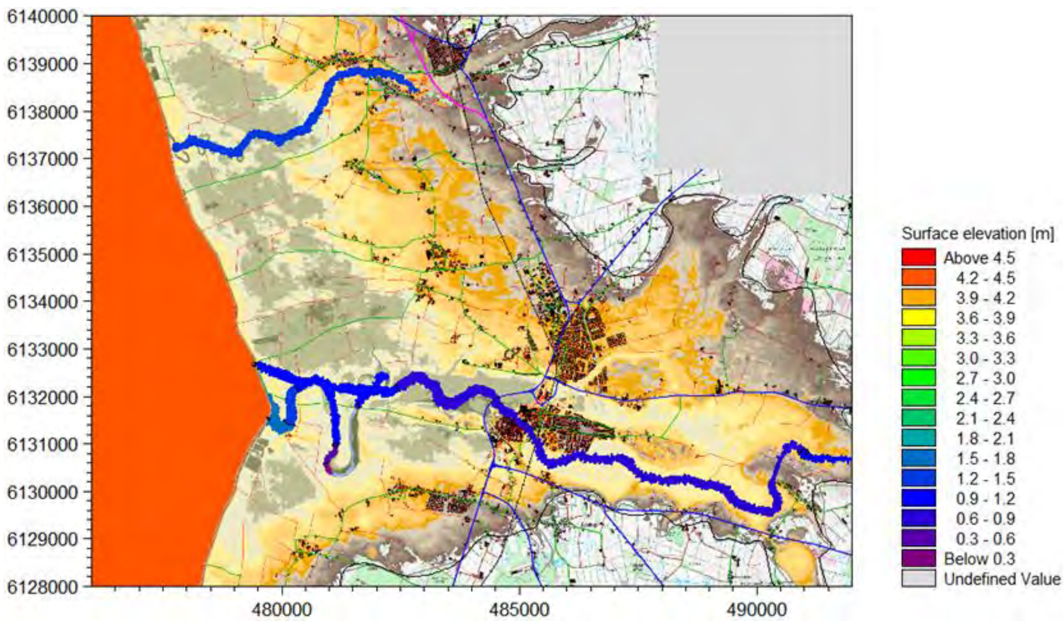


Figure E. 8 The conditions shortly after the breach

Figure E. 8 depicts the conditions shortly after the breach has occurred, corresponding to the left panel in Figure E. 7. Water is flowing into the protected areas through the narrow breach, and floods the lower part of Ribe Å and the abandoned meandering course of the creek. In Figure E. 8, corresponding to the right panel in Figure E. 7 12 hours later, the breach is almost fully developed to a width of 120 m. The water level outside the dike has fallen, but water is still flowing into the low-lying areas and is now affecting the low area between the elevated road and the city. In Figure E. 10, 18 hours after Figure E. 9, the flooded area has increased in particular towards north, the outer water level has decreased further and water is now flowing out through the breach and the sluice at the mouth of Ribe Å.

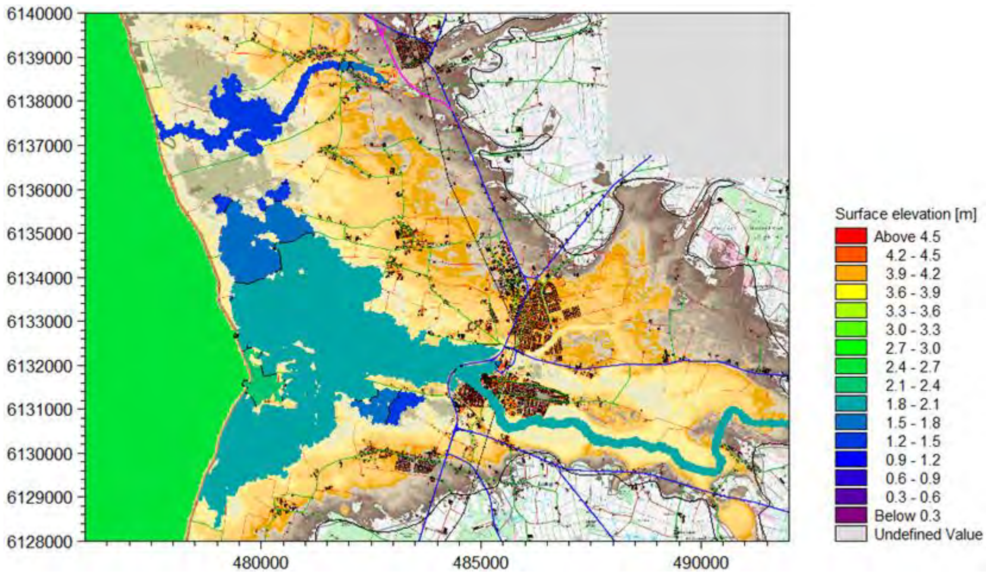


Figure E. 9 The conditions 12 hours later than in Figure E. 8, an almost fully developed breach

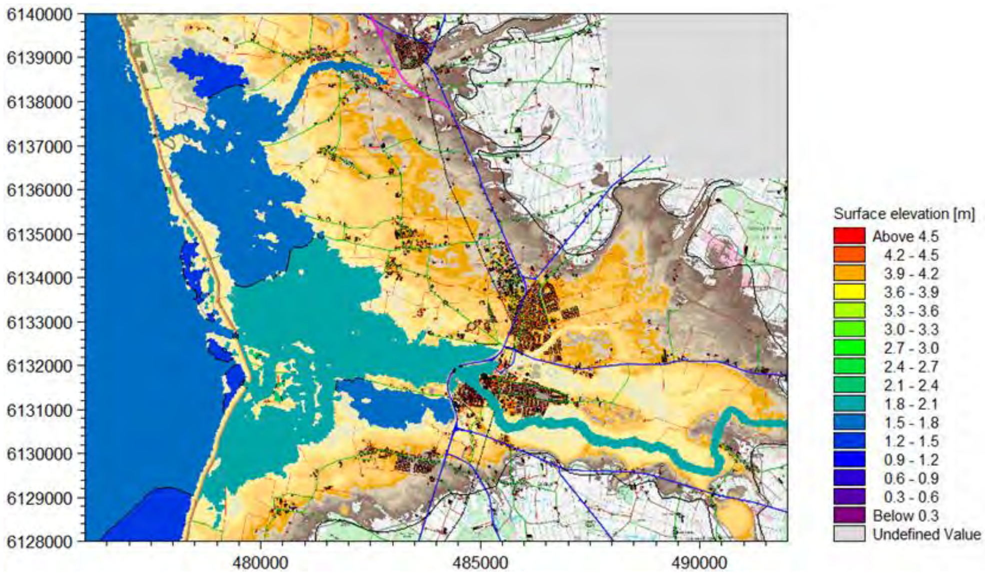


Figure E. 10 The conditions 18 hours after Figure E. 8. The outside water level has dropped and water is flowing out to the sea

The maximum water levels during the 10,000-year storm event are shown in Figure E. 11. It is seen that most of the flooded area has water levels around 1.8 m, which shall be seen in relation to the outer water level of more than more than 4.2 m at the initiation of the breach and more than 2.4 m when the breach is fully developed.

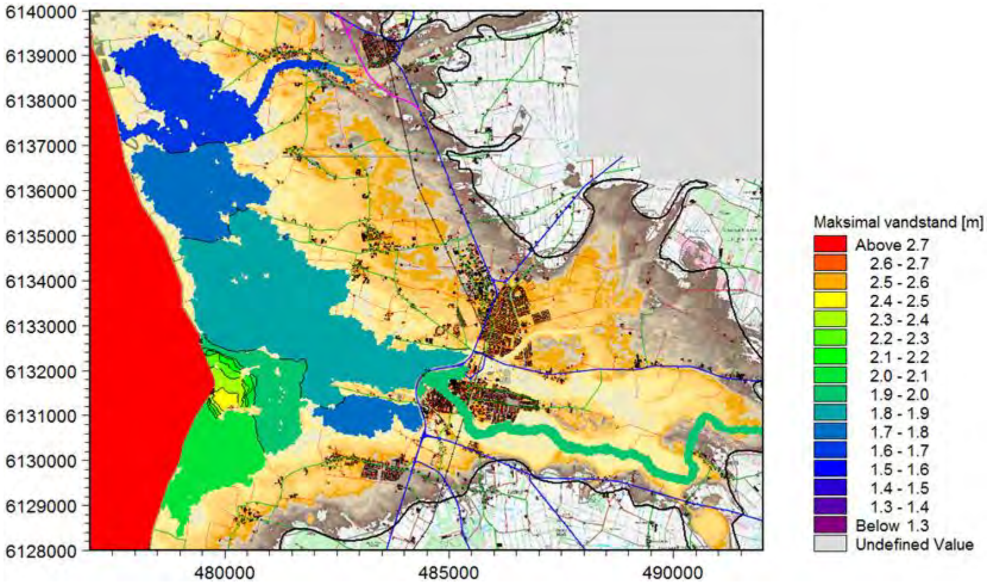


Figure E. 11 The maximum water levels during the flooding event

E.4 Crude estimate of the timescale of a flooding event

It is not possible a priory to determine whether it is necessary to make a detailed simulation of a given flooding scenario, or the flood levels in an area can be assessed simply on the basis of a digital terrain model and the maximum sea level. It will depend on a large number of factors, such as:

- the maximum sea level and the duration of the storm surge
- the size and time development of the breach
- the size of the area potentially flooded and its topography

Under some very simplified assumptions the relevant parameters can be identified:

1. The area risking flooding has the size A, it is completely flat without any hindrance or resistance to the spreading of the flood.
2. The storm surge is constant at the level H above the surface of the area A.
3. The breach has an effective width of B, and is scoured down to a level corresponding to the surface in the area A.

For this simple situation the time variation of the water level *H* in the area *A* can be found by simple calculations. The relative height of the water level h' = h/H can be found as a function of the time parameter: $t' = t\,B\sqrt{gH}\,/\,A$, where *t* is time and *g* is the acceleration of gravity (g = 9.81 m/s^2). The relation between h' and t' is shown in Figure E. 12. It is noted that the flood level in the area A reaches the maximum level *H* at the time t_0 corresponding to the dimensionless time $t_0' = 2.16$.

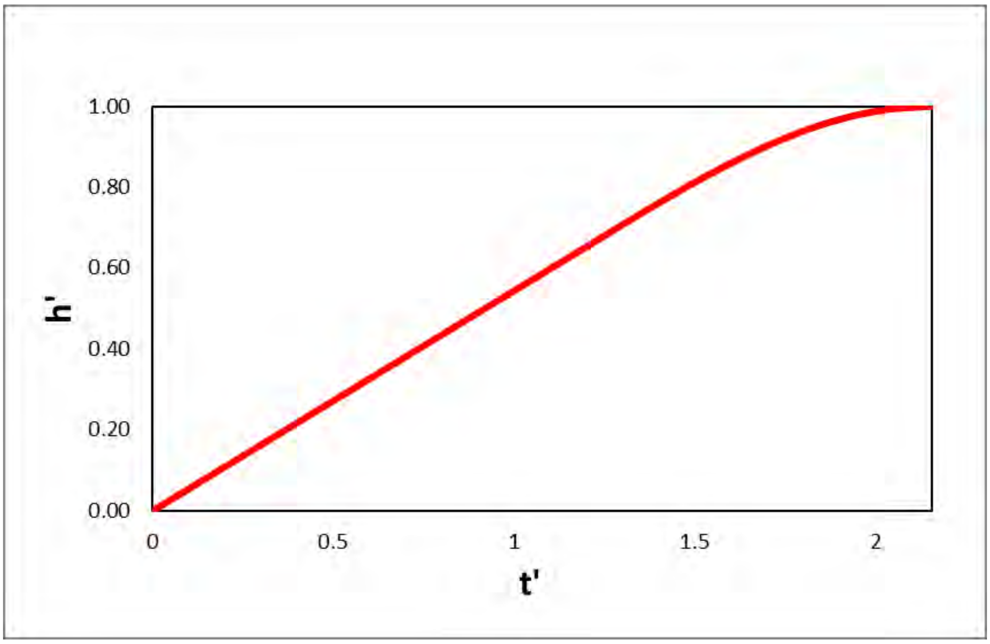


Figure E. 12 The time variation of the filling of the area A

This analysis is of course too simplified for practical application. But it may give an indication of when a proper flood simulation is required. However, it should be kept in mind that any obstruction to the flow inside the area A has been neglected, and the parameters found can therefore only be used to give a lower limit of the duration of a surge event, which would require a flood simulation for a realistic prediction of the flooding levels in an area.

An example is considered with parameters of the same order of magnitude as in the example considered above. The area considered to be in risk of flooding is A = 20 km^2 = 20,000,000 m^2, the effective width of the breach is estimated to be 100 m, and the surge level outside the breach is taken to be 3 m. The time t_0 necessary for the area to be completely filled to the level of 2 m is then found from t_0' = 2.16 as:

$$t_0 = 2.16\ A/(B\sqrt{gH}) = 2.16 \times 3.7 \times 10^4\ s = 8.0 \times 10^5\ s$$

which means that the water level outside the breach should be at the level of 3 m for more than 22 hours for the area A to be filled. For an outer water level of 2 m above the bed level in the flooded area the minimum time required for filling would be 31 hours. In reality the actual topography in the flood prone area will probably result in considerable longer time required for filling the area. If the actual surge is expected to be of a shorter duration or significant obstructions to the flood propagation are anticipated, a flood simulation will therefore give a prediction of more realistic and lower flood levels in the area.

E.5 Acknowledgement

The setting up of the MIKE 21 for the Ribe area and the simulations were carried out in collaboration with Peter A. Klagenberg of the Danish Coastal Authority, DCA, in a project made for DCA.

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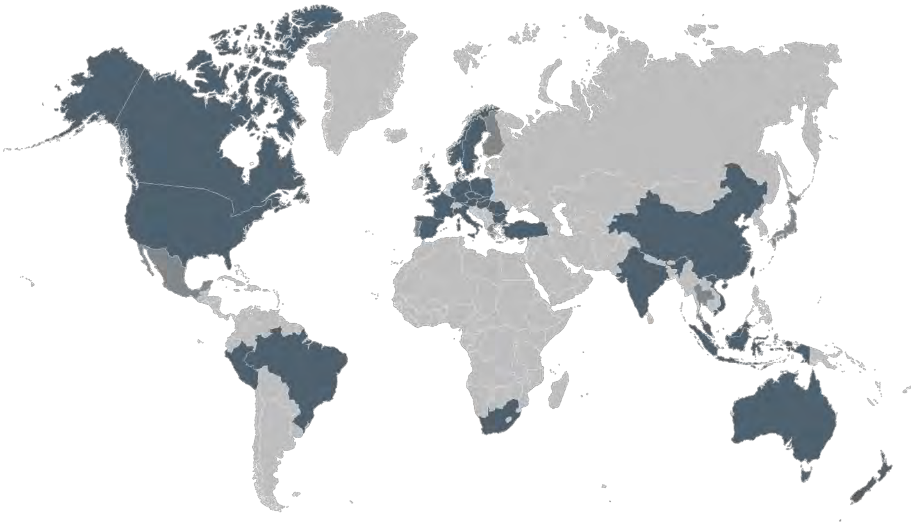

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