



PIANC

The World Association for Waterborne
Transport Infrastructure

Managing Climate Change Uncertainties in Selecting, Designing and Evaluating Options for Resilient Navigation Infrastructure



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PERMANENT TASK GROUP FOR CLIMATE CHANGE

Managing Climate Change Uncertainties in Selecting, Designing and Evaluating Options for Resilient Navigation Infrastructure

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CONTENTS

ABSTRACT	5
ACKNOWLEDGEMENTS	5
GLOSSARY	5
1 INTRODUCTION	8
2 USE SCENARIOS TO UNDERSTAND THE RANGE OF POSSIBLE CLIMATE FUTURES.....	8
2.1 Characteristics of Climate Change.....	8
2.2 Selection of Climate Change Scenarios.....	12
2.3 Unlikely-but-Plausible Scenarios.....	13
2.4 Use of Representative Conditions.....	14
3 PREPARE FOR THE UNPRECEDENTED.....	15
4 ADOPT ADAPTIVE AND FLEXIBLE SOLUTIONS.....	18
5 CONSIDER STRUCTURAL AND NON-STRUCTURAL ADAPTATION AND RESILIENCE OPTIONS.....	19
6 USE MONITORING DATA TO INFORM DECISION MAKING	22
7 SELECT EVALUATION METHODS THAT RECOGNISE AND ACCOMMODATE UNCERTAINTY.....	22
8 KEY MESSAGES	24
8.1 Understanding Climate Data Uncertainties	24
8.2 Selecting and Applying Climate Change Scenarios.....	24
8.3 Seeking Adaptive Solutions	24
8.4 Accommodating Climate Change Complexities in Evaluating Options.....	25
8.5 Delivering Resilient Solutions	25
9 REFERENCES	25

ABSTRACT

Climate change is now widespread, rapid, and intensifying [IPCC, 2021]. Impacts will vary regionally, but for some ports and waterways, climate-induced changes will be of fundamental, even existential, importance. However, there remain many uncertainties, particularly about how quickly changes in temperature, precipitation, sea level, wind, waves and associated physical processes will take place; their magnitude; and whether and when critical thresholds will be crossed.

These uncertainties have implications for all those involved in navigation infrastructure design, evaluation and investment, including the maintenance and modification of existing assets. Climate change both emphasises existing uncertainties and introduces new ones.

In order to manage the risks associated with climate change uncertainties and particularly to avoid the unintended consequence referred to as ‘maladaptation’, this PIANC Technical Note explains how designers, financiers and project owners can reduce climate change-related risks by:

- referring to a range of climate change **scenarios** to understand the variation between the different projected climate futures relevant to the project location
- reducing reliance on the use of **past data** to predict low probability future events
- considering **unlikely-but-plausible** scenarios when making major, long-term investments
- preparing for the **unprecedented**, including **joint occurrences** and **cascading failures**
- adopting adaptive and **flexible solutions**; considering **non-structural** (e.g. operational, institutional) as well as **structural** interventions; exploring **no-regret** options
- using **monitoring** to inform decision making (adaptive management)
- selecting **evaluation methods** that recognise and accommodate uncertainty.

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GLOSSARY

Adaptation pathways comprise alternative routes towards a defined objective, or broad directions of change for different strategic outcomes. They may be centred around performance-thresholds or transformation objectives. *Adaptation pathways* set out sequences of actions (measures, modifications, investments, etc.) that can be implemented progressively, depending on how the future unfolds and the development of knowledge. They are therefore particularly well-suited to climate change adaptation needs as their realisation is based on monitoring outcomes and reflexive learning.

Adaptive capacity describes the ability (capacity) to adjust to future change; to avoid potential damage; to take advantage of opportunities; to manage additional risks; or to respond to consequences. Systems or assets with high *adaptive capacity* are able to be re-configured without significant changes (declines or losses) in crucial functions.

Adaptive ready describes infrastructure that is capable of being modified in future in response to changing conditions; uncertainties are typically accommodated by the introduction of greater flexibility and *adaptive capacity*.

Cascading failures occur in complex, interlinked natural and socio-economic systems and sub-systems when multiple climate hazards occur simultaneously or climate and non-climatic risks interact, causing chain reactions that potentially extend across sectors or beyond the location of the initial vulnerability or both [IPCC, 2022]. For example, disruption due to prolonged severe weather affecting port operations can quickly escalate into supply chain problems, potentially impacting on the poorest in society. Inadequately accounting for *cascading failures* can lead to gaps in adaptation planning.

Critical thresholds, for the purposes of this Technical Note, are defined as thresholds beyond which an asset or operation suffers severe damage or disruption, in some cases becoming no longer viable. Some such changes may be irreversible. Critical thresholds should be derived using an analytical process taking into account systemic considerations where cascading effects are a possibility.

Deep uncertainty exists when parties to a decision do not know, or cannot agree on the system model that relates action to consequences; the probability distributions to place over the inputs to these models; which consequences to consider; and/or their relative importance. In a climate change context, this can include insufficient scientific knowledge or understanding. Deep uncertainty often involves decisions that are made over time in dynamic interaction with the system.

<https://www.deepuncertainty.org/>

Ensemble approaches to climate projections typically involve using a group of different but recognised climate models to provide a range of simulations, rather than relying on the output of a single model. Because different models describe climate processes in different ways, referring to a combination of outcomes to derive an *ensemble* spread (and average) can help to ensure all potential risks are assessed. *Ensemble* approaches are particularly relevant to large-scale or long-life projects in areas with a wide range of projected outcomes.

Maladaptation refers to an action, or inaction, that leads to an increased risk of an adverse climate-related outcome such as increased vulnerability, increased greenhouse gas emissions, or diminished welfare. An example of infrastructure *maladaptation* is a situation where an inadequate or inappropriate response to an anticipated change in a climate-related parameter results in the under- or over-design of an asset, resulting in a *stranded asset* or meaning that (part of) the investment is wasted. Another is where an inflexible solution (e.g. a design that cannot be modified if climate-related variables do not change in the originally-projected manner) results in an increase in vulnerability or a reduction in physical or material well-being over time [PIANC WG 178, 2020]. Maladaptation may also occur because a decision has not taken into account the wider system context, including spatial or temporal scale. Interventions that increase vulnerability at another location or of another sector are similarly considered as *maladaptation* [Noble et al., 2014]. *Maladaptation* is usually an unintended consequence [IPCC, 2022].

Nature-based solutions are defined by the International Union for Conservation of Nature [IUCN, <https://www.iucn.org/>] as actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. In a climate change context, nature-based solutions can contribute to the capture and retention of carbon dioxide in ecosystems such as marine and coastal habitats that act as carbon sinks ('blue carbon'). They can also involve enhancing and exploiting the natural function of healthy ecosystems (marshes, mangroves and other wetlands) including as buffers against wave energy, providing natural resilience against sea level rise and storm conditions.

No-regret (or low-regret) solutions provide (some) benefits under any foreseeable climate scenario including present day climate. The benefits of such solutions will therefore be realised irrespective of whether and how quickly climate parameters or associated processes change over time.

Resilience refers to the capacity of an asset, operation or system to cope with a hazardous event, trend or disturbance [IPCC, 2022]; to anticipate and plan for such eventualities; to resist losses and/or absorb

the impact of disturbances; to rapidly recover afterwards; and to adapt to short- and long-term stressors, changing conditions and constraints as quickly as possible. In natural systems, resilience helps maintain essential ecosystem structure and functions whilst retaining *adaptive capacity*.

Retrofitting means adding or installing something (e.g. a new or modified part, technology or feature) to an existing asset that was either not available or was not considered necessary at the time of its construction or manufacture.

Slow onset changes emerge and evolve gradually, over a period of years or even decades. In climate change terms, slow onset events include increasing temperatures and related physical processes; glacial retreat and related impacts; sea level rise; ocean acidification; and salinisation.

Stranded asset describes an asset that has to be written-off, suffers devaluation or becomes a liability (e.g. because it requires unanticipated conversion or modification or otherwise can no longer deliver its function). This may happen if its design has failed to take into account uncertainties in (the range of) possible future conditions due to climate change.

Tipping point: in climate science [IPCC, 2021], a tipping point in the climate system is a *critical threshold* beyond which a system reorganises, often abruptly and/or irreversibly. With regard to climate change adaptation, a *tipping point* exists at the moment (or condition) when vital functions can no longer be supported (e.g. an asset, activity or operation is no longer physically or economically sustainable).

Transformative or disruptive change is a response to a fundamental or existential challenge, for example when a *critical threshold* is exceeded and incremental changes are no longer efficient or sustainable.

1 INTRODUCTION

Climate change emphasises existing uncertainties and introduces new ones, among them uncertainty about emission scenario pathways; uncertainty in projections from the various Global Climate Models (GCMs)¹; and the challenges of distinguishing natural climate variability from climate change.

Option selection, design, and evaluation processes need to be able to recognise and accommodate these uncertainties to allow safe and cost-effective design while avoiding maladaptation. This Technical Note explores current good practice and offers some insights into how climate change uncertainties can be managed to reduce risks when designing and operating navigation infrastructure.

The note aims to provide a practical approach to enable informed decision making, and to facilitate the delivery of designs and operations that are more resilient and less prone to catastrophic failure, damage or downtime. The contents of the note are therefore relevant not only to infrastructure designers or project owners, but also to those authorising, financing, insuring or operating such assets.

2 USE SCENARIOS TO UNDERSTAND THE RANGE OF POSSIBLE CLIMATE FUTURES

2.1 Characteristics of Climate Change

Notwithstanding the growing scientific evidence, there remain many uncertainties, particularly about *how quickly* climate-induced changes will take place, their *magnitude*, and whether, *when* and how often critical thresholds will be crossed. The models that simulate changes in the earth's climate have improved significantly over recent years but there remain some inherent imprecisions. Such issues can affect models' resolution, scale and levels of detail; their representation of certain processes; and their simulation ability including where there are delayed responses, potential tipping points or nonlinear effects. Furthermore, as climate change effects will vary regionally, global data requires transformation into regional models.

In addition to the uncertainties associated with the climate models, there are also:

- uncertainties at a global level about the effectiveness of measures to reduce greenhouse gas emissions, and questions about how and when these measures will be delivered
- unknowns regarding the socio-economic and environmental changes that may take place, at both local and system level, in the meantime.

IPCC (2022) confirms that the magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions. Projected adverse impacts and related losses and damages escalate with every increment of global warming.

These severe uncertainties (or 'deep uncertainties', see V.A.W.J. Marchau et al. (2019)) mean it remains unclear exactly how much, and how quickly, temperatures will rise in the period up to and especially beyond 2050, and whether there will be significant local differences.

¹ Although global climate models (GCMs) are based on physical processes, each GCM has a finite spatial resolution. The parameterisation of processes on scales smaller than the model resolution is therefore needed to incorporate the effect of these processes and this parameterisation is different for each GCM. As a result, GCMs forced with the same emission scenario will produce different results [De Winter, 2014].

Figure 1 below illustrates this uncertainty. Under the different ‘Representative Concentration Pathways’ (RCP)² from the Intergovernmental Panel on Climate Change (IPCC) AR5 report³, temperature projections⁴ are shown to vary significantly from 2030 onwards and particularly after 2050, between the low-emissions RCP 2.6 and the continued emissions’ growth RCP 8.5 scenario⁵. In 2020, Schwalm et al. reported that cumulative CO₂ emissions were tracking along RCP 8.5. UNEP (2020) similarly concluded that, without a significant increase in policy ambitions, warming is on track for 3.4 to 3.9°C increase relative to pre-industrial levels by the end of the century. Notwithstanding the progress made and agreements reached at COP26 in 2021⁶, it is clear that warming in excess of the 2.0°C upper target of the Paris Agreement is currently (early 2022) still anticipated.

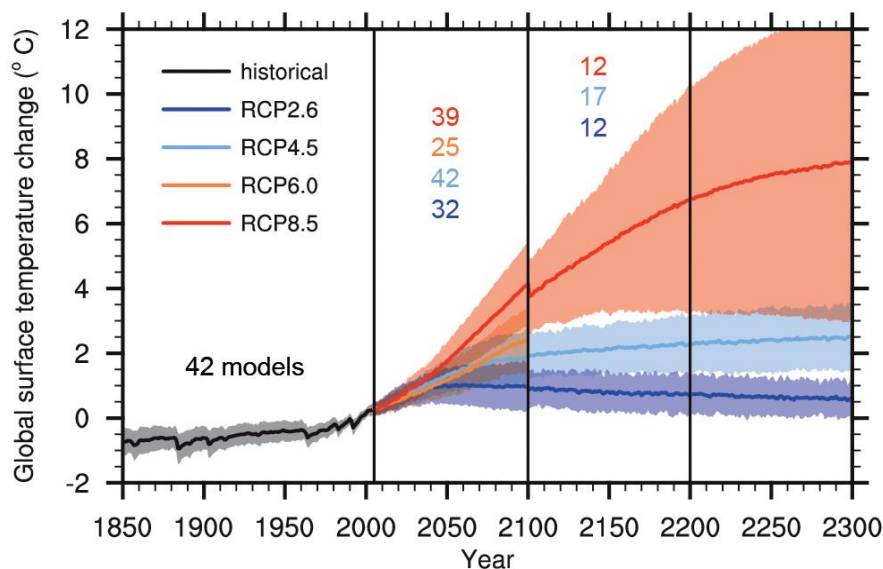


Figure 1: Projections of changes in global surface temperature according to the Intergovernmental Panel on Climate Change⁷

Changes in air and water temperature directly or indirectly influence many other parameters and physical processes of potential relevance to those designing or operating navigation infrastructure⁸. These include changes in precipitation; mean sea level; wind conditions; and water chemistry and, in

² Subject to the footnote below, the most widely-used climate change scenarios remain those based on ‘Representative Concentration Pathways’ (RCPs) greenhouse gas (GHG) concentration trajectories developed by the IPCC. Four pathways describe four different climate futures, depending on the quantities of GHG emitted in years to come [IPCC, 2013]. The RCPs are labelled according to a range of anthropogenic radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m², respectively):

- RCP 2.6 is an emissions pathway leading to very low GHG concentration levels
- RCP 4.5 is a stabilisation scenario where anthropogenic CO₂ emissions peak by 2040 [Meinshausen et al., 2011]
- RCP 6.0 is a stabilisation scenario where anthropogenic CO₂ emissions peak around 2080 [Meinshausen et al., 2011]
- RCP 8.5 represents a pathway with GHG emissions continuing to increase over time

³ The more recent IPCC AR6 report (2021) uses different processes and terminology to describe scenarios, but the end result is the same: significant uncertainties remain, and consideration of a range of scenarios is recommended

⁴ When referring to anticipated future changes in climate-related parameters and processes, the term ‘projection’ rather than ‘prediction’ is used. Predictions (i.e. probabilistic statements that something will happen based on what is known today) can be used for weather forecasting, for example, but projecting the future climate is different from weather forecasting because of the various uncertainties discussed in this paper.

⁵ RCP 6.0 is shown on Figure 1 above to 2100 only; the exceedance bands on Figure 1 are 5 %-95 %.

⁶ <https://ukcop26.org/wp-content/uploads/2021/11/COP26-Presidency-Outcomes-The-Climate-Pact.pdf>

⁷ For further explanation see https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter12_FINAL.pdf [Collins et al., 2013]

⁸ In addition to global climate change projections, for example available from the IPCC <https://www.ipcc.ch/> or the World Bank <https://climateknowledgeportal.worldbank.org/>, a wide range of regional or national resources are available to help understand the range of future climate conditions. Examples of tools that can be used to quantify the range of uncertainty include the U.S. Army Corps of Engineers (https://www.usace.army.mil/corpsclimate/Public_Tools_Dev_by_USACE/); the UK MetOffice (<https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/download-data>) and Norway’s relative sea level rise tool (<https://www.kartverket.no/en/at-sea/se-havniva/se-havniva-i-kart>).

turn, wave characteristics, ice and icing, fog, sediment dynamics, surge propagation, river flow, flooding (surface, river, coastal), wind loads, saltwater ingress, corrosion, etc. There will also be changes in associated biological characteristics. Changes in precipitation characteristics (intensity, distribution, and seasonal or annual totals) will be of utmost importance for many inland waterways. Sea level rise, along with changes in storm characteristics including wind, waves and surge, will impact on seaports and maritime transport. But both air and water temperature *per se* and the full range of potential consequential climate change effects need to be considered if maladaptation is to be avoided.

Varying levels and combinations of change can be expected. Regional differences along with varying rates of change can be significant for relevant parameters and processes. Examples include:

- (i) Gradual (or 'slow onset') changes in ambient air and water temperature, sea level, seasonal precipitation patterns and similar factors affecting daily operations [UNFCCC, 2012]
- (ii) Increases, in many regions, in the expected frequency and intensity of extreme hydro-meteorological or oceanographic conditions [IPCC, 2012]
- (iii) Combinations of these changes, for example a storm surge plus heavy rainfall plus a spring tide (i.e. associated with a new or full moon) superimposed upon an increased sea level

The many interrelationships and consequential effects, including the potential for system-level changes (such as the disappearance of glaciers in mountain areas), mean that there is unavoidable uncertainty about the rate and magnitude of change across a wide range of design and operational parameters.

Figure 2 illustrates how different aspects of navigation infrastructure might be impacted by changes in climate-related parameters and processes.

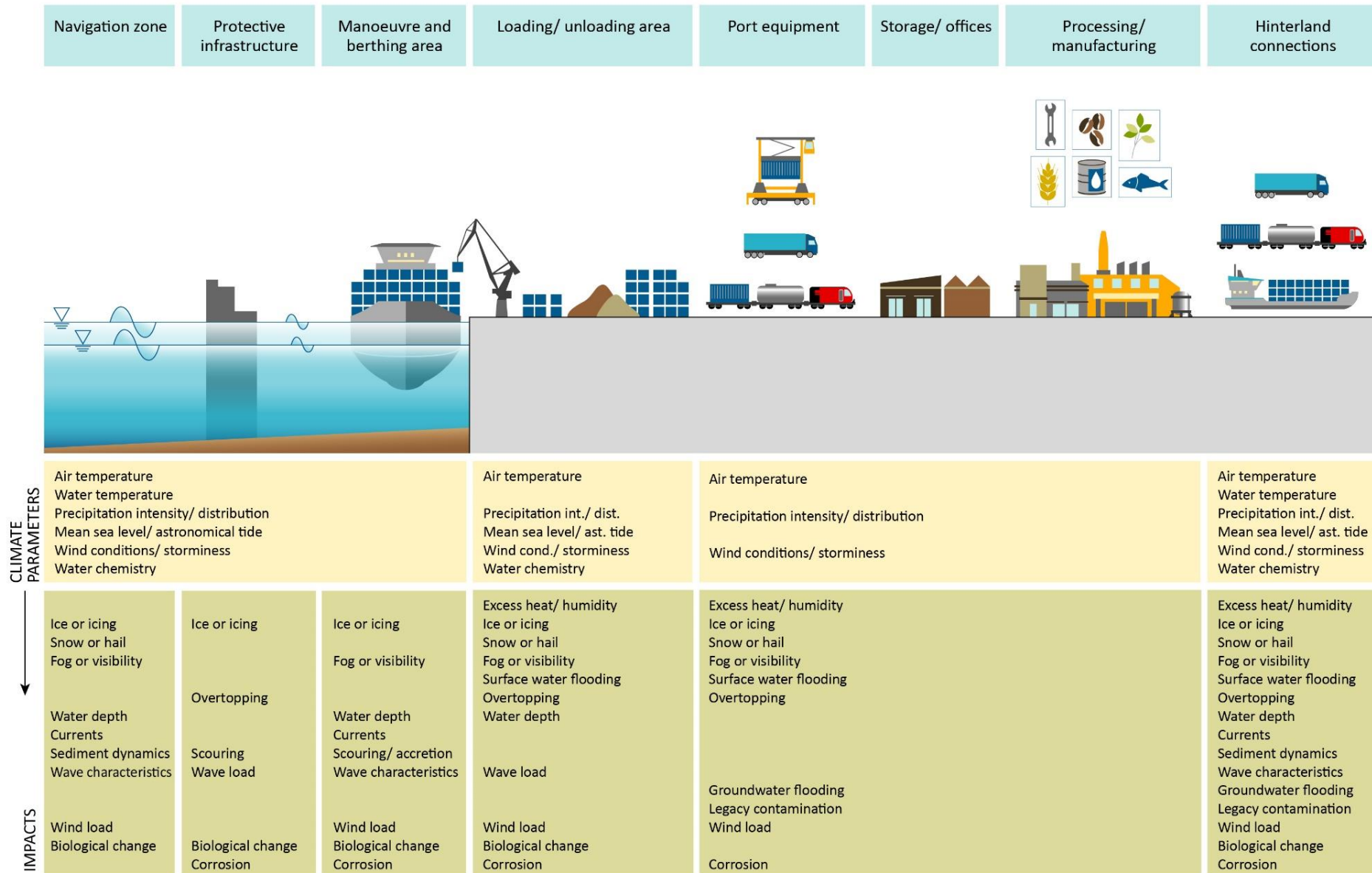


Figure 2: Illustrative relationship between climate parameters and impacts on port infrastructure/operations (From PIANC WG 178 (2020))

2.2 Selection of Climate Change Scenarios

Figure 1 illustrated that the RCPs and associated global mean surface temperature changes are indistinguishable in the short term (up to 10 years). Up to 2050 (i.e. around 30 years from the date of preparation of this Technical Note), the trajectories show a limited variation, but the different scenarios diverge significantly from around 2050.

Climate change-induced deviations from historical trends can therefore represent a significant challenge to ensuring the resilience of infrastructure or operations with a design or operational life of more than 10 years [PIANC WG 178, 2020]. This is particularly the case when, as is often the norm, historical data are used to predict the future conditions to which port, waterway or coastal protection infrastructure will be exposed over many decades.

Exploring a range of (location and scale-appropriate) climate change scenarios during the planning and design processes allows an asset or operation's sensitivity and tolerance to possible future climates to be tested. This is important to avoid decisions that lock the investor or project owner in to a single predetermined or 'presumed' climate change scenario, and hence to potentially significant investment risks (i.e. possible maladaptation).

The following examples illustrate situations that could lead to maladaptation, and indicate how the associated risks can be minimised and mitigated:

- A change in seasonal rainfall could lead to inundation of the access road to a proposed new storage facility as a result of surface water or river flooding. If only one climate change scenario is considered, the risk of flooding might be deemed acceptable; however, this conclusion could change when a range of different scenarios is reviewed if other scenarios show more frequent inundation. While it remains uncertain which climate change scenario will actually occur, evaluating the additional scenarios could lead the project promoter to explore alternative locations, either for the access route or for the new facility itself.
- If only one sea level change scenario is evaluated (e.g. assuming that mean sea level will rise by 0.2 m over the next 30 years), the height of a quay wall will be set accordingly. Examination of a range of sea level change scenarios – instead of just the one scenario deemed to have a high likelihood – may show that it is more cost effective to build a slightly higher wall now to address a potential 0.5-m sea level rise, rather than risk having to modify the structure at a later date⁹. Furthermore, there may be some sea level rise scenarios under which the potential for increased wave propagation leads to questions about the long-term viability of the harbour – a finding that could influence a decision on whether to invest at all.
- Rising temperatures are leading to the melting of mountain glaciers and hence to increases in river discharges. Care is required, however, in responding to this situation. To avoid possible maladaptation in the form of stranded assets, new infrastructure design must be cognisant of both additional (summer) discharges in the short to medium term, **and** of climate change scenarios that anticipate the disappearance of the glaciers in the second half of this century. Depending on the life of the asset involved, flexibility and adaptability may need to be incorporated into the design.

The selection of climate change scenarios (How many? Which ones?) is determined by the relative exposure and vulnerability of the asset or operation. In general, the more susceptible the asset or operation is to weather or climate-related damage or disruption, or the greater the magnitude of investment involved, and the longer the intended design or operational life, the more important it becomes to explore a full range of scenarios.

⁹ The following sections of this Technical Note consider approaches such as adaptation pathways and adaptive management to help with this decision making.

Unless the infrastructure in question is explicitly intended to be temporary, moveable or sacrificial, the logic recommended for adaptation planning in PIANC WG 178 (2020)¹⁰ suggests that:

- If a project will have a design or operational life of ten years or less **and** adequate historical data are available to understand recent trends in climate parameters, the application of climate change scenarios may not be required.
- If the planned infrastructure design or operational life is less than approximately 30 years (i.e. near-future), different climate scenarios should be used for sensitivity testing and to inform design decisions, but the number of scenarios might be reduced, for example by using a selected grouping or combination of projections.
- If the planned infrastructure design or operational life extends beyond 2050 (mid- to far-future) or if the asset or operation is particularly sensitive to weather or climate-related damage or disruption, or for high value investments, a wide range of possible future climate scenarios should be considered.

2.3 Unlikely-but-Plausible Scenarios

Where major, long-term investment is being made, special attention should also be paid to how the low-chance high-impact scenarios are defined. The IPCC (and other climate change projections) typically provide a 'likely' range. Climatological or physical developments and responses outside this range are not included, for example where current system understanding is limited. It is of concern that mass loss from glaciers, ice caps and ice sheets in Antarctica could greatly affect sea level rise in the second half of the 21st century [IPCC, 2019]; there is a growing body of evidence regarding the stability of the West Antarctic ice sheets in particular, and the possibility of a global sea level rise of up to 3 m by 2100 [IMechE, 2019].

In order to test vulnerability and plan for contingencies, those designing or investing in long-life and/or very expensive assets that are sensitive to parameters such as sea level rise, may therefore find it useful to consider unlikely-but-plausible scenarios appropriate to their specific project location or region. Indeed, IPCC (2019) suggest that stakeholders with a low risk tolerance (e.g. making long-term investments in critical infrastructure) consider the possibility of sea level rise above the likely range¹¹.

Box 1 provides an example from the UK, which describes the approach adopted for projections of sea level rise and storm surge [Fung et al., 2018]. Unlikely-but-plausible scenarios are not recommended as being the most appropriate scenario on which to base engineering designs; rather they are useful in providing an upper bound for evaluating the robustness of planned investments.

¹⁰ Other relevant guidance offers a further insight into defining and accommodating long-, medium- and short-term climate risks (e.g. British Standard 8631 (2021) offers some clear definitions on this question and on the appropriate 'complexity' of the responses on these timescales).

¹¹ While such considerations are especially true for facilities that are sensitive to sea level rise, the need to consider unlikely-but-plausible scenarios may also apply to infrastructure that is sensitive to extreme rainfall events, riverine flooding, or coincident riverine and coastal flooding.

Sea level rise projections typically assess the likelihood of future conditions within the 17-83 % or 5-95 % probability range (i.e. most likely/very likely). However, such a rise could be much larger if ice sheets become unstable resulting in (ongoing) mass loss.

UK guidance therefore recommends using multiple strands of evidence on future sea level rise when assessing vulnerabilities to future extreme water levels. These evidence strands include the so-called high-plus-plus (H++) scenarios, representing a low probability but high impact scenario

The unlikely-but-plausible H++ scenarios for the UK are derived using a combination of historic evidence (e.g. proxy data from deep ocean sediments, corals, or ice cores from the ice sheets, and estimated average rates of sea level rise during the last interglacial period) and available future projections taking into account known limitations (e.g. in the physics of the ice sheet models used in climate change projections). Recent local data and expert opinion are also used [Lowe et al., 2009].

Applying this approach resulted in a H++ scenario for time-mean sea level rise around the UK by 2100 in the range 0.93 m to 1.9 m. This indicative range is significantly greater than the then (2008) projected relative sea level increases by 2095 of 0.21 m to 0.68 m for London, i.e. based on projections where instability of the Antarctic ice sheet was not included.

Beyond a qualitative statement that the top of the H++ range is very unlikely to occur in the 21st century, no attempt was made to assign a precise probability to this range. It was acknowledged that these scenarios lie beyond the usual 'likely' and 'very likely' ranges, but they cannot be ruled out given past climate proxy observations and current process-based model limitations.

In the UK, these estimates are intended to be used for vulnerability testing purposes and to aid users in contingency planning when a high level of protection is essential [Fung et al., 2018], rather than as a basis for design.

Box 1 Development of low probability but plausible high++ UK sea level rise scenarios (adapted from PIANC WG 178 (2020))

2.4 Use of Representative Conditions

Evaluating multiple climate change scenarios need not be a cumbersome evaluation of many discrete projections of sea level rise, rainfall, or other forcing factors. Robust planning efforts may be conducted by choosing a relatively small number of projections, provided these represent the range of conditions that may occur over the project's functional life. Sensitivity analysis can then be used.

Figure 3 is based on an example of local relative sea level rise¹² projections by the U.S. National Oceanographic and Atmospheric Administration [NOAA; Sweet et al., 2017]. The 'extreme' curve is analogous to the example described in Box 1. The yellow boxes show how a set of four representative estimates (0.50, 1.25, 1.85 and 2.75 metres) span most of the projected sea level rise range at this specific location (Boston, Massachusetts, USA) through year 2100. A set of estimates such as this can be used to evaluate the sensitivity of planning and design choices. For instance, in this example the expected effects of a 1.25 metres sea level rise can be reasonably applied to planning decisions on the 'high' curve at year 2060, on the 'intermediate-high' curve at year 2070 or on the 'intermediate' curve at year 2100. Four sea level rise representative estimates, evaluated as a set, cover most of the range of low, intermediate, high and extreme projected curves over the years 2030 to 2100.

¹² Local relative sea level rise is calculated taking into account changes in global mean sea level alongside local factors such as changes in land elevation, winds, ocean circulation, etc.

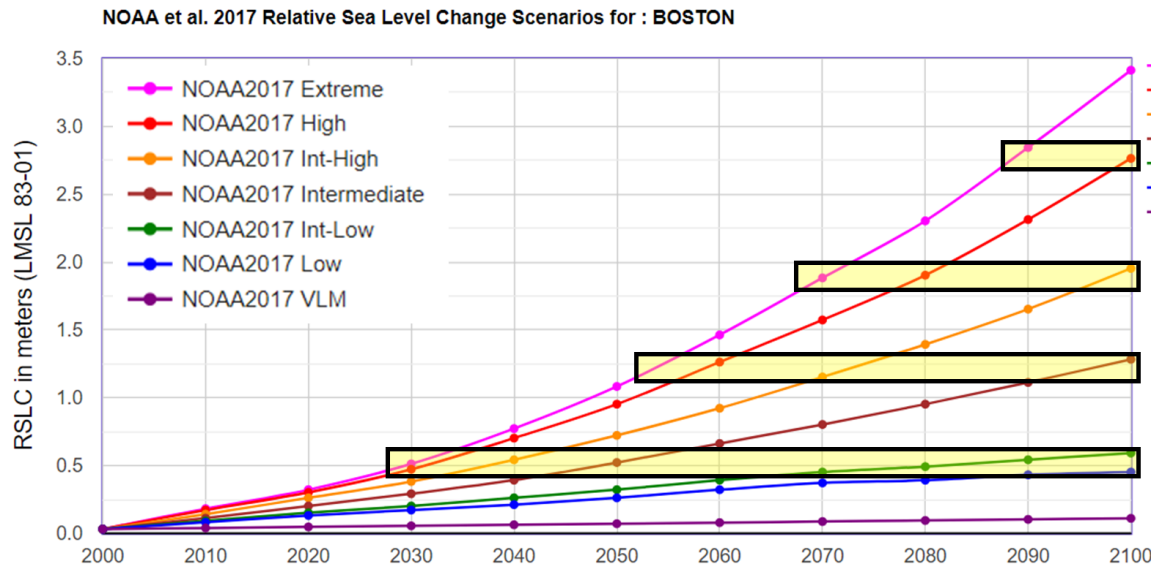


Figure 3: Illustration of using representative estimates to evaluate range of future sea level projections (modified from the USACE Sea-Level Change Curve Calculator¹³, Version 2021.12, using data from Sweet et al. (2017))

This kind of approach would be suitable for a planning study for high value investments occurring over a long period of time. To adjust the procedure for a detailed design, where the design life is likely more constrained, the boxes could be pulled closer together in time and to focus on the curves best representing the project's risk tolerance.

The approach ultimately taken to evaluate climate change scenarios for a particular investment therefore depends on the nature and scale of the investment, and on its planned functional lifetime. For large-scale or long-life projects in areas with a wide range of projected outcomes, a probabilistic¹⁴ approach to assessing the risks associated with all contributing climate change parameters and scenarios may be best to ensure all such risks are evaluated without being overly conservative or overly dismissive of less likely factors. Specialist advice may need to be sought, and relevant parties engaged to define and agree on risk tolerances.

For lower value investments, or where resources are scarce, consciously selecting options that are flexible and adaptive provides another way of managing these risks (see Section 4.0).

3 PREPARE FOR THE UNPRECEDENTED

Extreme hydro-meteorological or oceanographic conditions, including precipitation, wind, waves, heat or cold, can cause port or waterway closures, delays and disruption. These events also have the potential to significantly damage maritime infrastructure. In many parts of the world, climate change is expected to increase the frequency or intensity of extreme events [IPCC, 2019]. The design of new breakwaters, quay walls, terminals, storage facilities, drainage systems and other navigation infrastructure will need to provide for or otherwise accommodate such changes. The same applies to the design of post-construction modifications to these assets, known as retrofitting.

In 2019-2020, the partners in the Navigating a Changing Climate Global Climate Action initiative¹⁵ undertook a survey to understand whether and how ports are affected by extreme weather events. 67

¹³ <https://maps.crrel.usace.army.mil/projects/rcc/portal.html>

¹⁴ Climate change scenarios do not have probabilities; rather probabilities have to be derived. For example, the University of New South Wales Water Research Laboratory (Australia) convened a panel of experts to derive the probabilities of the RCP scenarios for a coastal hazard study through agreement on an assigned set of probabilities of each RCP over the assessment time frame.

¹⁵ <https://navclimate.pianc.org/>

responses were received, representing ports on every continent. 53 % of the ports responding to the survey indicated that they are already experiencing extreme weather events more frequently¹⁶. 41 % reported that, in the previous 5 years, they had experienced an event that was 'somehow exceptional, unprecedented or otherwise out-of-the ordinary'. Wind and extreme waves were the most frequently reported events, followed by unprecedented rainfall and overtopping (regardless of cause)¹⁷. These findings were broadly consistent with those of a 2014 Port Industry Survey on Climate Change Impacts and Adaptation by UNCTAD (2017).

Those owning, designing or evaluating navigation infrastructure should strive to understand and – as far as practicable – prepare for the possible consequences of such events. This does not necessarily mean designing to withstand the extremes; in most cases it will require action to strengthen both engineered and operational resilience. Resilience refers to the capacity to anticipate and plan for disruptions; to resist losses or absorb the impact of disturbances; and to recover quickly after an event [PIANC WG 193, 2020]. Strengthened resilience is not only achieved via physical measures such as incorporating engineered redundancy into design, but also through non-structural, system level measures including mapping vulnerable assets or areas within or outside of the project boundaries; preparing contingency plans; identifying climate-related thresholds for action; installing early warning systems; and otherwise improving adaptive capacity.

In a climate change context, it is vital to acknowledge and plan for the consequences of failure if an event exceeds design standards or a high-impact, low-probability event occurs. To some extent this can be addressed by designing-in redundancy; designing specifically to enable rapid replacement or repair; or using temporary (alternative) infrastructure. However, structures and operations that are prone to failure should also be designed to fail 'gracefully' rather than 'catastrophically' and/or measures should be implemented to manage the consequences of failure.

Designing a structure to fail in a controlled manner may involve deliberately weakening specific elements to retain a degree of control, or sacrificing components that are vulnerable to extreme climate loading in order to improve the structure's overall resilience. For example, a jetty deck might be designed to fail before damage is caused to the supporting structure. This could involve constructing the deck from wooden beams or slats that can be replaced quickly and easily using local timber as a temporary measure if needed, or it could involve a more sophisticated design as illustrated in Box 2 [PIANC WG 178, 2020].

¹⁶ PIANC-PTG CC Technical Note No.2 (2022, forthcoming).

¹⁷ This intentionally high-level survey did not seek to collect detail about the cause of each event; rather it was concerned to collate information about the associated costs and consequences.



When the wharf of the Lucinda Bulk Sugar Terminal in Australia was subjected to large waves during Tropical Cyclone Yasi in 2011, its concrete deck was stronger under wave uplift than the connections of the deck to the steel wharf structure. This led to the heavy concrete deck being lifted off the steel structure by waves, and then dropping down on it, causing significant impact damage to the wharf. Consideration of climate change issues when the wharf's repair was designed included the development of a hierarchy of structural capacities such that the deck will now fail before the deck's connections to the wharf do.

Box 2: Accommodating extremes in wharf repair design, Lucinda Bulk Sugar Terminal, Australia

Managing and minimising the adverse consequences of an unprecedented event can similarly be illustrated with a flood defence example. The potential damage and disruption caused by the failure of an earth embankment providing flood protection to a port estate might be reduced by:

- bunding or raising critical assets within the risk area, and/or
- nominating flood storage areas or identifying flood compartments for sacrificial inundation and designing preferential flow routes, and/or
- flood-proofing infrastructure in the risk area (e.g. raised electricity supply points and enhanced, appropriately-designed and well-maintained drainage capacity)

In both the above examples, including an early warning system as part of the overall project will usually provide a cost-effective option to ensure that any necessary preparatory measures can be taken in advance of a forecast extreme event.

The further into the future the intended design life of the asset, the greater the uncertainty in the climate change projections and the greater the risk of extreme events that challenge the integrity or functioning of infrastructure. As discussed in Section 2.4, for major longer-term investments, for major longer-term investments, a probabilistic approach to assessing these risks for all relevant parameters is recommended, with specialist advice sought where needed. Preparations should be effective, flexible and durable.

If maladaptation is to be avoided, it is similarly important to acknowledge and accommodate the risk of cascading failures where interdependencies exist between interlinked natural and socio-economic systems and sub-systems. Extensive flash flooding at Port Klang, Malaysia, in December 2021 for example resulted not only in weather-related delays to vessel berthing but also staffing shortages due to travel difficulties and flooding impacts on local communities. The consequential disruption to the movement of containers and cargo, and the backlog of waiting vessels, resulted in the port having to prioritise deliveries of essential goods particularly food items, medical supplies and refrigerated goods¹⁸. Other widely-reported cases of cascading effects include the regional impacts of Hurricane Sandy on both transport supply chains and energy infrastructure in New York in 2012; and the extensive flooding in Bangkok in 2011, which led to a global shortage in semiconductors and a slowdown in the global computer manufacturing [IPCC, 2022].

The very nature of ports as hubs for trade mean that such interlinkages are not unusual. Nonetheless, inadequately accounting for this type of complexity can lead to significant blind spots in adaptation planning [Lawrence et al., 2020].

Adaptation pathways (sequences of risk-reduction actions, which can be implemented progressively, depending on how the future unfolds and the development of knowledge [Werners et al., 2021]) can be of benefit at system as well as asset or port level, and can thus help to facilitate responses where interdependencies exist. As discussed below in Section 5.0, such pathways do not always have to be complicated or expensive. The following sections of this paper elaborate on how a common-sense approach to reducing risks can be applied to a wide range of infrastructure and operations.

4 ADOPT ADAPTIVE AND FLEXIBLE SOLUTIONS

Uncertainty can often be accommodated and maladaptive responses to climate change avoided by adopting flexible solutions with multiple benefits [IPCC, 2022]. For infrastructure, this can involve introducing engineered flexibility and adaptive capacity into both designs and operational systems to facilitate future modification as conditions change. This is sometimes known as ‘adaptive ready’.

When developing solutions for climate change, project owners/planners and designers should consider changes in both the mean and the variance (i.e. extremes) of climate parameters such as sea level, wind strength or wave height. Changes to one or both of these metrics can result in a shift of magnitude and frequency of extreme conditions. Extreme conditions applied in the design of maritime structures typically correspond to conditions that occur on average once every 50, 100 or 200 years. Port and waterway operations, on the other hand, are generally governed by lesser environmental conditions (i.e. conditions occurring on a monthly or annual basis).

With climate change, the conditions relating to a given return period are likely to change over time. The IPCC Oceans and Cryosphere special report [IPCC, 2019] concludes that “Extreme sea level events that are historically rare (once per century in the recent past) are projected to occur frequently (at least once per year) at many locations by 2050 in all RCP scenarios, especially in tropical regions”. There is greater uncertainty, however, in the projections for changes in other parameters that are important in many types of design, including changes in storminess, surges, wind speed and significant wave height. Likewise, for maritime operations, it is not (yet) possible to determine with any confidence when the wind, wave or fog conditions typically experienced annually in the recent past might become monthly or even weekly occurrences, and so on. On inland waterways, there are equivalent uncertainties with regard to high or low river levels and flows, flooding and droughts. Potential future system level changes, such as the disappearance of glaciers in mountain areas, also need to be considered.

As the climate continues to change, conventional statistical methods that rely on historic data about past events to predict the magnitude of low probability future events (e.g. 100, 500, 1,000, 2,000-year

¹⁸ <https://www.porttechnology.org/news/port-klang-suffers-severe-flooding-affecting-port-and-logistics-operations/>

average return periods) will become increasingly less appropriate, even if a long-term dataset exists [PIANC WG 178, 2020].

Escalating climate uncertainty over time means that critical assets and operations will benefit from greater levels of inbuilt resilience. Resilience can be achieved in many different ways: it is thus important is to anticipate and as far as possible respond to the conditions and risks that may be faced during the asset or operation's lifetime. There is increasing evidence¹⁹ to demonstrate that proactively incorporating climate-related design considerations from the start of the process can be significantly less costly and less complex than having to modify designs, reactively, at a later date. Box 2 described one adaptive solution to cater for extreme conditions. Figure 3 covers a situation where an asset may need to be raised, strengthened or otherwise modified as conditions change or as additional information becomes available in future.

A breakwater or flood defence may be expected to provide protection against a 1 in 100-year storm but there may be insufficient certainty to understand what this storm will look like in 30, 50, or 100 years' time. Rather than locking in to a single climate change scenario and investing in a structure of a certain height, consideration should be given to whether the asset can be designed to be raised and strengthened in future years as conditions demand (i.e. 'adaptive ready'). This principle is illustrated by the example of the 'climate dyke' provided in Figure 4 (taken from PIANC WG 178 (2020)). Similar 'adaptability' principles can be applied to many other types of physical infrastructure. The foundations for a breakwater, for example, might be constructed so as to withstand the load of subsequent raising if wave conditions exceed current projections; or it may be prudent to purchase additional land as a contingency (e.g. to facilitate future strengthening works, or to have space to construct additional structures such as flood protection bunds or wind deflectors at a later date).

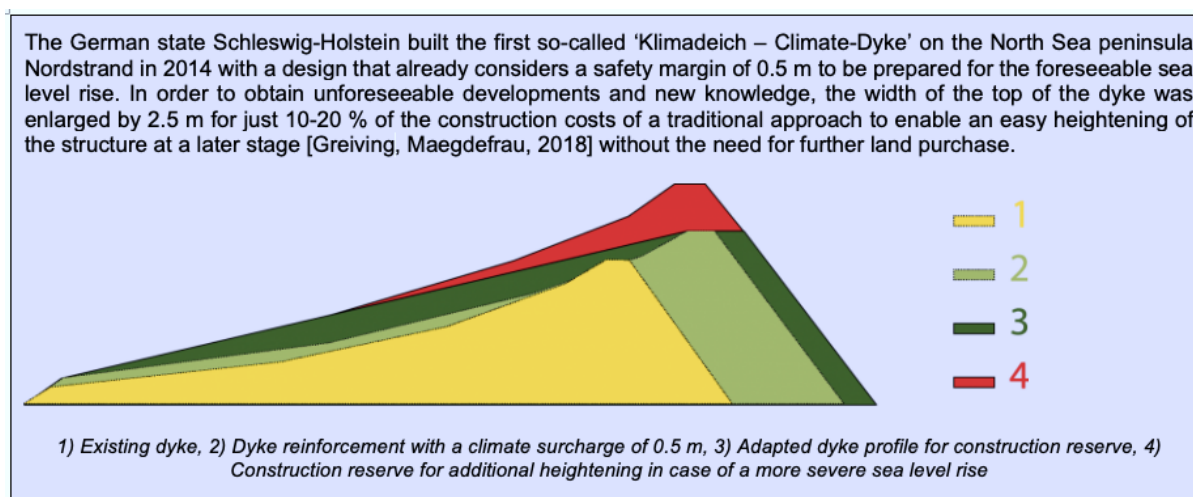


Figure 4: The 'climate dyke' of the German Federal State Schleswig Holstein

5 CONSIDER STRUCTURAL AND NON-STRUCTURAL ADAPTATION AND RESILIENCE OPTIONS

As already indicated, structural interventions are not the only option for responding to and managing climate-related risks. Depending on the type of risks identified and the associated uncertainties, changes in operation, management, maintenance or behaviour might be appropriate or cost-effective as a supplement, or alternative, to a structural intervention. Nature-based solutions as promoted by PIANC's Working with Nature philosophy [PIANC WG 176, 2018], which enable a port or waterway to

¹⁹ <https://econadapt-toolbox.eu/infrastructure-costs-and-benefits-adaptation>; Global Centre on Adaptation and World Resources Institute, 2019.

capitalise on nature's resilience while at the same time delivering co-benefits, may represent a cost-effective option depending on the particular hazards faced. Institutional change, for example in land-use policy, project financing or insurance, might similarly form part of an overall, long-term solution.

Climate change often demands innovation. No-regret options that deliver benefits under a range of climate scenarios are expected to play an increasingly important role in future. So too will interim or short-term measures that buy time. More expensive or longer-term solutions can then be adopted, designed and implemented as data availability and understanding (e.g. of local rates of change) improve.

In the same way that exploring a range of scenarios will facilitate understanding of different risks, a range of options therefore needs to be considered if effective, efficient and appropriate solutions are to be identified.

PIANC's WG 178 report (2020) presents a portfolio of different types of physical, behavioural and institutional measures for strengthening resilience or adapting existing and new navigation assets, operations and systems. Table 1 taken from this report, illustrates a wide variety of generic measures. The WG 178 report also contains Annexes of measures specific to different types of climate change impact (different types of flooding, high or low river flow conditions, changes in wind or fog, heatwaves, etc.).

Options to strengthen resilience by designing and adapting navigation infrastructure to the changing climate may involve simple choices or there may be complex combinations of measures delivered simultaneously or consecutively. Adaptation pathways can be used to set out sequences of actions (measures, modifications, investments, etc.) that can be implemented progressively, depending on future dynamics [Zandvoort et al, 2017; BS 8631, 2021]. According to Werners et al. (2021), adaptation pathways may comprise alternative routes towards a defined objective or broad directions of change for different strategic outcomes, for example centred around performance-thresholds or transformation objectives. Adaptation pathways can also help to identify the potential for poor outcomes several stages into the future where large interventions may be required, for example to maintain port or waterway functionality. Monitoring outcomes and reflexive learning enable the realisation of such pathways in different decision contexts.

In the navigation infrastructure context, an adaptation pathway might support the implementation of interim or temporary measures in the first instance, allowing additional data to be collected and uncertainty reduced during a period of acceptable risk; or it may recommend a staged investment or construction process, incumbent on certain thresholds being met. For example, action may be triggered when measured mean sea level reaches a certain point, or when a pre-determined frequency of maximum wind speed or significant wave height is exceeded. Economic, financial or business continuity thresholds might also be relevant, for example to facilitate a proportionate response to cascading impacts. Adaptation pathways allow climate change risks to be dealt with in a flexible way or future options to be kept open so the risk of maladaptation can be minimised [PIANC WG 178, 2020].

The PIANC WG 178 report further highlights that, while adapting to climate change is often an incremental process, in some cases transformative or disruptive change is needed. For example:

- increases in the frequency of flooding, in rates of erosion or in the incidence of extreme waves in coastal areas surrounding a seaport may eventually make a currently cost-effective operation untenable, meaning that (part of) the port will need to be closed or re-located; or
- an increased incidence of drought or low water levels may force a change to smaller or shallower drafted vessels if waterborne transport is to remain viable on a certain waterway.

Physical Measures Structures, systems, technologies, services	Social Measures People, behaviour, operations, information	Institutional Measures Governance, economics, regulation, policy
<p>Prioritise maintenance to maximise operational resilience and improve adaptive capacity</p> <p>Install real-time monitoring infrastructure</p> <p>Use Cloud (back-up) for data storage to reduce physical risks to systems</p> <p>Relocate vulnerable assets and equipment out of high-risk areas</p> <p>Revert to phased array for radar</p> <p>Invest in redundancy, temporary infrastructure or other physical back-up provision for critical assets (including power and water supply)</p> <p>Reinforce, raise, strengthen or otherwise protect or modify critical assets</p> <p>Install or develop new, responsive or demountable infrastructure or equipment</p> <p>Install warning equipment</p> <p>Nominate or provide physical sanctuaries</p> <p>Increase storage capacity</p> <p>Install multi-modal equipment</p> <p>Apply nature-based solutions, Working with Nature, soft engineering</p> <p>Install treatment or reception facilities</p> <p>Incorporate flexibility in new or replacement infrastructure design to allow for modification as conditions change</p> <p>Modify material or equipment selection to accommodate changing conditions</p> <p>Invest in SMART technology</p>	<p>Undertake climate change risk assessment, prepare risk maps</p> <p>Prepare and raise awareness of contingency, emergency or disaster response plans</p> <p>Introduce and regularly review warning systems</p> <p>Prioritise asset inspection</p> <p>Educate workforce, stakeholders, local communities</p> <p>Liaise and coordinate with utilities and other service providers; develop information-sharing protocols</p> <p>Improve (or instigate) monitoring, record keeping and data management, consider cybersecurity issues</p> <p>Undertake trend analysis or forecasting</p> <p>Develop revised operational protocols; modify working practices as conditions change</p> <p>Introduce and implement adaptive management procedures, base operations or working arrangements on monitoring outputs</p> <p>Allow for flexibility and responsiveness in programming (increase operational hours, modify staffing rotas, vessel scheduling, lock operation, etc.)</p> <p>Revert to traditional, low tech, ways of operating; ensure binoculars, telephone, paper charts, two-way radios are available</p> <p>Ensure availability of transport and accommodation for personnel during an incident</p> <p>Temporarily or permanently restrict activities in high-risk areas</p> <p>Nominate safe routes and areas, identify diversions</p> <p>Identify and exploit interconnectivity and intermodal options to maintain business continuity during events</p> <p>Provide training on new tools, codes of practice, procedures or protocols, ensure importance of redundancy is understood</p> <p>Facilitate technology transfer</p>	<p>Prepare strategic level climate change adaptation strategies</p> <p>Strengthen international cooperation and planning at river basin level</p> <p>Review and revise relevant codes of practice, standards, specifications or guidelines to accommodate changing conditions</p> <p>Review health and safety requirements and revise if needed</p> <p>Introduce penalties for non-compliance with standards Require zoning of assets, operations or activities based on risk</p> <p>Use local regulations (e.g. byelaws) to reduce risks, especially in multi-use locations</p> <p>Policies to encourage relocation out of high-risk areas</p> <p>Collaborate with land-use planning systems e.g. to introduce set back or buffer areas</p> <p>Limit new infrastructure development in high-risk areas</p> <p>Identify, secure and coordinate alternative transport routes or modes</p> <p>Promote reduced insurance premiums if improved resilience is demonstrated</p> <p>Set up contingency or disaster response fund</p> <p>Introduce and enforce build-back-better or build-out-of-harm's- way policy</p> <p>Facilitate diversification in facilities and employment as conditions change</p> <p>Improve legal protection for vulnerable habitats with risk reduction role (e.g. absorbing wave energy, providing erosion protection)</p> <p>Provide grants or incentives e.g. for development or maintenance of resilient infrastructure</p> <p>Research and develop novel tools and methods</p>

Table 1: Generic measures for strengthening resilience or adapting assets, operations or systems

6 USE MONITORING DATA TO INFORM DECISION MAKING

Even with the application of scenarios, many situations will demand more robust and adaptive solutions than is currently the norm. Adaptive management, where decisions are informed by monitoring and an understanding of thresholds for action, is an important concept in delivering cost-effective climate change-resilient solutions in the face of uncertainty. Where appropriate, data collection and local monitoring can be used to ensure investment is made on a responsive, ‘just in time’ basis. Real-time data and early warning systems can similarly enable action to be taken to avoid or reduce the risk of damage or disruption.

Site specific information is essential to generate local understanding, identify trends and inform decisions. The following examples illustrate how such data can be used to inform decision making:

- Local hydro-meteorological or oceanographic data can help to understand local trends and assess whether these are in line with projected national rates of change, informing location-specific adaptive management decisions and allowing optimal selection of design criteria^{20 21}
- Knowledge about the condition and performance of physical assets, including records of the (cumulative) effects of extreme events or changes in natural conditions, can help determine *when* a response is needed or a measure should be implemented
- Post-event data from extreme weather events, such as the extent and duration of inundation from storm tides and flooding, can be used to validate predictions about likely impact zones or models of future conditions
- A record of the costs and other consequences of damage, disruption or downtime associated with extreme events can facilitate an informed assessment of the financial and economic benefits of adaptation vs. the consequences of inaction, in turn supporting the business case for intervention
- Knowledge about the effectiveness or performance of already-implemented adaptation and resilience measures can inform decisions on future modifications or measures.

As indicated elsewhere in this paper, the collection, collation, effective management and use of these types of data can be vital in reducing uncertainty, facilitating the selection of appropriate measures, and supporting the preparation of long-term strategic adaptation and resilience plans. Ongoing appraisal of key scientific developments in climate change monitoring and modelling is also important for informed decision making.

7 SELECT EVALUATION METHODS THAT RECOGNISE AND ACCOMMODATE UNCERTAINTY

Investing in adapted infrastructure and improved resilience will often involve additional incremental costs. These costs need to be justified. It is therefore important to ensure that the methods used for the evaluation of potential measures and for option selection are appropriate to both the asset at risk and the relevant range of climate change-related factors, as well as being acceptable to those financing the project.

There are a number of important uncertainty-related considerations in this regard, including:

- If the benefits resulting from expenditure on improving infrastructure resilience are to be fully demonstrated, the consequences and costs of *inaction* (i.e. the implications of not taking relevant measures) need to be understood. Ideally, site-specific historic data on downtime, delays, clean-up costs and/or damage repair would be used to provide a baseline for this evaluation, but the possible

²⁰ Monitoring should be fit-for-purpose. In some cases, a simple log book or conventional site measurements may suffice. In others, satellite images might usefully supplement on-site monitoring. Real-time operational systems with hydro-meteorological data or model runs may be valuable in allowing timely warnings to be issued and operational responses instigated.

²¹ Downscaling (interpreting information from the large-scale global climate models to make predictions at the local scale) can be helpful in understanding projected rates of change [Tetra Tech ARD, 2014]. However, the specialist knowledge, cost and complexity involved in effective and reliable downscaling means that it is only likely to be supported for large-scale investments.

financial or business implications of extreme events can be difficult to foresee if the organisation has no prior experience of such extreme events²².

- Modelling and/or monitoring will help an organisation make timely decisions about *when* to invest, or where ‘just-in-time’ action is needed. Setting thresholds based on acceptable levels of risk helps inform decisions on investment in adaptation and resilience interventions. Either a specific change in a climate parameter or the consequence of a future extreme event could trigger an investment decision. The adaptation pathway or strategy should recognise these trigger conditions to inform long-term monitoring, proactive adaptation, and the preparation of reserves or procurement of insurances to meet financial needs after an extreme event.
- Uncertainty about how quickly some climate parameters will change means it can be difficult to be sure exactly *when* the benefits of resilience or adaptation measures will be realised.
- The application of high discount rates (i.e. an estimation of the rate of return used to discount future cash flows back to their present value) potentially further increases the risk of maladaptation because less value is placed on future benefits. The most climate-effective solution may be overlooked or rejected as a result.
- Conventional cost-benefit assessment or net present value calculations may not adequately reflect the complexities of climate change investment decisions, even if low discount rates are used. Methods must be fit-for-purpose. It is also important to capture less easily quantifiable social or environmental costs and benefits to avoid under-estimating potentially serious effects.
- Implementation time and the lifespan of a measure(s) should be taken into account: under a (rapidly) changing climate, the functionality and lifespan of a measure could be shorter than under present-day conditions
- The potential for upstream, downstream or transboundary costs and benefits should always be scrutinised when evaluating options. For example, certain technical solutions to increase drainage or flood conveyance capacity to accommodate intense rainfall, can result in an increased risk to life and property downstream. Evaluation methods must be capable of capturing, quantifying and including such consequences if maladaptation is to be avoided.
- Using multi-criteria analysis, decision-tree analyses, iterative risk management, robust decision making, real options analysis, portfolio analysis or similar tools can help to make better decisions and to reduce the risk of maladaptation [Tröltzsch et al., 2016].

Addressing these evaluation-related issues is crucial in ensuring risks are properly recognised to deliver strengthened resilience and effective adaptation. As DeFries et al. (2019) confirm, economic assessments that only extrapolate from past experience, or that use inappropriate discounting, do not provide a clear indication of the potential risks. Many economic assessments of the potential future risks of climate change have omitted or grossly underestimated the most serious consequences precisely because these risks are difficult to quantify. In such cases, the risk of maladaptation increases.

Taking climate change into account in infrastructure and operational design is, however, increasingly becoming an important pre-requisite for financing and, indeed, for securing attractive financing conditions²³. Proactive adaptation action can bring multiple benefits, often referred to as the triple dividend (ability of the investment to reduce future losses; positive economic benefits through reduced risk, increased productivity or innovation; and social and environmental benefits). At the scale of the planet, the Global Commission on Adaptation estimates that investing \$ 1.8 trillion globally in five areas²⁴ from 2020 to 2030 could generate \$7.1 trillion in total net benefits by 2030 as a result of this triple dividend [Global Center on Adaptation and World Resources Institute, 2019]. At least two of the areas they identify (early warning systems and climate-resilient infrastructure) are directly relevant to waterborne transport.

IPCC (2022) similarly recognise the multiple benefits – including for health and well-being, livelihoods, and biodiversity as well as risk and damage reduction – derived from adaptation planning and implementation, while at the same time stressing the need to consider systemic issues. The latter is important to avoid prioritising immediate and near-term risk reduction in cases where such a focus reduces the opportunity for the type of transformational adaptation highlighted in Section 5.0 above. This report [IPCC, 2022] also highlights the cumulative benefits that can accrue from measures such

²² PIANC-PTG CC Technical Note No.2 (2022, forthcoming).

²³ <https://www.financing-smafi.org/>

²⁴ Early warning systems; climate-resilient infrastructure; improved dryland agriculture; mangrove protection; and resilient water resources.

as early warning systems and disaster risk management plans that have broad applicability across sectors: in some cases, when combined, these can provide greater benefits than other adaptation options.

8 KEY MESSAGES

Climate change introduces new and increased uncertainties into design choices and decision making for investment in new or upgraded navigation infrastructure and operations. The following points summarise some of this Technical Note's key messages for each stage of the project planning process.

8.1 Understanding Climate Data Uncertainties

- Climate change is leading to changes including slow onset changes (in temperature, precipitation characteristics and sea level); in the frequency and intensity of extreme hydro-meteorological or oceanographic events; and in combinations of such changes.
- Effects will vary regionally; global data requires transformation into regional models.
- Beyond ten years from the present, there is increasing uncertainty about how much and how quickly relevant climate parameters will change. Conventional statistical methods that rely on historic data about past events to predict the magnitude of low probability future events will become increasingly less appropriate.

8.2 Selecting and Applying Climate Change Scenarios

- Climate change scenarios should be identified and sensitivity testing should be applied to proposed permanent assets or long-term operations with a design life of more than ten years.
- The more exposed, vulnerable or susceptible the asset, the longer its intended design or operational life, or the greater the magnitude of investment involved, the more important it is to test the asset or operation's sensitivity and tolerance to a full range of possible future climates.
- For major, long-term investments, special attention should be paid to how the 'worst case' scenario has been defined: it may be useful to consider location-specific 'unlikely but plausible' scenarios as an upper-bound for sensitivity testing purposes.
- Evaluating multiple climate change scenarios need not involve a cumbersome evaluation of many discrete projections: a relatively small number of carefully-selected representative projections may cover the range of conditions potentially occurring over the project life.
- Joint occurrences (for example, a storm surge plus heavy rainfall plus a spring tide, superimposed upon an increased sea level) will exacerbate effects. Unprecedented conditions may increase the risk of cascading failures where interdependencies exist between interlinked natural and socio-economic systems and sub-systems.
- Such uncertainties can be accommodated in risk assessment and management through probabilistic analysis of the contributing parameters and/or the inclusion of selected groupings or combinations of climate projections.

8.3 Seeking Adaptive Solutions

A range of options should always be considered if effective, efficient and appropriate navigation infrastructure solutions are to be identified.

- Maladaptation can be avoided, and the resilience of critical assets and operations improved, by selecting flexible and adaptive designs that can be modified as conditions change.
- No- or low-regret solutions that deliver benefits irrespective of how the climate changes, and nature-based solutions that capitalise on nature's resilience, both play an important role in accommodating uncertainty.
- Structures and operations prone to failure should be designed to fail gracefully rather than catastrophically, and designs should include measures to manage the consequences of failure.
- Structural solutions are not the only option for reducing climate-related risks. Changes in operations, management, maintenance or behaviours might prove more appropriate or cost-effective than a structural intervention. Institutional change may also form part of a long-term solution.

- The potential consequences for cascading failures in complex, inter-related systems should always be considered; failure to acknowledge such interlinkages can result in maladaptation.

8.4 Accommodating Climate Change Complexities in Evaluating Options

The consequences and costs of inaction need to be properly understood if the benefits of expenditure on improved resilience are to be fully demonstrated.

- Methods used to differentiate between options should be appropriate to the climate change context; in particular, economic assessments that only extrapolate from past experience may no longer be fit-for-purpose if future climate risks are to be incorporated.
- Conventional cost-benefit assessment or net present value calculations may not adequately reflect the complexities of climate change investment even if low discount rates are used.
- In adapting to climate change, difficult-to-quantify social and environmental impacts can be important; attempts should be made to capture these effects to avoid underestimating potentially serious consequences.

8.5 Delivering Resilient Solutions

- Adaptation pathways, describing sequences of actions that can be implemented progressively depending on how the future unfolds, can help deal with uncertainties. Appropriate short-term, interim or temporary interventions might be implemented while longer-term (and sometimes more complex and/or costly) responses are developed.
- Adaptive management is an important concept; a combination of good data and inbuilt flexibility can help avoid maladaptation and deliver resilient solutions: local monitoring helps inform 'just in time' investment decisions as conditions require.

By highlighting these key messages, and by describing good practice in managing the challenges of dealing with climate change uncertainties, this Technical Note explains how an informed, flexible and responsive approach can help reduce risks, avoid maladaptation and deliver appropriate and resilient navigation infrastructure.

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