PIANC

The World Association for Waterborne Transport Infrastructure

WATERBORNE TRANSPORT, PORTS AND WATERWAYS: A 2023 UPDATE OF CLIMATE CHANGE DRIVERS AND IMPACTS

EnviCom Task Group Report N° 3 – 2023

PIANC TASK GROUP N° 3

ENVIRONMENTAL COMMISSION

WATERBORNE TRANSPORT, PORTS AND WATERWAYS: A 2023 UPDATE OF CLIMATE CHANGE DRIVERS AND IMPACTS

October 2023

PIANC has Technical Commissions concerned with inland waterways and ports (InCom), coastal and ocean waterways (including ports and harbours) (MarCom), environmental aspects (EnviCom) and sport and pleasure navigation (RecCom).

This original TG3 report was produced by an international Working Group convened by the Environmental Commission (EnviCom). Members of the Working Group represented several countries and are acknowledged experts in their profession. The update has been prepared by members of PIANC's Permanent Task Group on Climate Change (PTGCC).

The objective of this report is to provide information and recommendations on good practice. Conformity is not obligatory and engineering judgement should be used in its application, especially in special circumstances. This report should be seen as an expert guidance and state-of-the-art on this particular subject. PIANC disclaims all responsibility in the event that this report should be presented as an official standard.

PIANC HQ
Boulevard du Roi Albert II 20 B. 3
1000 Brussels | Belgium

http://www.pianc.org

VAT BE 408-287-945

ISBN 978-2-87223-030-3

TABLE OF CONTENTS

WATERBORNE TRANSPORT, PORTS AND WATERWAYS: A 2023 UPDATE OF CLIMATE CHANGE DRIVERS AND IMPACTS

Update Group Members

Several members of the PIANC Permanent Task Group on Climate Change (PTG CC) contributed to the update of the Task Group 3 which was originally published in 2008. Experience of the members encompassed a broad cross section of pertinent disciplines, including climate change science and adaptation, hydrology and hydraulics, oceanography, port and coastal engineering, infrastructure design and strategic planning in the field of maritime and inland navigation.

Members

Brooke, Jan	Chair, PIANC PTG CC; Director, Jan Brooke Environmental Consultant Ltd, UK
Cox, Ron	Member PIANC PTG CC, EnviCom, CoCom; Hon. Assoc. Prof. Water Research Laboratory UNSW, Australia
Dahl, Travis	Alternate Member PIANC PTG CC; Research Hydraulic Engineer, USACE
Holm, Olli	First Delegate and Chairperson of PIANC Finland, Member PIANC PTG CC, EnviCom and ProCom; Senior advisor, Finnish Transport Infrastructure Agency
Arntsen, Øivind	Member of PIANC PTG CC. Associate Professor in Marine Civil Engineering, Norwegian University of Science and Technology (Retired), Norway
Giovando, Jeremy	Climate Champion, InCom, Research Civil Engineer, USACE
Herbert, Laure	Young Professional PIANC PTG CC; Senior Maritime Engineer, Setec, France
Boersen, Stef	Young Professional PIANC PTG CC, Hydraulic & Coastal Engineer, Royal HaskoningDHV, the Netherlands

ACKNOWLEDGEMENTS

The members of this group would like to thank Brian Joyner, USA, for the excellent technical review and comments. His feedback was very helpful and improved this document substantially.

PIANC'S PERMANENT TASK GROUP ON CLIMATE CHANGE

PIANC's 2019 **Declaration on Climate Change** recognises the importance of the climate change challenge and undertakes to actively pursue the sustainable future of the waterborne transport industry by supporting its members in addressing this challenge.

The goal of the cross-commission Permanent Task Group on Climate Change (PTG CC) is to facilitate the delivery of the commitments made in the PIANC Declaration on Climate Change by:

- Supporting ports, harbours, marinas and inland waterways by sharing knowledge and preparing practical technical guidance to help them manage the climate change challenge Contributing to the global discussion, to ensure that waterborne transport infrastructure interests are properly acknowledged, and to disseminate key messages to PIANC members and the wider port and navigation community, for example via the preparation of guidance.
- Joining forces with other waterborne transport infrastructure stakeholders to meet new challenges, explore opportunities and contribute to a responsible, informed and sustainable way forward.

WATERBORNE TRANSPORT, PORTS AND WATERWAYS: A 2023 UPDATE OF CLIMATE CHANGE DRIVERS AND IMPACTS

Summary

The initial EnviCom Task Group 3 'Climate Change and Navigation' report [PIANC TG 3, 2008] introduced the topic of climate change and explored the then current projections likely to affect ports and waterborne transport infrastructure. It was based on the internationally-agreed assumptions and findings of the 4th assessment report of the Intergovernmental Panel on Climate Change [IPCC AR4, 2007].

Since 2008, IPCC has completed several major new reports including the 5th assessment report [IPCC AR5, 2013], the Special Report on Global Warming of 1.5°C [IPCC SR15, 2018], the Special Report on the Ocean and Cryosphere (SROCC) in a Changing Climate [IPCC SROCC, 2019] and the 6th assessment report [IPCC AR6, 2021].

The assumptions, definitions and findings of the various IPCC reports represent a peer-reviewed body of knowledge that identifies how climate has changed during the 20th and early 21st century, and projects future changes. The IPCC reports discuss future climate change effects within a framework of greenhouse gas emissions and concentrations scenarios, originally called Representative Concentration Pathways (RCPs) and, more recently, Shared Socio-economic Pathways (SSPs). By relating future climate change effects to such scenarios, unknowns including future decisions by policy makers and uncertainties in the climate system can be accommodated. As it is not known which of the RCPs and/or SSPs will be realised, it is always good practice to consider future climate change effects and their impacts as ranges instead of absolute values.

Among the headline findings of the various IPCC reports are the following:

Rates of air/sea surface temperature change, magnitude of total air/sea surface temperature and ocean acidity will typically increase whilst oxygen levels in water will typically reduce.

Sea levels will continue to rise at an increasing rate in most areas: projections for 2100 include a global mean sea level rise of at least 1 m in many parts of the world and this trend is projected to continue into the future in all climate change scenarios.

Climate change is already affecting weather and climate extreme events in every region across the globe: extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones will become more intense and/or frequent.

Even if emissions of greenhouse gases (especially carbon dioxide CO_2) were to stop today, many of these effects would continue for decades, and sea level rise will continue for centuries.

Many of the climate-related changes that matter most to ports and waterways are driven by changes in temperature. Rising air and water temperatures will not only affect seasonal precipitation, sea level and the frequency and severity of extreme events but also winds and waves; storms and surges, hydrodynamics and morphology, and the chemical and biological characteristics of water bodies .

This report updates PIANC TG 3 (2008) with the improved climate change knowledge as of late 2022. The update reviews, and presents an overview of the key messages regarding, the projected climate change impacts on maritime and inland navigation including from changes in air and water temperature, sea level rise, wind conditions, wave action, tidal and surge propagation and range, ocean circulation, storms, coastal hydrodynamics, ice conditions, icing, water supply and quality in inland rivers, extreme hydrological conditions, and coastal, estuarine and river morphology. Relevant chemical and biological changes and their potential implications for navigation are also discussed . The need for adaptation responses and measures to strengthen resilience is highlighted.

Navigation contributions to greenhouse gas (GHG) emissions are also briefly reviewed, along with opportunities for navigation to contribute to overall reductions in anthropogenic GHG emissions.

1 THE STARTING POINT FOR THIS REVIEW

1.1 Global Climate Change

Significant changes in climate and their impacts are already visible regionally and are expected to become more pronounced in the next decades. Since the industrial age, a global average temperature increase of about 0.85°C occurred over the period between 1880 to 2012 (Figure 1.1, top); and the regional variability for both land and ocean temperature was already evident.

The original PIANC TG 3 report was based on the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) published in 2007. The assumptions, definitions and findings of the subsequent IPCC reports [IPCC AR5, 2013 ; IPCC SR15, 2018 ; IPCC SROCC, 2019 ; IPCC AR6, 2021] are taken as the basis for this update to the original TG 3 report.

It should be noted that the IPCC reports discuss future climate change effects within a framework of greenhouse gas emissions and concentrations scenarios, originally called Representative Concentration Pathways (RCPs) and, more recently, Shared Socio-economic Pathways (SSPs). By relating future climate change effects to such scenarios, unknowns including future decisions by policy makers and uncertainties in the climate system can be accommodated. As it is not known which of the RCPs and/or SSPs will be realized, it is always good practice to consider future climate change effects and their impacts as ranges instead of absolute values.

The effect of anthropogenic contributions to global temperature increases are shown in (Figure 1.1, top). There are regional differences for observed temperature increases, however in all areas the land and ocean temperatures are elevated above those which would have occurred with only natural forcings. Notwithstanding the significant improvements in climate science and modelling with each progressive IPCC report, there are still many inherent uncertainties in climate projections. These uncertainties become much wider when translated into the potential impacts on a specific sector, such as navigation. Projections for 2100 suggest that temperature will rise by between 0.3 to 5.3°C relative to the 1986-2005 levels for the range of selected RCP scenarios[1] (Figure 1.1, bottom,).

The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [IPCC SROCC, 2019] is particularly relevant to the navigation sector as it specifically looks in detail at oceans and the cryosphere (sea and land ice). Global mean sea level (GMSL) is rising, with acceleration in recent decades due to increasing rates of ice loss from the Greenland and Antarctic ice sheets (very high confidence), as well as from continued glacier mass loss and ocean thermal expansion. Increases in winds and rainfall, and increases in extreme waves, combined with relative sea level rise, exacerbate extreme sea level events and coastal

[1] RCP scenarios: Representative Concentration Pathways are different future scenarios of human emissions of greenhouse gases leading to levels of radiative forcing (in Wm^{-2}) in the year 2100. Four low to very high RCP scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5) are included in IPCC AR5, IPCC SR15, and IPCC SROCC.
The most recent IPCC AR6 (2021) includes 5 different scenarios named as Shared Socio-economic Pathways each encompassing a range of radiative forcing in the year 2100. These range from a low SSP1-1.9 to very high SSP5-8.5 scenario. For further information see: **https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html**.
Box SPM.1, Table 1: Description and relationship of scenarios and modelled pathways considered across AR6 Working Group reports in the Summary for Policymakers at **https://www.ipcc.ch/report/ar6/syr/** illustrates the relationship between the RCPs and the more recent SSPs.

hazards (high confidence). Figure 1.2 (from IPCC SROCC (2019), Figure SPM-1) summarises some of the important climate and system projected responses:

The rates of air/sea surface temperature change, magnitude of total air/sea surface temperature and ocean acidity will increase whilst oxygen level decreases. The cryospheric changes are projected to increase in the second half of the 21st century if a high GHG emissions scenario (RCP8.5) is realised. Conversely, realisation of strong reductions in greenhouse gas emissions (under RCP2.6) in the coming decades would reduce further changes after 2050.

Sea level will continue to rise at an increasing rate, and this trend is projected to continue into the future. For a high emissions scenario (RCP8.5), projections of global mean sea level rise by 2100 are greater than in AR5 [IPCC AR5, 2013] due to a larger contribution from the Antarctic Ice Sheet. In coming centuries under RCP8.5, sea level rise is projected to exceed rates of several centimetres per year resulting in a rise of 2.3 to 5.3 m in 2300. In contrast, for RCP2.6 sea level rise is projected to be limited to around 1 m in 2300.

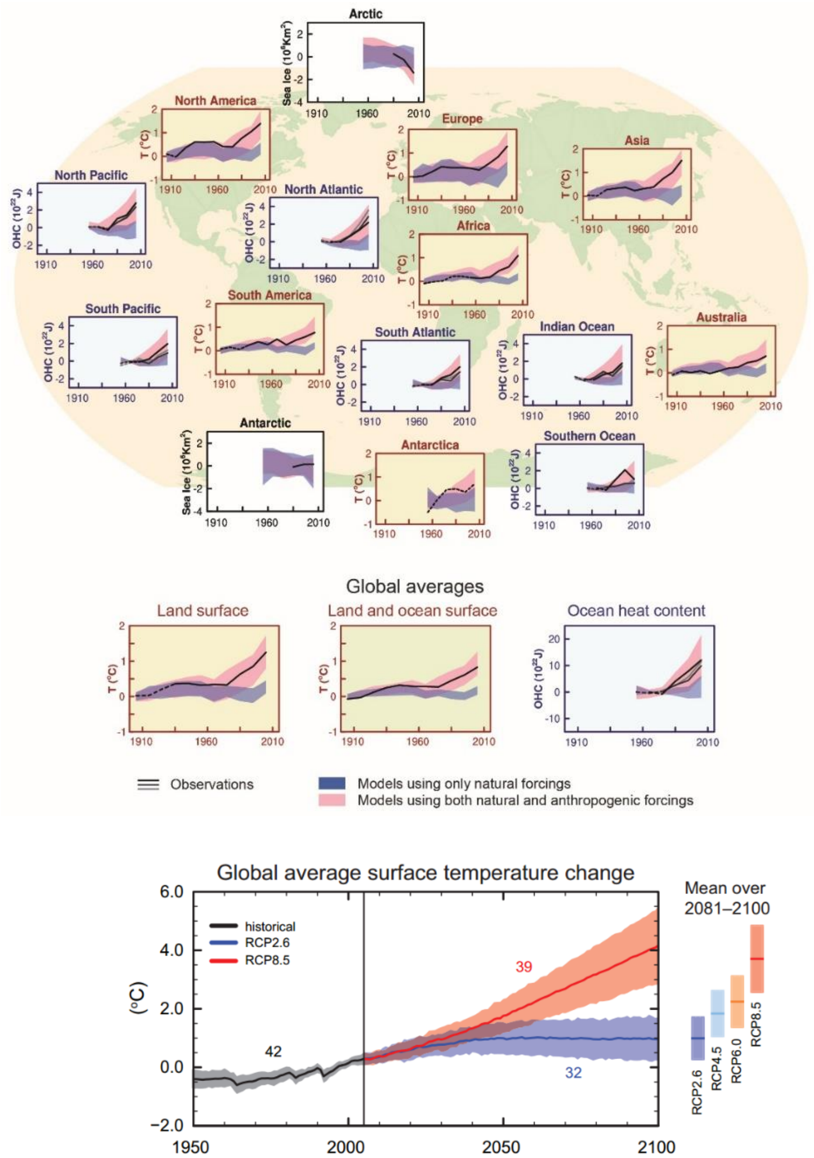


Figure 1.1: Observed temperatures and Ocean Heat Content (OCH) (top) and Simulated time series from 1950 to 2100 for global annual mean surface temperature (bottom) due to climate change (reproduced from Figures SPM.6 and SPM.7(a) of AR5, SPM [IPCC AR5, 2013])

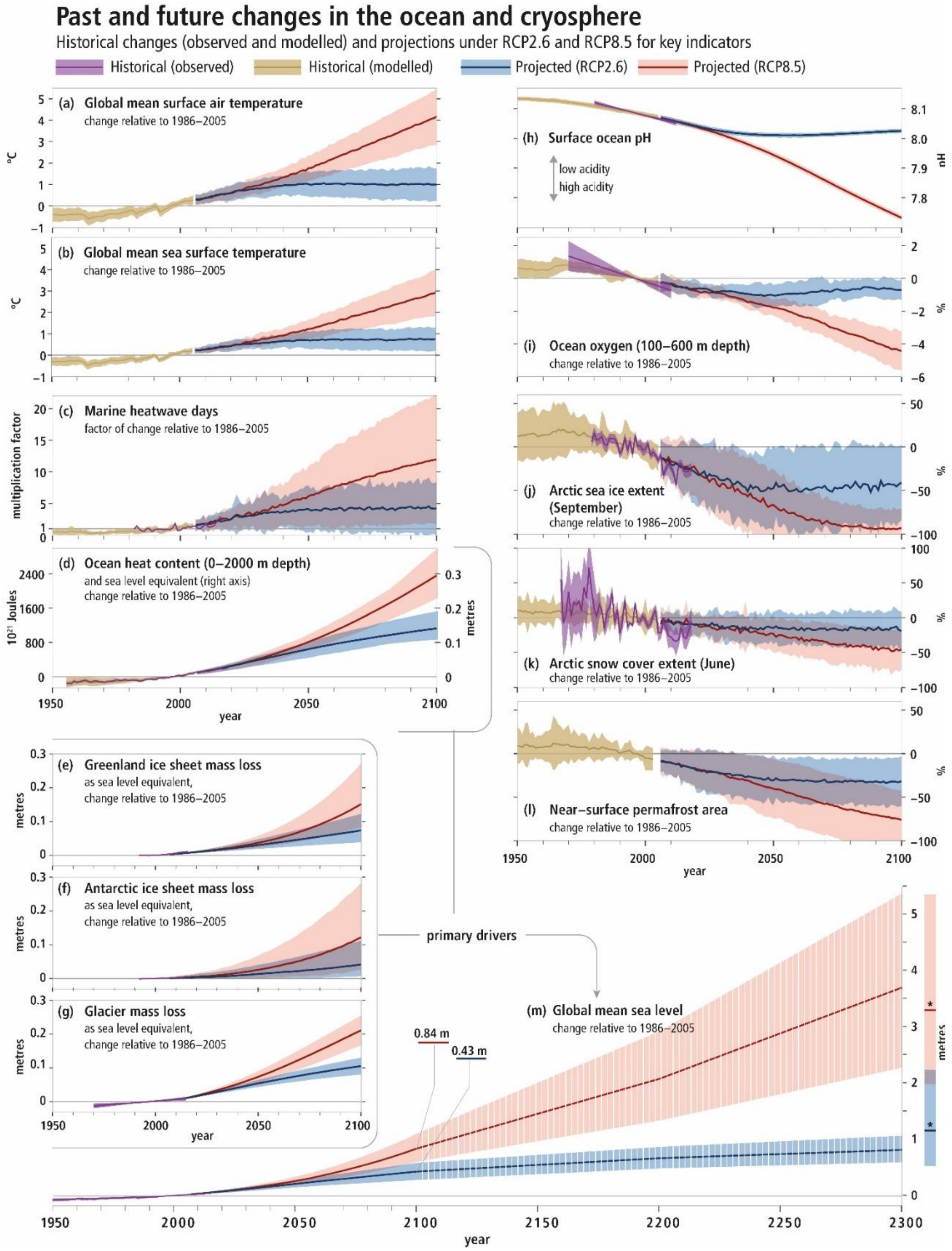


Figure 1.2: Past and future changes in the oceans and cryosphere (reproduced from IPCC SROCC (2019), Figure SPM-1)

Furthermore, climate change is already affecting many weather and climate extremes in every region across the globe. The IPCC AR6 synthesis report (**https://www.ipcc.ch/report/ar6/syr/**) confirms that, with every additional increment (degree) of global warming, changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones will become larger. Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation, and very wet and very dry weather and climate events and seasons (high confidence).

1.2 Carbon Management

Historically much of the work related to GHG emissions has been focused on quantifying the amounts emitted by various industries and activities. Of the anthropogenic emissions, transport is responsible for about 14 % of energy related GHG emissions; navigation/shipping contributes about 12 % of the transport component or about 2 % of the total anthropogenic emissions [IPCC AR5 2014c ; SLOCAT, 2021]. A significant proportion of these emissions come from shipping, but there are also GHG emissions associated with the development and operation of waterborne transport infrastructure.

Although global quantification of GHG is an important first step, mitigation measures to reduce emissions from infrastructure will be implemented by individual infrastructure owners and operators. From that perspective, a carbon management plan should be considered for new and existing infrastructure. To develop such a plan, guidance has been provided in the PIANC WG 188 (2019) report 'Guide on Carbon Management for Port and Navigation Infrastructure'. WG 188 provides a framework and useful estimates of emissions from waterborne transport, ports, and waterways. Using this framework, estimates of direct and indirect emissions sources form defined boundaries. The direct emissions sources include sources directly under the control and operations of the infrastructure owner entity (e.g. fleet vehicles, buildings, locks, etc.). Indirect sources consist of both energy (e.g. electricity) used by the infrastructure as wells as emissions that are a result of raw material processes that are needed to design, build and operate the facility (e.g. forging steel to build a ship, mining copper, etc.). An important step when estimating emissions is determining geographic boundaries to use within the framework. In addition, all infrastructure lifecycle components should be included (i.e. design, construction, use, and end-of-life). WG 188 has detailed descriptions of each step in developing a carbon management plan for waterborne infrastructure.

1.3 Climate Change Impacts and Responses

Climate change has a real impact not only on ecosystems [PIANC WG 195, 2021] and biodiversity but also on human life and many economic activities including navigation. Consequently, the current discussion in science and policy is not about if climate change is happening but about how fast it is going to progress and about the vulnerability of both natural and anthropogenic systems on Earth. There are international as well as national strategies and policies in force to minimise the anthropogenic influence on climate change (Montreal Protocol [United Nations, 1987], Kyoto Protocol [United Nations, 1998] and the 2015 Paris Agreement [UNCC, 2018]). Their goal is to reduce emissions, adapt to unavoidable changes, reduce damage, and realise opportunities associated with climate change. Against this background it is necessary and timely to consider the vulnerability of navigation and related infrastructure, and to develop adaptation strategies for this sector to be prepared for climate change.

2 NEED FOR AND APPROACH TO THIS REPORT

2.1 Need

The IPCC takes the global lead on assessing and summarising information on past and future climate change. Individual countries or sectors then focus on their particular interests, with the aim of providing specific guidance on climate change issues for actual use within that country or sector. For example, the United Kingdom Climate Impacts Programme organises and reports in more detail for UK interests[2], whilst keeping faith with IPCC approaches and conclusions. Another example is the U.S. Global Change Research Program which delivers a report to the U.S. Congress and President every four years summarising the observed climate changes and effects on a range of national focus areas (e.g. agriculture, energy production, human health and welfare, etc.). The 'Fourth National Climate Assessment', summarises how climate change is affecting weather and climate across the country [USGCRP, 2018][3].

While international and national guidance is often multi-sectoral, PIANC's responsibility is to the special interests of the navigation sector. As several updated IPCC reports have been released since PIANC published its original TG 3 report, it is timely for PIANC to update its position and recommendations regarding climate change. This report therefore focuses on climate change issues relevant to navigation and ports and other waterborne transport infrastructure.

A.

In the meantime, other relevant, recently published PIANC Working Group reports have included:

- PIANC WG 188 (2019): "Carbon Management for Port and Navigation Infrastructure".
- PIANC WG 175 (2019): "A Practical Guide to Environmental Risk Management (ERM) for Navigation Infrastructure Projects".
- PIANC WG 178 (2020): "Climate Change Adaptation Planning for Ports and Inland Waterways".
- PIANC TG 193 (2020): "Resilience of the Maritime and Inland Waterborne Transport System".
- PIANC WG 195 (2021): "An Introduction to Applying Ecosystem Services for Waterborne Transport Infrastructure Projects".
- PIANC WG 203 (2021): "Sustainable Inland Waterways: A Guide for Inland Waterway Managers on Social and Environmental Impacts".
- PIANC PTG CC Technical Note 1 (2022): "Managing Climate Change Uncertainties in Selecting, Designing and Evaluating Options for Resilient Navigation Infrastructure".

Further Working Groups and other activities on climate change issues specific to the inland, maritime and recreational sectors are also planned.

For inland navigation, climate change could exacerbate existing issues of reliability, and it may pose an existential challenge for some facilities. A small change in the level (up or down) of

---

[2] https://www.ukcip.org.uk/

[3] https://nca2014.globalchange.gov/

water in rivers, estuaries and ports, for example due to a shift in seasonal precipitation patterns, may affect the number of days per year that a waterway can be used without restriction. For industries using inland waterways as the primary mode of transportation for their goods, climate change is therefore a fundamentally important question, not only for navigation infrastructure but for the future location of certain production facilities.

For both inland and maritime navigation, extreme weather conditions can be directly linked to hazardous conditions which cause damage to infrastructure and the environment. Such conditions can also disrupt operations such as pilotage and berthing with consequences for sea/land side supply chains. Extreme heat or inundation can provide challenges for port estate operations.

Maritime navigation has always been sensitive to storminess and wind/wave conditions, and also to sea level in ports, but climate change introduces new challenges and uncertainties [PIANC, 2022]. A risk analysis of climate change impacts including coastal flooding, sea level rise, and heat stress under a high-end warming scenario on the operation of more than 2,000 ports worldwide [Izaguirre et al., 2021] concluded that – in the absence of adaptation – the number of ports at high, very high or extremely high risk will increase significantly by 2100.

In a survey of international ports by UNCTAD (2017), the impacts of climate changing parameters were identified against categories of port assets and operations. The survey, although limited to 44 respondent ports, highlighted the growing impacts of winds, precipitation and storm surge on ship and terminal operations (see Figure 2.1).

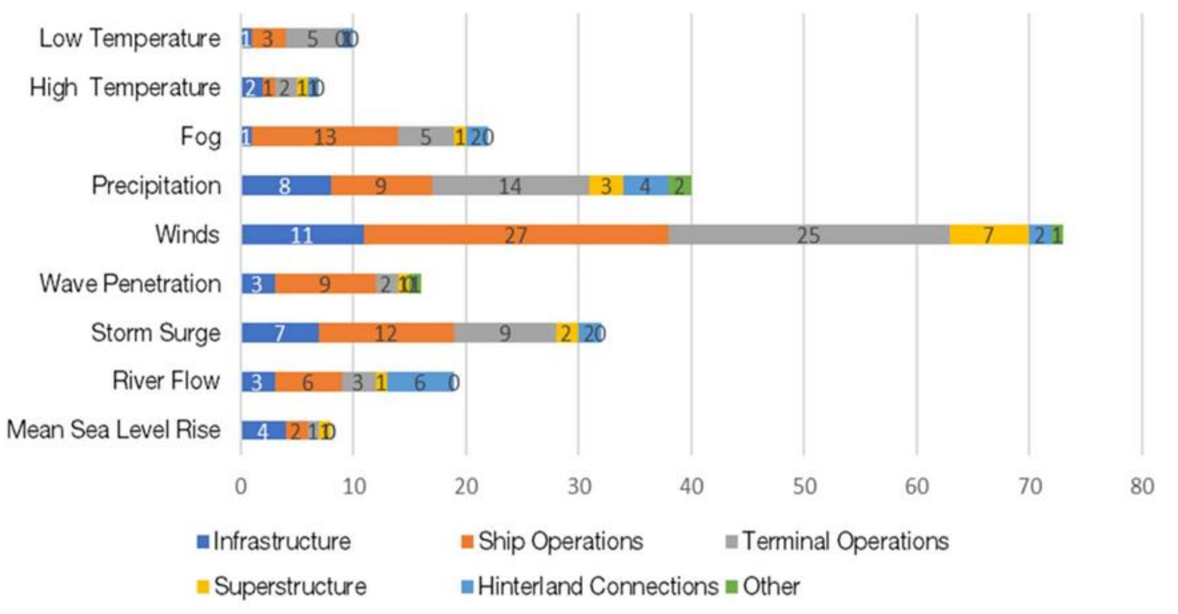


Figure 2.1: Impact of climate factors on port infrastructure, operations and services – Number of respondent ports – (reproduced from UNCTAD (2017), Figure 3.3)

Ports and waterways therefore need to prepare, and where necessary adapt their infrastructure, facilities and operations as well as navigational equipment and in some cases the vessels themselves, to be able to continue to operate successfully in the future.

2.2 Terms of Reference

In line with the original TG 3 Terms of Reference, this updated report informs the reader about how navigation may be affected by climate change and in what fields action will have to be taken to guide investment decisions, inform infrastructure design and operation, and develop adaptation strategies in a proactive way.

The updated report covers the following topics:

- Discussion of the latest climate science, climate model projections and relevance of climate change to maritime and inland navigation.
- Examples of where climate change already creates problems for navigation and how the changing climate might be expected to continue to impact maritime and inland navigation, including examples of some of the responses required to prepare the navigation sector for the projected climate scenarios. These are provided with the aim of strengthening resilience and adapting navigation infrastructure, equipment and operations for future sustainability, some aspects of which are also elaborated in other PIANC reports.
- A short summary of the content of PIANC WG 178 on Climate Change Adaptation Planning (2020) and of WG 188 on Carbon Management (2019). The latter provides an overview of how the navigation sector should contribute to reduce GHG emissions and support navigation as an environmentally sound and sustainable mode of transportation.

This updated TG 3 report adopts the established IPCC and PIANC terminologies for climate change and navigation. This includes the definition of 'climate change' as referring to change in climate over time, whether due to natural variability or as a result of human activity.

2.3 Review of Pertinent Literature

Although large-scale climatic processes are driven by the ocean-atmosphere exchange system, few studies are available on maritime impacts compared to continental (land-based) impacts. This is due to generally shorter data series on maritime impacts as well as fewer human consequences observed relative to the latter impacts. Coastal issues, port vulnerability and effects on low-lying coastal areas are relatively better documented and studied as well as hydrologic evolution of some large river basins. Nonetheless, many impacts on navigation still have to be deduced from research undertaken in specific fields (e.g. coastal risks, water supply, nuclear plant protection) and more generally from the IPCC Working Group II report[4], which assesses impacts, adaptation and vulnerabilities related to climate change.

The schematic shown in Figure 2.2 depicts some of the main potential climate change impacts on navigation-related activities and infrastructure.

[4] **https://www.ipcc.ch/working-group/wg2/**

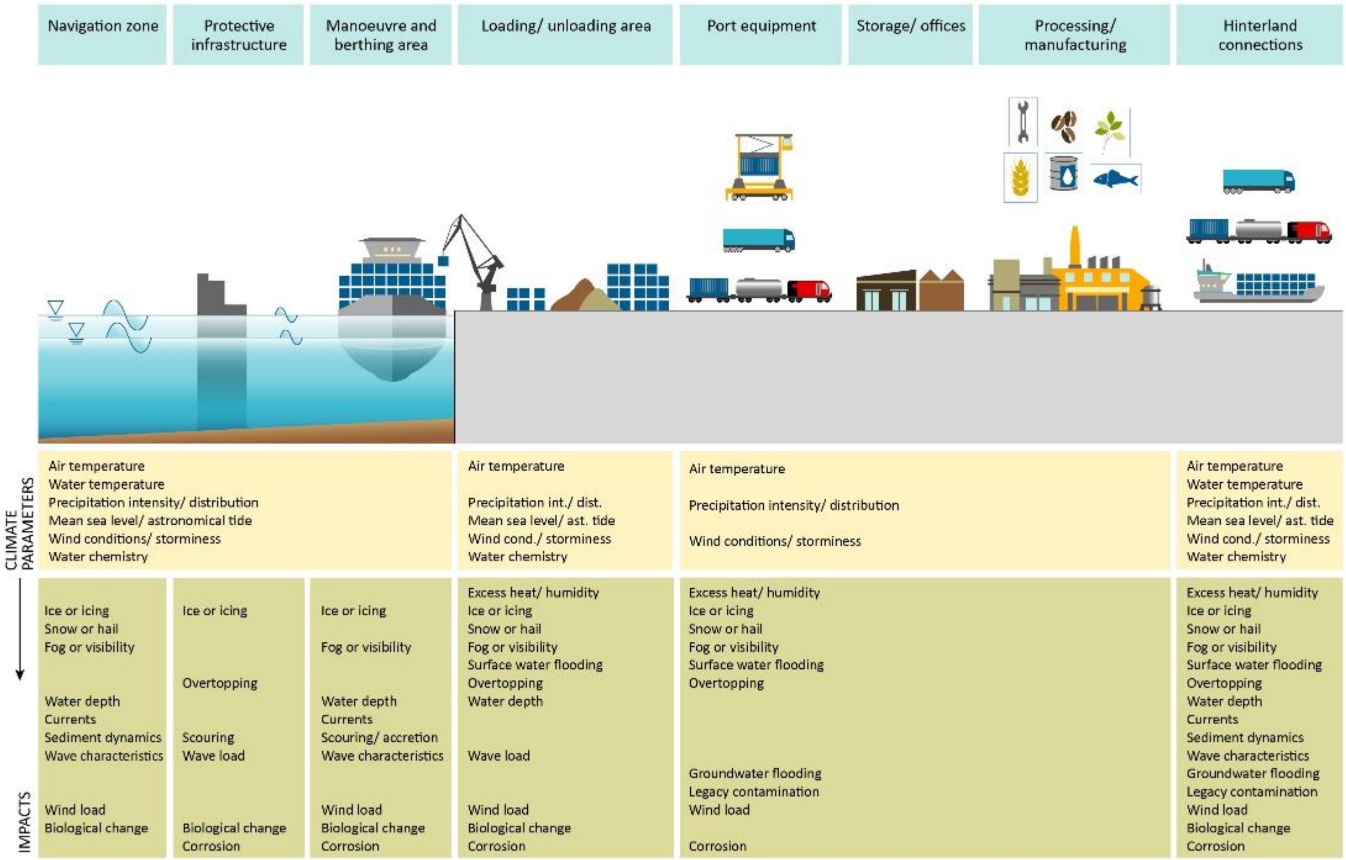


Figure 2.2: Interactions between climate parameters and processes and representative port assets and operations (reproduced from PIANC WG178 (2020))

2.3.1 Understanding Climate Change Scenarios and Projections

It is important for the navigation community to understand the use of global climate change scenarios developed and applied by IPCC and other researchers; the spatial variability of observed and projected impacts; and the uncertainties inherent in both trend analysis and projections.

For its fifth Assessment Report [IPCC AR5, 2013] and following IPCC SR15 (2018), IPCC SROCC (2019), IPCC presents climate change scenario projections in terms of Representative Concentration Pathways (RCPs). The RCPs present emissions target levels for 2100 and comprise four scenarios which include: a mitigation scenario leading to a low forcing level (RCP2.6), two medium stabilisation scenarios (RCP4.5/RCP6) and one high forcing level emission scenario (RCP8.5). The RCPs are represented as alternative emissions of global greenhouse gas and aerosol concentrations and are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (i.e. RCP8.5 represents a radiative forcing of 8.5 Watts/m^2 in 2100). A study by Gasser et al., (2015) suggests that in order to limit emissions to the RCP2.6 scenario we must reduce the net amount of CO_2 we release into the atmosphere, either by producing significantly less CO_2 (conventional mitigation) or by capturing more CO_2 (negative emissions). IPCC SR15 (2018) examined in further detail the opportunities and steps necessary to limit global mean temperature increase to 1.5°C above pre-industrial levels.

The most recent IPCC sixth Assessment Report [IPCC AR6, 2021] adopts five different scenarios named as Shared Socio-economic Pathways (SSP) each encompassing a range of radiative forcing in the year 2100. These range from two low scenarios SSP1-1.9 and SSP1-2.6 to a very high SSP5-8.5 scenario. The model projections for the SSP1-2.6, SSP2-4.5 and SSP5-8.5 are closely related to those for the earlier report projections for RCP2.6, RCP4.5 and RCP8.5 respectively[5].

This TG 3 updated report continues to use figures and information that reference RCPs from previous studies to convey the potential impacts on navigation. This is because, at the time of preparing this update, the SSPs are yet to be used/referenced in much of the climate change literature. In any case, both the RCPs and the SSPs underline the importance of considering a range of scenarios to reflect the outstanding uncertainties about exactly how much and how quickly the climate will change.

Under current circumstances (and without both substantially increased carbon reduction targets under the Paris Agreement [UNCC, 2018] and accelerated development of negative emission technologies) neither the RCP2.6 nor the 1.5°C warming targets are likely to be achieved. In 2023, many players in the wider transport sector are therefore using RCP4.5 rather than RCP2.6 as the starting point for climate impact assessments. In planning for climate change, however, it is important that decision making includes sensitivity testing of outcomes to the full range of possible scenarios and over various time periods.

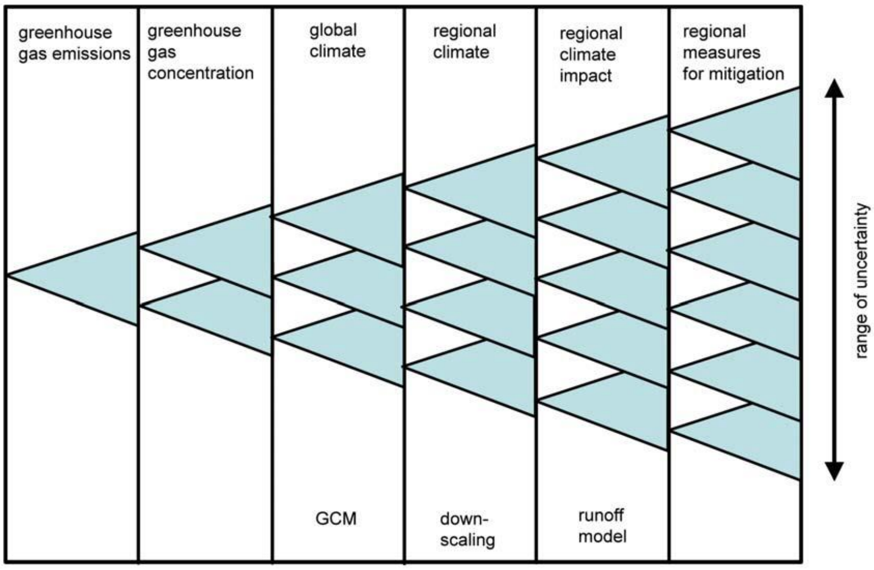
2.3.2 Understanding Uncertainty in Climate Change Projections

IPCC has invested considerable time and effort in developing a consistent framework and specific language to describe uncertainties, including both value and structural uncertainties. This information is presented both in an IPCC Uncertainty Guidance Note [WMO and UNEP, 2005] and in the various IPCC working group reports. In this process, they have drawn a careful distinction between levels of confidence (ranging from very low to very high confidence, being less than 1 out of 10 chance to at least 9 out of 10 chance, respectively) in scientific understanding and the likelihoods of specific results (ranging from exceptionally unlikely < 1 % probability to virtually certain > 99 % probability). In view of the international peer review of IPCC uncertainty guidance, PTG CC has adopted the same terminology in its discussion of climate impacts. For the exact definitions of the different levels of confidence, reference should be made to IPCC AR5 (2013).

The navigation community should work with the climate researchers to incorporate and to understand the propagation of uncertainty from GHG forcing, through climatological variables, to navigation related variables (Figure 2.3, top) when considering impacts, responses, vulnerabilities, and opportunities. Thus, complexity and uncertainty may be inversely related to spatial scale (Figure 2.3, bottom) but proportional to scientific understanding of processes. This is demonstrated in the upper line showing the significant increase in uncertainty with the complexity of process for projections of temperature to sea level rise, winds, waves and sediment transport to water quality and finally ecosystem function.

---

[5] Further information about the relationship of the RCP and SSP modelled pathways is presented in Box SPM.1, Table 1 of the AR6 Synthesis report, see **https://www.ipcc.ch/report/ar6/syr/**



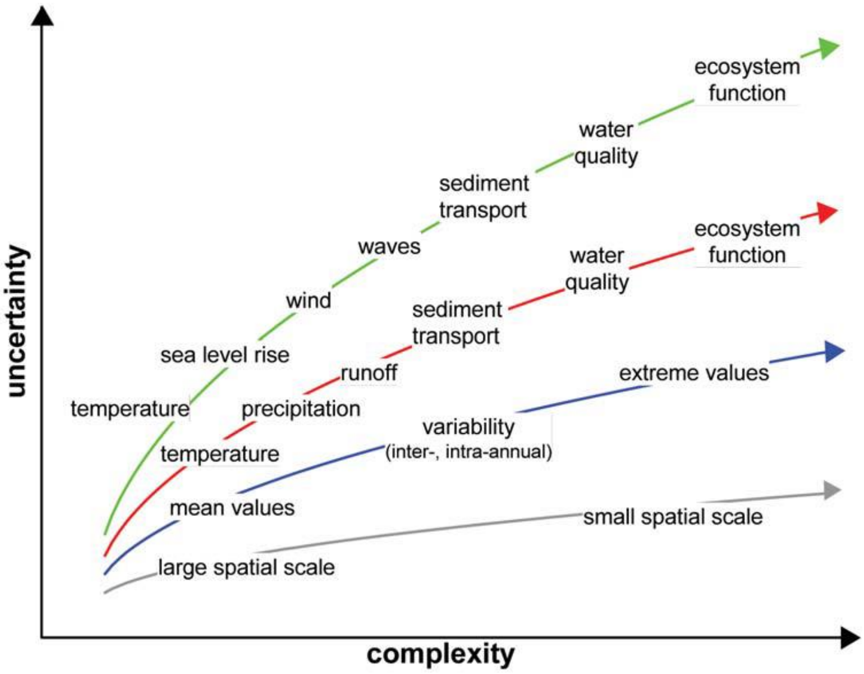


Figure 2.3: Illustrations of the spread of uncertainties: (top) from greenhouse gas forcing to navigation; (bottom) a red curve representing inland navigation issues and a green curve representing maritime navigation issues [IPCC AR4, 2007]

Furthermore, Figure 2.4 (reproduced Chapter 12 of IPCC AR5 (2013)) reveals that there are significant differences in regional projections between the scenarios. The figure shows projected surface temperature changes for the early and late 21st century relative to the period 1986-2005. Models agree on large-scale patterns of warming at the surface, for example, that the land is going to warm faster than oceans, and the Arctic will warm faster than the tropics. However there are inevitable uncertainties in future external forcings, and the climate system's response to them, which are further complicated by internally generated variability. The use of multiple scenarios and models have become a standard choice in order to assess and characterise them, thus enabling consideration of a wide range of possible future evolutions of the Earth's climate. The trends in projected change and likely impacts are important – more so than taking model projections as absolute due to the remaining uncertainties in pathways and complex modelling assumptions.

The PIANC PTG CC Technical Note 1 (2022) on 'Managing Climate Change Uncertainties' elaborates on how climate change scenarios can be selected, and sensitivity testing applied, in identifying, designing and evaluating options for resilient navigation infrastructure. Such an approach helps to ensure timely investment and to minimise risks such as stranded assets.

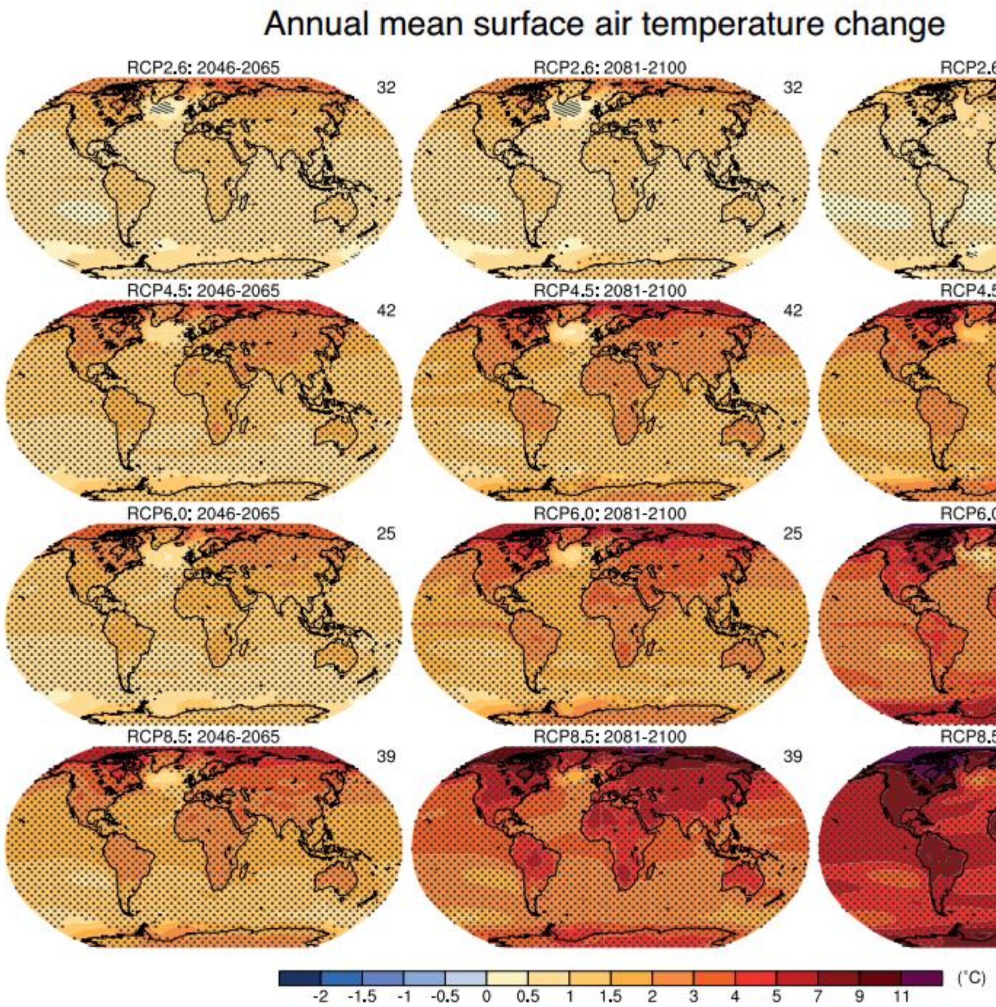


Figure 2.4: Global mean temperature change (relative to 1986-2005), illustrating uncertainties between models and between scenarios (reproduced from IPCC AR5 (2013), Figure 12.11). The figure shows the multi-model ensemble average of surface air temperature change (compared to 1986-2005 base period) for 2046-2065, 2081-2100, 2181-2200 for RCP2.6, 4.5, 6.0 and 8.5. Hatching indicates regions where the multi-model mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean change is greater than two standard deviations of internal variability and where at least 90 % of the models agree on the sign of change. The number of CMIP5 models used is indicated in the upper right corner of each panel.

3 MARITIME NAVIGATION

3.1 Drivers of Change Relevant to Maritime Navigation

Most of the drivers discussed in this section are common meteorological and oceanographic (MetOcean) variables such as temperature, rainfall/precipitation, wind, waves, sea level and ice. Some are more complex geographical response variables such as ocean circulation or estuarine morphology; others are related to water chemistry and ecology (e.g. related to habitat suitability for native, non-native or commercially fished species and wider protected area designations). The common features of these drivers are that they are outside the control of the navigation sector, might be subject to climate change, and increasingly are likely to impact upon navigation.

3.1.1 Air and Water Temperature

Globally, air temperatures are rising. The extent of warming will depend on a variety of factors as discussed in Section 2.3.1. Figure 2.4 illustrates the range and regional variability of anticipated change in surface air temperatures. As air temperature increases, so does the temperature of the oceans. IPCC SROCC (2019), as illustrated in Figure 1.2, shows the rates and magnitudes of air/sea surface temperature increases, ocean acidity increases, oxygen level decreases and cryospheric changes are projected to increase in the second half of the 21st century in a high greenhouse gas emissions scenario (RCP8.5). Conversely, if strong reductions in GHG emissions (RCP2.6) are achieved in the coming decades, this would reduce the magnitude of further changes after 2050.

IPCC SROCC (2019) concluded it is virtually certain that the global ocean has warmed unabated since 1970 and has taken up more than 90 % of the excess heat in the climate system (high confidence). Since 1993, the rate of ocean warming has more than doubled (likely). Marine heatwaves have very likely doubled in frequency since 1982 and are increasing in intensity (very high confidence). Figure 3.1 presents the variation in annual mean temperature change across the world's oceans and land masses for global warming levels 1.5°C, 2°C and 4°C. The IPCC AR6 (2021) best estimate of 2100 future global average temperature is 3°C with a likely range of 2.5°C to 4°C (high confidence). This compares to the description of a range of 1.5°C to 4.5°C in (IPCC AR5, 2013) which did not provide a best estimate. The important message found in both AR4 and AR5 and repeated in Figure 3.1 (from AR6) is the significant spatial variation in future temperature increases.

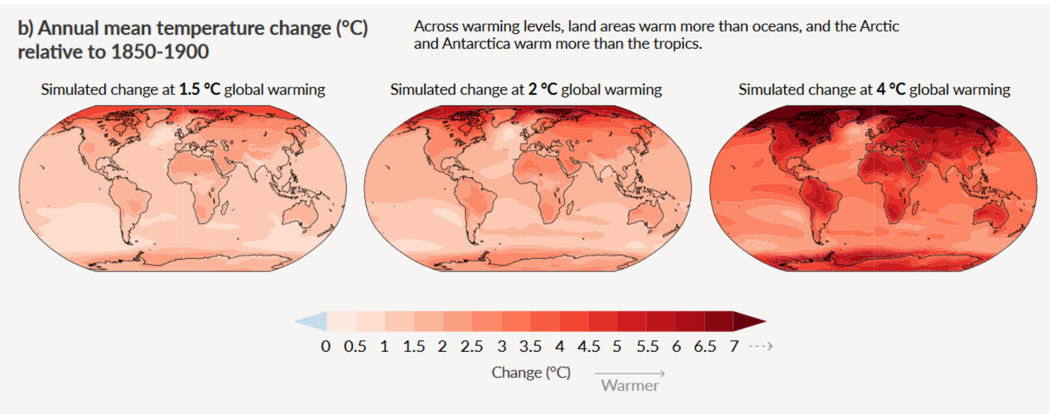


Figure 3.1: Simulated annual mean temperature change (°C) at global warming levels of 1.5°C, 2°C and 4°C (20-yr mean global surface temperature change relative to 1850-1900) – Reproduced from IPCC AR6 (2021), Figure SPM.5b

3.1.2 Sea Level

Chapter 3 of IPCC AR5 (2013) concluded it is very likely that global mean sea level has risen at a rate of 1.7 [1.5 to 1.9] mm/year between 1901 and 2010 and has increased to 3.2 [2.8 to 3.6] mm/year between 1993 and 2010. The IPCC AR5 (2013) climate model projections for sea level rise are similar to those of IPCC AR4 (2007) and suggest, as shown in Figure 3.2, that the global average rate of rise over the 21st century will be 2-5 mm/year. The observed records in Figure 3.2 highlight variability of 0.1 to 0.2 m in the observed annual mean sea levels. It has also been highlighted that there is significant spatial and seasonal variability in observed and projected changes in sea level.

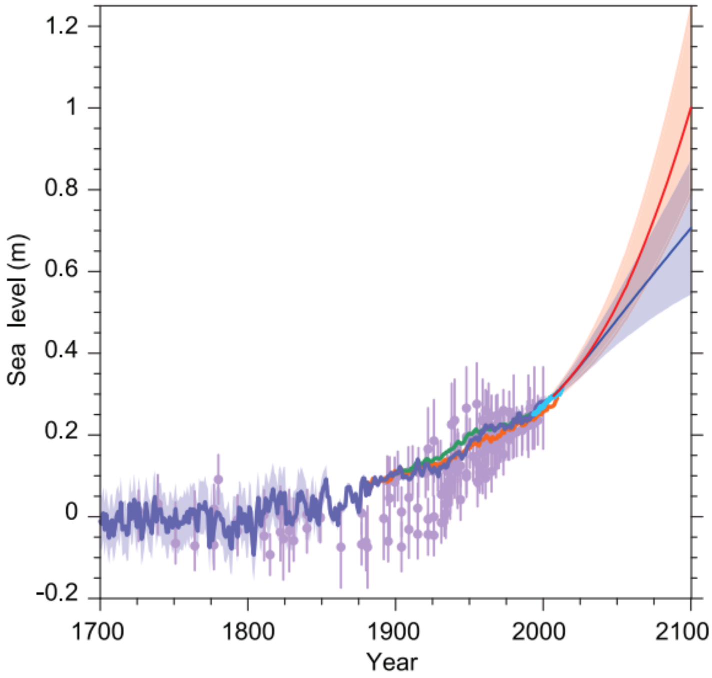


Figure 3.2: Observed and projected sea level rise relative to pre-industrial values (reproduced from Chapter 13 of IPCC AR5 (2013)). The figure illustrates a compilation of paleo sea level data, tide gauge data, altimeter data and central estimates and likely ranges for projections of global mean sea level rise for RCP2.6 (blue) and RCP8.5 (red) scenarios, relative to pre-industrial values.

In the more recent and more detailed IPCC SROCC (2019) (see Figure 1.2), sea level is projected to continue to rise at an increasing rate. Extreme sea level events that are historically rare (once per century in the recent past) are projected to occur frequently, up to once per year, at many locations by 2050 in all RCP scenarios, especially in tropical regions. The increasing frequency of high water levels can have severe impacts in many locations depending on exposure. Sea level rise is projected to continue beyond 2100 in all RCP scenarios. For a high emissions scenario (RCP8.5), projections of global mean sea level rise by 2100 are greater than in IPCC AR5 (2013) due to a larger contribution from the Antarctic Ice Sheet. In coming centuries under RCP8.5, sea level rise is projected to exceed rates of several centimetres per year resulting in a multi-metre rise, reaching 2.3 to 5.3 m in 2300. In contrast, for RCP2.6 sea level rise is projected to be limited to around 1 m in 2300. IPCC AR6 (2021) includes sea level rise projections from IPCC SROCC (2019).

When considered in combination with other factors like land subsidence and glacial isostatic adjustment (GIA), sea level rise relative to the land will be highly localized. At mid latitudes the mean sea level rise will be generally higher than in the equatorial area [IPCC AR5, 2013] due to changes in ocean density distribution (steric sea level rise). In upper Canada, and Norway glacial rebound is almost a metre per century (see Figure 3.3) meaning that the land is rising faster than the sea level, resulting in a net sea level fall. Therefore, it is important to note that relative sea levels will not rise uniformly around the world. Regional and local sea level changes will always need to be assessed for planning and design purposes.

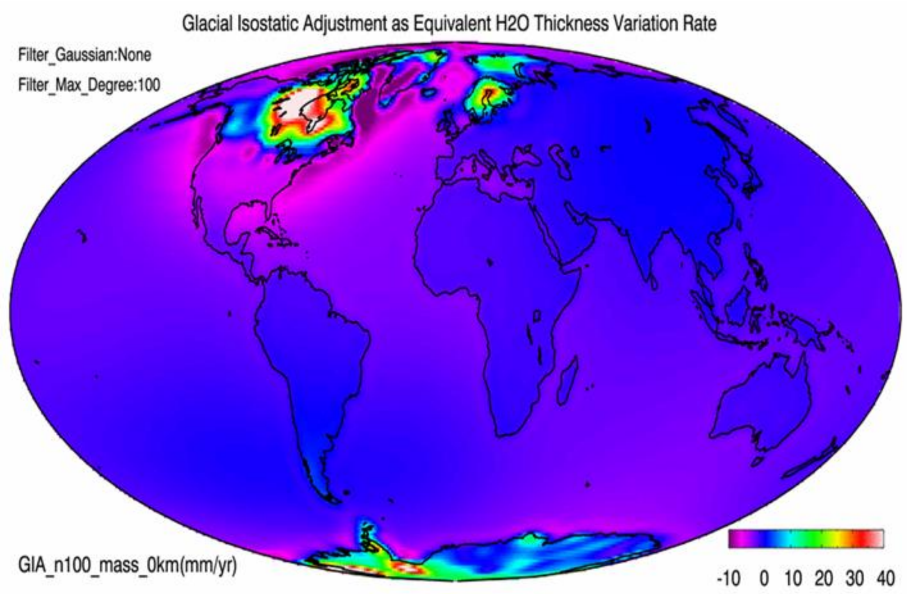


Figure 3.3: Spatial distribution of GIA rates (mm/yr of equivalent water), adjusted for actual water level changes (reproduced from Wahr and Zhong (2013))

Rising sea levels have significant repercussions, particularly when they coincide with extreme tide or storm surge events. Extreme water levels can lead to sea water encroaching onto public and private assets and impacting hinterland connections and landside supply chains, including via roads and rail [McEvoy and Mullett, 2013].

IPCC SROCC (2019) includes probability analysis for extreme sea levels events for several regionally varying locations – as indicated in Figure 3-4 reproduced from Figure 4.11 of IPCC SROCC (2019). This type of analysis provides very useful sea level design information for coastal port locations.

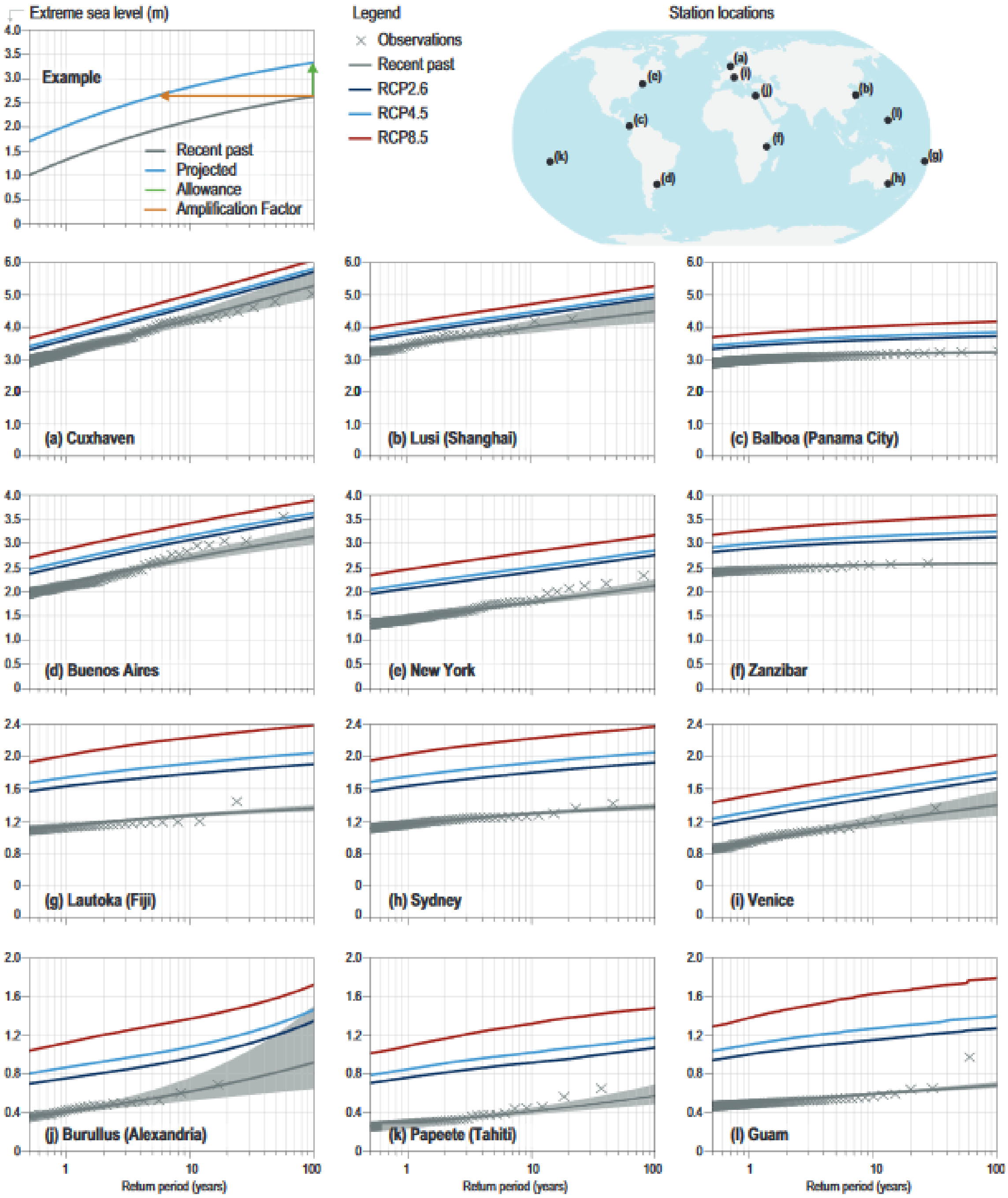


Figure 3-4: The relation between expected extreme sea level (ESL) events and return period at a set of characteristic tide gauge locations (see upper left for their location), referenced to recent past mean sea level, based on observations in the GESLA-2 data base (grey lines) and 2081-2100 conditions for three different RCP scenarios. The grey bands represent the 5-95 % uncertainty range in the fit of the extreme value distribution to observations. The upper right hand panel provides an example illustrating the relationship between ESL events and return period for historical and future conditions; the blue line in this panel shows the best estimate ESL event above the 1986-2005 reference mean sea level. The coloured lines for the different locations show this expected ESL events for different RCP scenarios. The horizontal line denoting the amplification factor expresses the increase in frequency of events which historically have a return period of once every 100 years. In the example, a water level of 2.5 m above mean sea level, recurring in the recent climate approximately every 100 years in recent past climate, will occur every 2 to 3 years under future climate conditions. The allowance expresses the increase in ESL for events that historically have a return period of 100 years. (Reproduced from IPCC (2019), Figure 4.11)

3.1.3 Wind Conditions

Wind conditions could be affected by temperature and other climate changes in several aspects. The seasonal distribution of wind speeds, wind directions, and the frequency, intensity, pathways and/or durations of storms and cyclones (hurricanes) could all change.

IPCC AR6 (2021) has new insights on the prevailing wind conditions. Figure TS.22 of IPCC AR (2021) reveals that a decrease in average wind speed is expected with medium to high confidence, especially over ocean areas. The severe wind and the tropical cyclones are, in line with IPCC SROCC (2019) and IPCC AR5 (2013), expected to increase. The increase in severe winds and tropical cyclones is regionally-dependent, and large variations between difference areas are projected.

Peirson et al (2014), for example, reported on the ability of eight selected Global Climate Models (GCMs) to discriminate, without downscaling, extreme design variables of pressure, winds, rainfall and water levels for East Coast Lows (large scale climate events) impacting the south east coast of Australia. GCM projections for climate changes in the design variables (including winds) were found to be statistically negligible. More detailed regional probabilistic downscaled climate models have subsequently been concluded for east coast Australia – these show significant spatial variability with climate change into the future. Regional downscaled models for Norway [Haugen and Iversen, 2008] indicate that there will be more frequent occasions of storms of mid force, and also that extreme storms may be more intense.

At this stage, regional downscaled climate projections for changes to prevailing winds should be adopted where these are available. In the absence of such projections, it would not be sensible to design for any specific change in prevailing wind conditions. Rather it is important to be aware that wind characteristics could change, to instigate monitoring if appropriate, and to explore recent data from time to time when operations dependent upon wind are being reviewed. In contrast, as discussed in Sections 3.1.4 and 3.1.8, intensity and thus wind speeds, waves and precipitation arising from impacting cyclones, hurricanes or typhoons are projected to increase. Sensitivity testing to assess likely increases should therefore be undertaken.

3.1.4 Wave Action

Waves could be affected by climate change in several ways. The seasonal distribution of wave heights (and periods and directions), the frequency and pathway of spells of high waves, the frequency and pathway of cyclones (i.e., hurricanes, typhoons) and/or the duration of storms could change. In polar regions the change in the location and extent of the local ice fringe may cause changes to wave conditions.

Projected changes in wind-wave conditions derived from the Coordinated Ocean Wave Climate Projection (COWCLIP) project [Hemer et al., 2013] are shown in Figure 3.5 to Figure 3.7. The wave climate (height, period and direction) shows significant spatial variability whilst the projected changes are very different spatially and with the seasons January, February, March (JFM) to July, August, September (JAS). Changes in wave direction are of considerable significance as wave energy direction at the coast directly influences shoreline orientation. Any change in wave energy direction at the shoreline can be expected to result in shoreline re-orientation and altered coastal sediment transport with likely impacts on port and navigation activities.

IPCC SROCC (2019) reports that new studies on observed wave climate change from 1985-2018 showed small increases in significant wave height of +0.3 cm/year and larger increases in 90th percentile wave heights of +1 cm/year in the Southern Ocean, and +0.8 cm/year in the North Atlantic ocean (medium confidence). Sea ice loss in the Arctic has also increased wave heights over the period 1992-2014 (medium confidence). Future projections indicate an increase in the mean significant wave height across the Southern Ocean and tropical eastern Pacific (high confidence) and Baltic Sea (medium confidence) and a decrease over the North Atlantic and Mediterranean Sea under RCP8.5 (high confidence). Extreme waves are projected to increase in the Southern Ocean and decrease in the North Atlantic and Mediterranean Sea under RCP4.5 and RCP8.5 (high confidence).

Increases in tropical cyclone winds and rainfall, and increases in extreme waves, combined with relative sea level rise, will all exacerbate extreme sea level events and coastal hazards (high confidence).

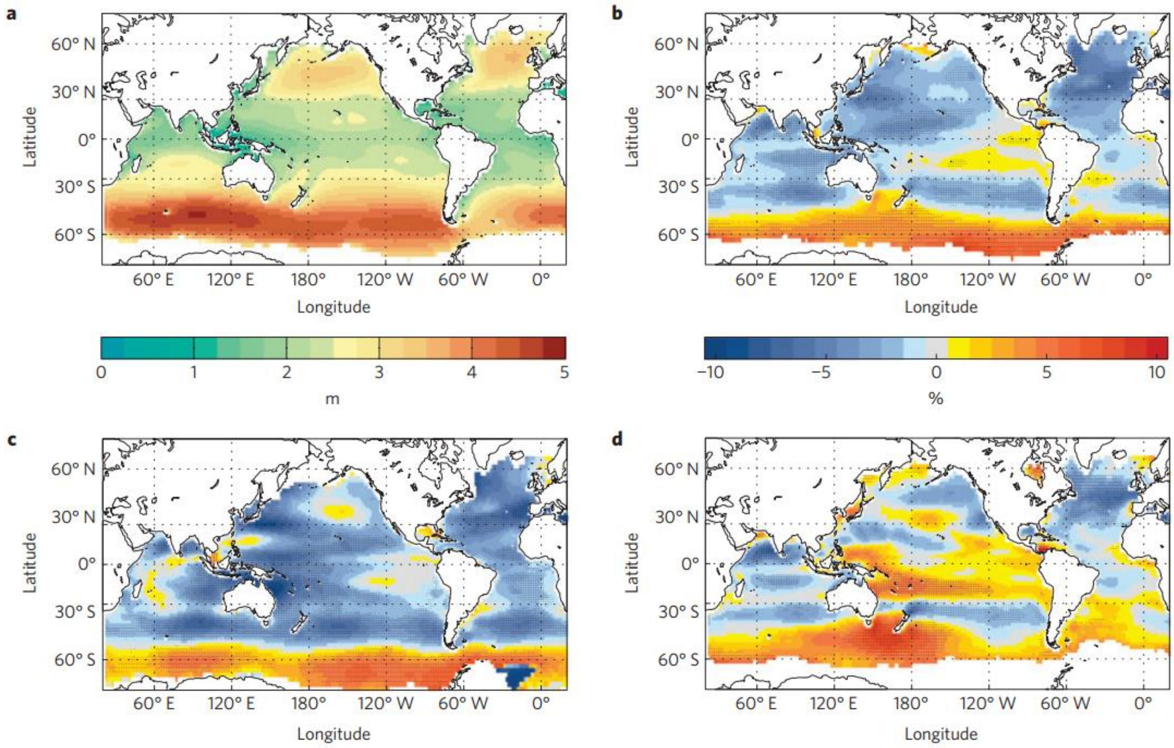


Figure 3.5: Projected future changes in multi-model averaged significant wave height. (a), Averaged multi-model annual significant wave height (Hs, m) for the time-slice representing present climate (~1979-2009). (b)-(d), Averaged multi-model projected changes in annual (b), JFM (c) and JAS (d) mean Hs for the future time-slice (~2070-2100) relative to the present climate time-slice (~1979-2009) (% change). Stippling denotes areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation. Results for individual models are included in the Supplementary Information. (Reproduced Figure 2 from Hemer et al. (2013))

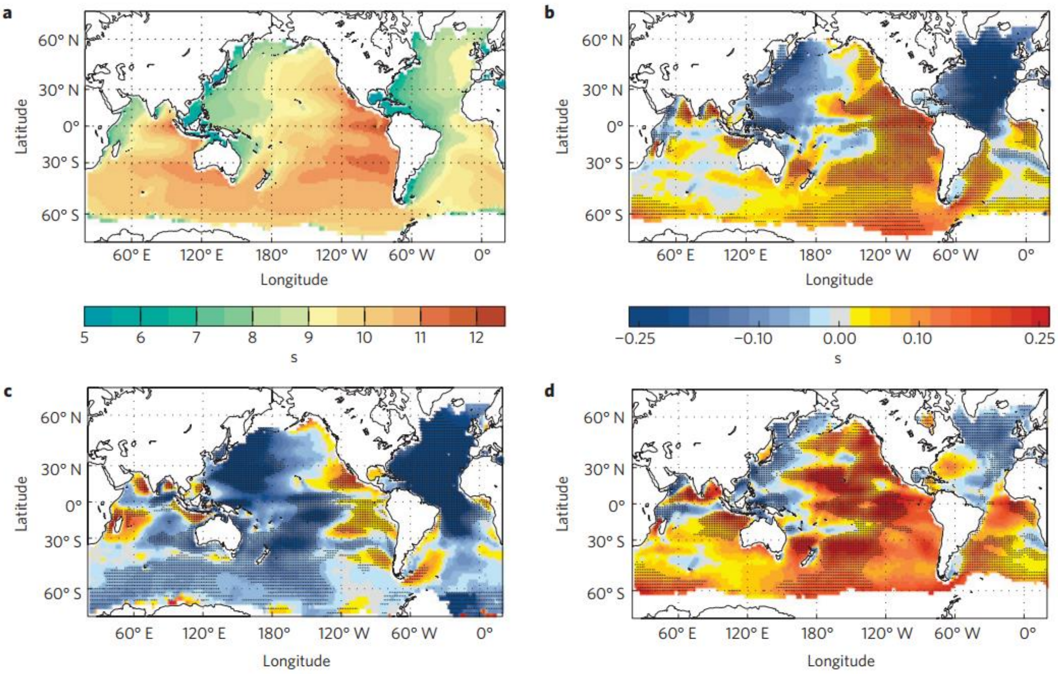


Figure 3.6: Projected future changes in multi-model averaged mean wave period. (a), Averaged multi-model annual mean wave period (Tm, s) for the time-slice representing present climate (~1979-2009). (b)-(d), Averaged multi-model projected changes in annual (b), JFM (c) and JAS (d) mean TM for the future time-slice (~2070-2100) relative to the present climate time-slice (~1979-2009) (absolute change, seconds). Mean wave period from only two groups is used (HEA12 and FEA12). Stippling denotes areas where the two models agree on the sign of change. Results for individual models, including MEA10, are included in the Supplementary Information (Reproduced Figure 3 from Hemer et al. (2013))

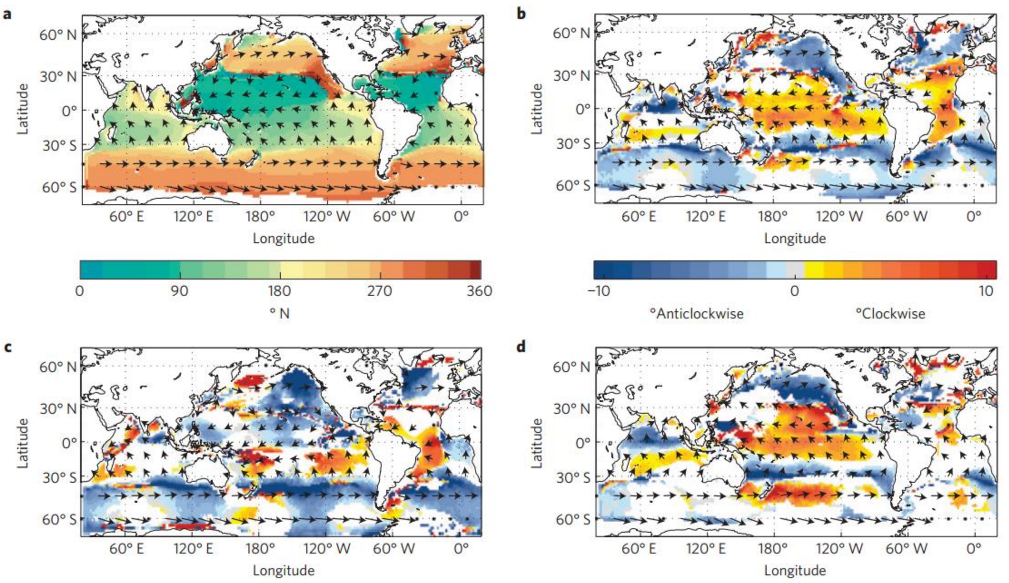


Figure 3.7: Projected future changes in multi-model averaged mean wave direction. (a), Averaged multi-model annual mean wave direction (θ_m, °N) for a historical time-slice (~1979-2009). The vectors indicate the directions shown in the left colour bar. (b)-(d), Averaged multi-model projected changes in annual (b), JFM (c) and JAS (d) mean wave direction (θ_m) for a projected time-slice (~2070-2100) relative to historical climate (absolute change, ◦ clockwise). The vector direction denotes θm for the historical time-slice. Colour denotes the magnitude of projected change according to the right colour bar. Mean wave directions from three groups are used (HEA12, MEA10 and FEA12). Only areas where groups agree on the sign of change are coloured. Results for individual models are included in the Supplementary Information (Reproduced Figure 4 from Hemer et al. (2013))

3.1.5 Tide and Surge Propagation and Range

The effect of sea level rise has a direct effect on the water level but also an effect on tide propagation. Numerical modelling [Flather et al., 2001] has demonstrated that tide propagation and range around the UK can be affected by sea level rise, but that the additional increase in extreme sea level caused in this way is relatively small. It has also been demonstrated [Hulme et al., 2002] that plausible changes in surge propagation due to storms tracking differently around the UK, for example, could have a significant impact (over and above that directly due to mean sea level rise) on extreme sea level. Even around the British Isles, however, these effects are localised, with some areas showing higher than average and some areas showing lower than average sea level rise, and this is based on uncertain projections of future wind and pressure changes. This example illustrates how, without site-specific downscaled climate modelling projections, it remains difficult to make specific allowance for changes in tide and surge propagation and range.

3.1.6 Ocean Circulation and Coastal Hydrodynamics

As outlined in IPCC SROCC (2019), over the 21st century the ocean is projected to transition to unprecedented conditions with increased temperatures (virtually certain), greater upper ocean stratification (very likely), further acidification (virtually certain), oxygen decline (medium confidence), and altered net primary production (low confidence). Marine heatwaves (very high confidence) and extreme El Niño and La Niña events (medium confidence) are projected to become more frequent. The Atlantic Meridional Overturning Circulation (AMOC) is projected to weaken (very likely). The rates and magnitudes of these changes will be smaller under scenarios with low greenhouse gas emissions (very likely). Ocean circulations could be affected by climate change, and these effects could be either gradual or sudden. For example, while it is very likely that the Atlantic Ocean Meridional Overturning Circulation (AMOC) will weaken during the course of the 21st century, it is very unlikely that AMOC will undergo an abrupt transition or collapse in the 21st century and it is unlikely that AMOC will collapse beyond the end of the 21st century under the RCP scenarios considered (Chapter 13 of IPCC AR5 (2013)).

Coastal hydrodynamics may be disproportionately affected by small changes in sea level or wave height, period and direction, but these changes would vary from one location to another and could only be quantified through detailed site-specific modelling.

3.1.7 Coastal and Estuarine Morphology

Climate change impacts on coastal morphology are difficult to assess because bathymetry-induced variations modify the physical phenomena that generate them (waves and current). Coastal responses to MetOcean forcing (e.g. dune rebuilding, submersion frequency, speed of retreat) are research fields, even given present climate knowledge and advances in numerical modelling. Field measurements, and physical and numerical modelling, show that longshore sand transport (beach drift) and hence coastal and estuarine morphology, are sensitive to small changes in wave height, period or direction. Erosion of low-lying beaches and salt marshes is affected by changes in waves or/and sea levels. These sensitivities could only be quantified through detailed site-specific modelling.

3.1.8 Precipitation and Storm Events

It is virtually certain that, in the long term, overall global precipitation will increase with increased global mean surface temperature [IPCC AR6, 2021]. Changes in average (total or seasonal) precipitation in a warmer world will exhibit substantial spatial variation.

Figure 3.8 presents the variation in annual mean average precipitation across the world's oceans and land masses for global warming levels of 1.5°C, 2°C and 4°C.

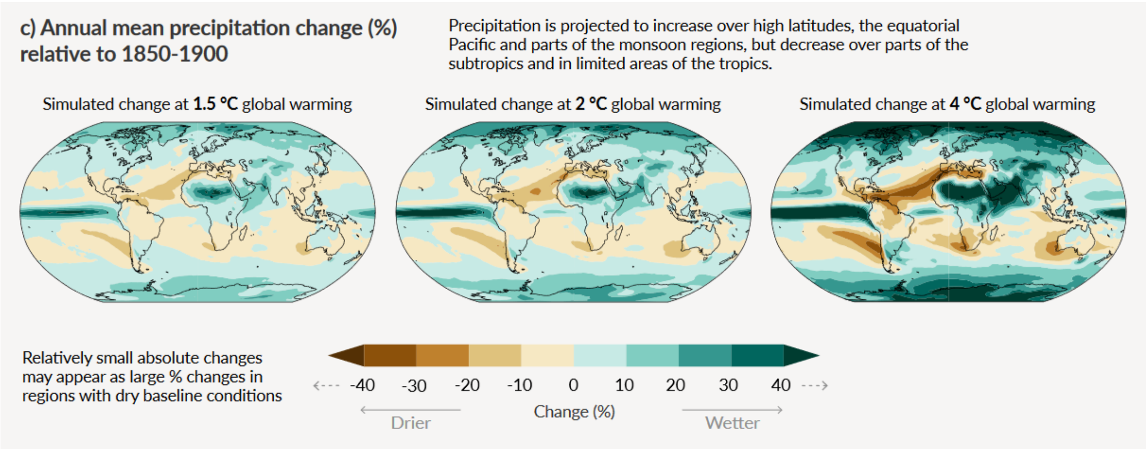


Figure 3.8: Simulated annual mean precipitation change (%) at global warming levels of 1.5°C, 2°C and 4°C (20-yr mean global surface temperature change relative to 1850-1900). Reproduced from IPCC AR6 (2021,) Figure SPM.5c.

As noted previously in regard to projections for temperature change in Section 3.1.1, the important message found in both AR4 and AR5 and repeated in Figure 3.8 (from AR6) is the significant spatial variation in future precipitation associated with global warming.

Measured changes (1951 to 2010) and projected worldwide changes in precipitation to 2100 for various RCP scenarios are shown in Figure 4.2 and (reproduced from IPCC AR5 (2013)). High latitude land masses are likely to experience increased average precipitation due to increased specific humidity and increased transport of water vapour from the tropics; whereas many mid-latitude and subtropical regions will likely experience less precipitation and increased risk of drought and desertification. Globally short duration precipitation events will shift, with more intense storm events and fewer weak storms being likely as temperatures increase. Over most of the mid latitude land-masses and over wet tropical regions, extreme precipitations events will very likely be more intense and more frequent.

As stated in IPCC AR6 (2021), "*it is very likely that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7 % for each 1°C of global warming (high confidence). The proportion of intense tropical cyclones (categories 4-5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (high confidence)*".

Recent extreme precipitation events have resulted in disastrous flood events in many parts of the world. It has been confirmed in various post-flood investigations that the intensification of shorter than daily rainfall extremes increases significantly above the 7 % for each 1°C of global warming. The intensification increases with a reduction in event duration. Specific local studies are necessary to better examine the likelihood of extreme flooding impacts on both port infrastructure, drainage, operations and landside supply chains.

Increasing use of higher resolution downscaled models of GCMs, with linkages to hydrometeorological weather models, make possible regional quantification of likely changes in extreme storms (including cyclones/hurricanes). However, projections vary both regionally and between the climate models.

3.1.9 Sea Chemistry

Carbon emissions from human activities lead to warmer sea surface temperatures, and can cause acidification. They may also result in changes in oxygen levels (with consequences for nutrient cycling and primary production) and/or salinity and stratification [IPCC SROCC, 2019]. Oceanic observations provided in IPCC AR5 (2013) provide strong evidence that oceanic properties of relevance to climate have changed during the past 40 years. Ocean salinity changes are an indirect but potentially sensitive indicator for detecting changes in precipitation, evaporation, river runoff and ice melt. Rhein et al. (2013) suggest it is very likely that regional trends have enhanced the mean geographical contrasts in sea surface salinity from 1950 to 2008. It is very likely that saline surface waters in the evaporation-dominated tropical and polar regions have become more saline, while the relatively fresh surface waters in rainfall-dominated tropical and polar regions have become fresher. Similarly, it is very likely that the Atlantic has become saltier and the Pacific and Southern Oceans have freshened.

Rhein et al., (2013) also report that ocean biogeochemistry is changing, largely due to oceanic absorption of approximately 155 gigatonnes of carbon (GtC) from the atmosphere over the last two and a half centuries. This has impacted pH and dissolved oxygen (decreasing trends), and has resulted in decreasing ocean pH and a fundamental change in the distribution of carbon species (CO_2, carbonate and bicarbonate) in all ocean regions, particularly in the cooler, high latitude waters [IPCC AR5, 2013 ; Poloczanska et al., 2016]. These changes in turn impact nutrient cycling and primary productivity.

In estuaries, climate change impacts on water chemistry vary from location to location. In some cases, rising sea levels will result in the inland migration of the mixing zone between fresh and saline water [Robins et al., 2016] with potential consequences for both surface and ground water bodies. Changes in precipitation may also affect the salinity of coastal waters, for example if droughts reduce fresh water input into tidal rivers and bays.

3.1.10 Marine and Coastal Biology

The changing climate will affect marine and coastal biology in many ways, both directly and indirectly. Biological and ecological responses to warming oceans include species' distribution shifts, predominantly polewards but also deeper and in other directions [Malin et al., 2020]. These shifts are caused by changes in suitable habitats and environmental conditions; earlier spring events and delayed autumn events at mid to high latitudes; reduced calcification in corals. due to ocean acidification; and other impacts on growth and reproduction [Poloczanska et al., 2016; Pyke et al., 2004]. Marine organisms have, on average, expanded the leading edges of their distributions by 72.0 ± 13.5 km per decade (generally polewards), while marine phenology in spring has advanced by 4.4 ± 1.1 days per decade [Poloczanska et al., 2013]. The occurrence of harmful algae blooms and pathogenic organisms in coastal areas has increased since the early 1980s in response to warming, deoxygenation and eutrophication [IPCC SROCC, 2019].

All types of species are potentially affected by such changes. Predator and prey species including primary producers may migrate; fish stocks are likely to shift; and global marine animal biomass and fish catch are projected to decrease [IPCC SROCC, 2019]. Local conditions may no longer support protected habitats or species within currently designated areas [Bruno et al., 2018]. There may be damage to sensitive habitats such as coral reefs or seagrass meadows due to increased grazing; sea level rise may exceed the capacity of coastal and nearshore ecosystems such as saltmarshes, sand dunes, or mangrove forests to build vertically or otherwise expand [IPCC SROCC, 2019]. Non-native species for which the environment was previously inhospitable may thrive, potentially exacerbating invasive alien species-related problems for infrastructure integrity and equipment operability as well as for biodiversity [Cottier-Cook et al., 2017].

3.1.11 Ice Cover Conditions

Historically, about 10 % of the Earth's surface is permanently covered by ice. Chapter 9 of IPCC AR6 concludes that the volume and extent of ice (and snow cover) on the Earth is decreasing, and that this trend will continue. For freshwater systems, observation evidence across North America indicates reduced ice cover duration [U.S. EPA, 2020]. In Alaska, a 20 % reduction in ice cover length was found between 2008-2018 compared to 1984-1994 [Yang et al., 2020]. In Canada, later freeze-up dates (by 5-15 days) along with earlier break up dates (by 10-25 days) are also expected [Dibike et al., 2012].

Recent observations show that changes in ice cover in the Arctic Ocean are occurring more rapidly than previously known, see Figure 3.9. The Arctic ice cover is shrinking, i.e. reducing its area of extent and its average thickness. Over the period 1979-2012, the annual Arctic sea ice extent decreased with a rate that was, very likely between 3.5 and 4.1 % per decade (0.45 to 0.51 million km^2 per decade) (Chapter 4 of IPCC AR5 (2013)). These trends continue based on the updated IPCC reports. Chapter 3 of IPCC SRROC (2019) found declines in Arctic seas for all months since 1979. Chapter 9 of IPCC AR6 [IPCC AR6, 2021] reported a reduction in the area of Arctic sea ice averaging 25 % during the period of 2010-2019 for the months of August, September, and October. In contrast, Antarctic sea has no significant trend in areal extents since 1979. There is a lot more information on observed and expected changes in ice and snow, including regional variations, in Chapter 9 and Chapter 12 of IPCC AR6 (2021).

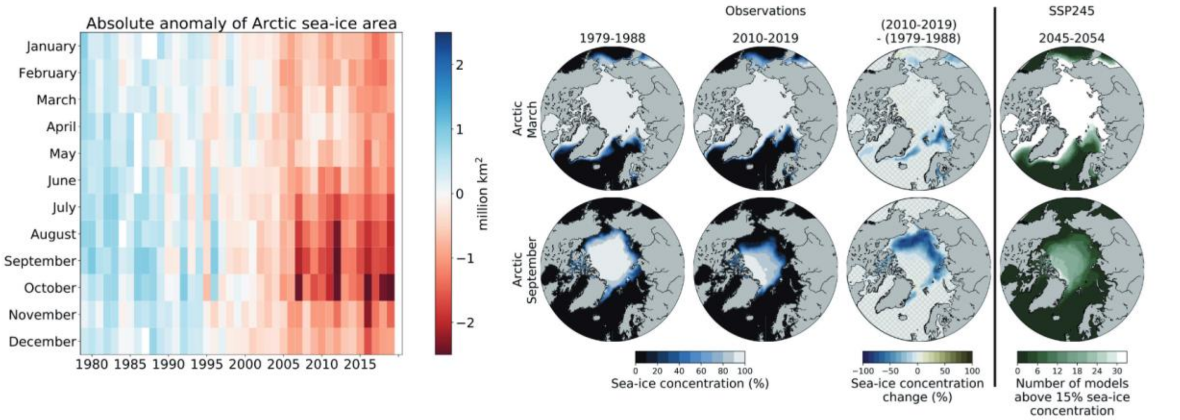


Figure 3.9: Arctic sea-ice historical records and CMIP6 projections. Left: Absolute anomaly of monthly-mean Arctic sea-ice area during the period 1979 to 2019 relative to the average monthly-mean Arctic sea-ice area during the period 1979 to 2008. Right: satellite retrieved Sea-ice concentration in the Arctic for March and September. First and second column: Mean sea-ice concentration. Third column: Absolute change in sea-ice concentration with grid lines indicating non-significant differences. Fourth column: The project rejected sea-ice metrics in SSP2-4.5 (IPCC AR6 (2021), Figure 9.13)

3.1.12 Icing

Chapter 12 of IPCC AR5 (2013) reports that model projections show fewer mid-latitude storms and poleward shift of the storm tracks of several degrees, particularly notable in the Southern Ocean by the end of the 21st century. Lower central pressures for these poleward-shifted storms will result in increased wind speeds and extreme wave heights in those regions, with an associated increase in sea spray icing.

Overland (1990) presents a method to predict sea spray icing based on threshold wave heights and wind speeds. The US National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Prediction (NCEP) uses these algorithms to predict vessel icing, which is available via the internet[6].

Ice accretion from freezing rain can be estimated by using theoretical models such as those described in Jones (1966). Løset et al. (2006) gives the fundamentals of action and action effects of ice on structures, associated risk assessments, ice physics and mechanics, ice features, ice forces, icing in the ocean and ice management. It is meant as a reference book for engineers working with the effects of ice on structures in the Arctic and in other cold climate areas.

3.2 Potential Impacts on Maritime Navigation

Climate change will result in a number of typical impacts on navigation and port operations as well as on related infrastructure. These are summarised in

Table 3-1 (adapted from PIANC WG 178 (2020)), where the ticks indicate the climate parameter or process associated with potential impacts on navigation infrastructure or operations. Such impacts are discussed in the remainder of the section according to the various projected climate changes presented in Table 3-1.

[6] https://ocean.weather.gov/icing_rates/compare.php?area=ak&fhour=012

Impact susceptibility (Parameter or process >>)	Air temperature	Water temperature	Precipitation	Storminess	Sea level rise
Coastal flooding due to overwhelmed drainage systems or high groundwater levels			✓	✓	✓
Overtopping due to high tides or storm surges			✓	✓	✓
High flow velocities or changes in sea state			✓	✓	✓
Changes in bathymetry, or sediment or debris transport			✓	✓	✓
River or sea bank erosion			✓	✓	✓
Damage to breakwaters or other port structures				✓	✓
Fog or other reduced visibility issues	✓	✓	✓		
Wind speed, strength, direction, duration	✓			✓	
Interruptions to sea and/or land side supply chains	✓		✓	✓	✓
Extreme cold, ice or icing	✓	✓			
Extreme heat or humidity	✓				
Changes in water chemistry		✓			
Changes in biological character	✓	✓	✓		

Table 3-1: Examples of typical relevant parameters and processes based on impact susceptibility

3.2.1 Air and Water Temperature

In addition to the gradual (or slow-onset) changes in air and sea water surface temperatures, it is widely predicted that the frequency of both air and ocean heatwaves will increase. Rising temperatures will not only have consequential effects for sea levels, seasonal precipitation, wind, waves, storms, etc. They will also have direct and indirect effects on certain types of port or navigation assets or activities.

Figure 3.10 presents the changes in the intensity and frequency of hot temperature extremes over land that are projected to occur over 10 years for a nominal *10-year event* and over 50 years for a nominal *50-year event* at global warming levels of 1°C, 1.5°C, 2°C, and 4°C. It is noted that the terminology in the figure can be misleading – the nominal *10-year* and *50-year events* are better referred to as 10 % and 2 % AEP (annual exceedance probability) or 1 in 10 and 1 in 50 ARI (average recurrence interval) events.

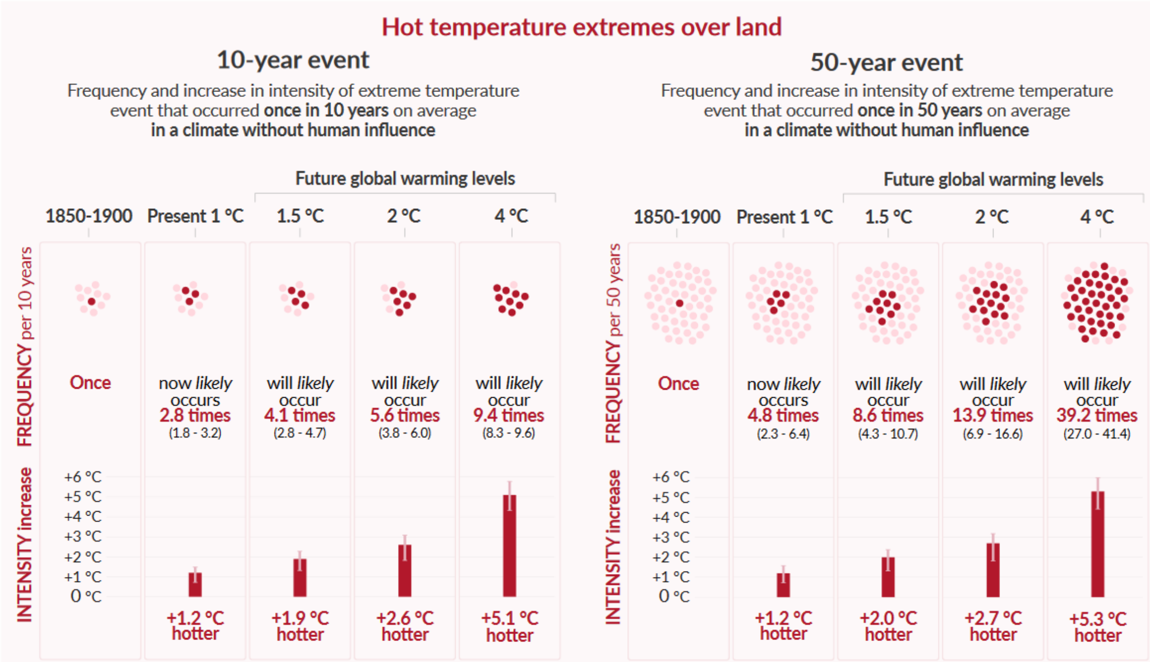


Figure 3.10: Projected changes in the intensity and frequency of hot temperature extremes over land. Projected changes are shown at global warming levels of 1°C, 1.5°C, 2°C, and 4°C and are relative to 1850-1900 representing a climate without human influence (Reproduced from IPCC AR6 (2021), Figure SPM.6)

Without adaptation, increases in maximum (or minimum) air temperatures or high humidity levels could compromise the health and safety of port personnel working outside, in offices or storage facilities, or operating equipment. High temperatures or humidity levels can also adversely impact on the handling or storage of sensitive cargo. Operating limits for plant and equipment may be exceeded. Heatwaves (where temperatures exceed a defined threshold for a number of days) can cause problems for road pavements or for rail tracks and overhead wires and therefore for onward transport. Extreme heat can also compromise the operating mechanisms of locks, swing or lifting bridges and similar.

Water temperature changes can affect both native and non-native species, with direct or indirect consequences for navigational safety, infrastructure integrity or operational efficiency. Some port users' commercial interests may also be impacted. Potential biology-related changes are elaborated in Section 3.2.11.

3.2.2 Increase of the Global Mean Sea Level and Change in Storm Surges

Mean sea level has increased in the recent past, and will continue to rise in the future, likely at an accelerated rate [IPCC AR6, 2021]. For navigation purposes, extreme low and high sea levels are of greater practical interest than mean sea level. In the absence of other information, one might expect low and high levels to increase by the same amount as mean sea level, but a change in tidal propagation, and surge behaviour associated with weather conditions, means that this is not necessarily the case.

Sea level rise would affect harbour infrastructure and the standard of service of coastal and port structures. It may allow greater penetration of wave energy to the coastline and into harbours, causing increased coastal erosion in areas with a soft coastline. It may also increase the salinity of bays and estuaries.

A change in high and extreme sea levels may cause an increased number of incidents of overtopping and lowland flooding, and reduced top clearance between vessels and infrastructure such as bridges (air draft). Where the elevation at which wave forces attack a structure increases, this potentially increases the vulnerability of that structure. Sea level changes may also increase the exposure of decks of wharfs and piers, as well as the corrosion rate and the degradation over time of materials specifically designed for a particular range of sea level conditions. In Polar Regions there may be more wave action and sea spray on navigational installations.

Other potential impacts include more sedimentation or erosion at river outlets, development of submerged reefs, changes in exchange processes and current speeds between ocean and inland seas, and altered tidal flows in narrow straits and bay inlets.

3.2.3 Change in Wind Conditions

Anthropogenic induced changes in prevailing wind conditions are projected to be relatively small, and the IPCC AR6 (2021) projections for wind note low confidence and high uncertainty. This is in contrast to high confidence projections for cascading impacts of increasingly more intense winds, more extreme waves and extreme water levels with more intense storms and cyclones [IPCC AR6, 2021].

In addition to the obvious potential to produce higher waves, any local or regional increase in wind speed would also have some direct effects on navigation. Preferred shipping routes may change. Manoeuvring around tight bends or through narrow channels would become more difficult. Many modern vessels are more sensitive to wind than older ones, and passenger vessels subject to wind and wave operational criteria may suffer more downtime. Related possible impacts include reductions in calm weather window times at high risk (e.g. oil and gas) terminals, increased berthing time for ships at terminals, and delayed departure times – any or all of which may necessitate larger areas for anchoring of waiting vessels. Furthermore, in addition to the direct effect of windage on vessel manoeuvrability, there are consequences for the use of tugs and pilot transfers.

3.2.4 Evolution of Wave Action

Many offshore loading and unloading operations are wave height dependent. For example, a buoy loading ship facility may require significant wave height conditions $H_s < 4.5$ m for connection, and must disconnect if $H_s > 9$ m. There may also be a maximum wave period criterion for operation, for example that mean wave period is below 15 s, even when wave height is acceptable [Thoresen, 2010].

Potential impacts at the coast and on port structures include changes in overtopping or even the stability of breakwaters, increased forces from waves coupled with attack at a higher level on a structure due to sea level rise, and changes in sediment (seabed and/or beach) movement.

Changes in wave climate might affect ship routing and port operations. As well as affecting large vessels, any change in wave action (including extreme storm wave characteristics) may affect local (small boat) fishing fleets, floating equipment such as aquaculture plants, and a range of other coastal and marine activities and infrastructure. Bunkering activities may similarly be impacted.

3.2.5 Evolution of Tidal Propagation and Range

Although tidal range may be significant in some estuary and port locations, it is generally the case that only minor changes are expected relative to the effects of changes in mean sea level, wind and waves discussed above. The increased extent of salinity intrusion to estuaries and rivers can change the location and magnitude of salinity-induced settlement rates of cohesive sediments with possible impacts on navigability.

3.2.6 Changes in Ocean Circulations and Coastal Hydrodynamics

Although a change in ocean circulation could affect navigation, research suggests any direct impacts are expected to be small. Changes in coastal hydrodynamics could result in locally significant impacts on navigation. These would vary greatly from one site to another but might include narrowing or widening (or even opening or closing) of channels, changed dredging requirements, erosion or accretion of beaches or intertidal areas protecting port structures and/or changed current velocities.

3.2.7 Changes in Coastal and Estuarine Morphology

Navigation interests could be affected through changes in the shape and depth of channels, formation of submerged reefs, or other impacts on sediment dynamics necessitating a change in maintenance dredging or beach nourishment requirements. Erosion or accretion of beaches protecting port structures may affect the safety of structures or the probability of flooding. Heimhuber et al. (2019) report that the risk of flooding in coastal wetlands is projected to increase, with impacts on society and natural ecosystems/ecosystem services. Any such changes will be very site-specific, with some gains and some losses, so generic guidance may be limited to consideration of the potential impacts of changes in morphology to indicate whether more detailed studies are needed. In arctic regions, land-based navigation infrastructure may be destabilised as permafrost melts [IPCC SROCC, 2019].

3.2.8 Changes in Precipitation and Storm Events

Changes in precipitation or storm events may be manifested directly through the overall distribution of wind, wave or rainfall conditions, through the seasonal or spatial distribution of storm occurrence, or via other changes in seasonal precipitation patterns or intensity.

As noted in section 3.1.8, changes in rainfall intensity and duration are associated with projected temperature rise, with increasingly intense but shorter duration extreme events. Figure 3.11 presents the projected changes from IPCC AR6 (2021) in the intensity and frequency over 10 years of the nominal *10-year* extreme daily precipitation event over land at global warming levels of 1°C, 1.5°C, 2°C, and 4°C. The 10-*year event* is better referred to as 10 % AEP (annual exceedance probability) or 1 in 10 ARI (average annual interval) event.

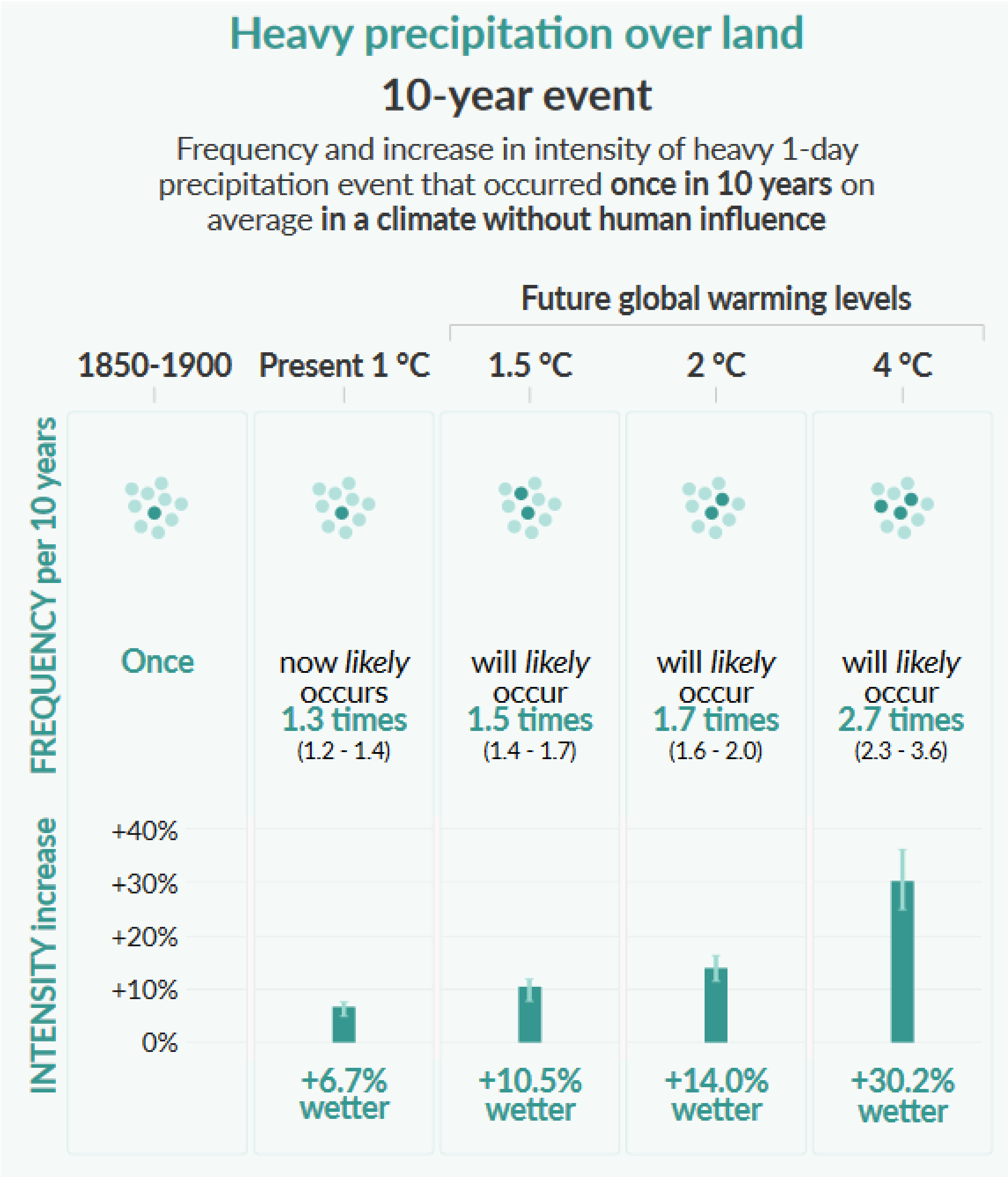


Figure 3.11: Projected changes in the intensity and frequency of extreme precipitation over land. Projected changes are shown at global warming levels of 1°C, 1.5°C, 2°C, and 4°C and are relative to 1850-1900 representing a climate without human influence (Reproduced from IPCC AR6 (2021), Figure SPM.6)

Projected changes in precipitation may lead to an increased risk of pluvial (rainfall-related) flooding on and around the port estate. Increases in flow rates during severe events may lead to increases in scour at structures located along coasts and estuaries. In the UK, for example, projected changes by 2070 include wetter winters and drier summers; a 25-% increase in extreme hourly rainfall intensity of the once in two years event; and a shift towards more rain from higher intensity frontal rain events in winter and short, high intensity showers in summer

[Met Office, 2019]. Increases in precipitation intensity along with possible changes in storm duration and/or frequency may lead to reduced operational reliability for ports, increased downtime and the requirement for more storage capacity for use in cases of port or terminal closure. Changes in the frequency, duration and/or intensity of storm events may also adversely affect the capacity of natural systems to recover from storm erosion, potentially leading to permanent loss of sand offshore and degradation of structures (i.e. retreat of coastal landscapes and loss of economically viable land).

Other impacts might include changes in visibility due to more intense precipitation, changes in sunshine available for sun powered equipment, changed accessibility to malfunctioning installations such as beacon lights, and changed extent of moist and cold air. Higher thunderstorm activity is expected in higher latitudes which would put higher demands on lightning systems and electronics. Hailstorms may also increase in some areas, potentially impacting ports handling cargoes, such as vehicles, that are susceptible to hail damage.

3.2.9 Changes in Visibility

Climate-change induced changes in visibility, for example as a result of fog, but also associated with blizzards or potentially smoke from bushfires caused by extreme heat and/or drought, are frequently overlooked.

Whether the number of fog days increase or decrease is very much location dependent. In the Arctic, the number of days with fog may increase due to reduced ice-cover. The large-scale decrease in visibility over the 21st century is in the range of 8 %-12 % in the Arctic and 0 %-5 % in the North Atlantic [Danielson et al., 2020]. By way of an example, the number of fog days is generally expected to reduce in most locations around the UK. However, in South East England winter fog days may increase by up to 30 %, bringing potential issues for busy, multi-user systems such as the Thames Estuary through London where conflict between recreational and commercial uses already requires careful management [Port of London Authority, 2015]. Changes in fog frequency can also have consequences for pilotage, as well as for land transport to and from the port. Changes in the frequency or intensity of blizzard conditions may also be an important consideration for certain ports.

Reduced visibility not due to fog or blizzards but extensive bushfire smoke has, in recent years, increasingly interrupted navigation and operations of ports in the Sydney region of Australia. Although currently unusual, with increased risk of major bush or wildfires worldwide with increased temperatures and climate change this may occur more frequently [Calfas, 2021].

3.2.10 Changes in Sea Chemistry

Changes in salinity/stratification, acidity/pH impacts, oxygenation and nutrients linked to warming sea surface temperatures may result in a variety of impacts on navigation operations and navigation infrastructure.

Increased corrosion and associated deterioration of port structures (and vessels) can be linked to acidification in marine waters. For example, rates of corrosion of reinforcement in reinforced concrete structures may be accelerated [McEvoy and Mullett, 2013] and [Ghanooni-Bagha et al., 2020]. Furthermore, the drop in seawater pH as the ocean absorbs carbon dioxide compounds the effects of warming waters. This means that coral reefs suffering from heat stress-related bleaching have insufficient calcium carbonate to rebuild their protective exoskeletons [Lindsey, 2018]. As reefs deteriorate, their natural role in absorbing wave energy/buffering against storms is compromised. Where coral reefs are damaged or lost, ports and other marine facilities that currently benefit from their buffering effects may need to invest in upgraded or alternative flood defense or erosion protection works.

In addition to the salinity changes noted in Section 3.2.5 associated with changes in sea level and tidal characteristics, changes in salinity may affect port and navigation operations and infrastructure. Less salty and warmer water in the higher latitudes may contribute to local increases in sea levels. Fish and other commercially important species may be unable to adapt to changes in salinity and temperature, or in oxygen or nutrient levels. Walther et al. (2002) note changes in primary and secondary productivity that affect plankton and hence fish populations, as well as climate-induced changes in upwelling systems, that could reduce fish populations (e.g. as observed in the North Pacific). If commercially significant species are lost or migrate from a particular area, industries that depend on those species (e.g. fishing, wildlife watching) will also need to relocate or adapt. Such changes will have economic consequences for affected ports and harbours (Chapter 2 and Chapter 6 of IPCC AR5 (2013) ; Chapter 6 of IPCC AR5 (2014a) and Chapter 30 of IPCC AR5 (2014b)).

3.2.11 Changes in Marine and Coastal Biology

Warming sea surface temperatures, rising sea levels and changes in other parameters such as storminess can have profound consequences for marine ecosystems. Predicting species or ecosystem response in the face of climate is complex (e.g. Davis et al. (1998)). Detailed local studies may be required to assess changes, including to environmentally protected areas. Ibáñez et al. (2006) suggest that identification of vulnerabilities and leading indicators of change, plus carefully designed monitoring, can provide the most insight into potential climate change impacts and responses. Hannah et al. (2007) evaluate the use of protected areas as mitigation for climate change impacts under a moderate climate change scenario and find that they can be an important conservation strategy.

Changed climatic conditions may also advocate for the relocation of some environmentally protected areas, with associated opportunities or problems for the navigation sector. Wildlife-dependent tourism at a particular location, for example, may no longer be economically viable if species migrate and protected areas are de-designated, but fishing fleets or recreational anglers may move into areas that are no longer protected (Chapter 2 and Chapter 6 of IPCC AR5 (2013) ; Chapter 6 of IPCC AR5 (2014a) and Chapter 30 of IPCC AR5 (2014b)). Range or distributional shifts in commercially valuable fish species (e.g. Engelhard et al. (2014)) will likewise lead to changes in demand for and the provision of supporting infrastructure in fishing harbours. Production of zooplankton would increase in polar areas due to reduced ice cover (see 3.2.12), tending to cause relocation of fish from south to north in the northern hemisphere, in turn leading to a northward shift of commercial fishing activity. Defining protected areas based on previous estimates of sustainable catch limits may not be directly applicable in these newly opened areas.

Like coral reefs many other sensitive or protected coastal habitats provide natural protection against storms, severe wave conditions and associated flooding or erosion. A combination of rising sea levels and changes in storms, salinity or other climate-related factors threaten this vital function, along with other ecosystem services such as the provision of fish nurseries or water purification [PIANC WG 195, 2021]. Salt marshes and sand dunes may lose elevation (i.e. relative to sea level) or be unable to migrate landwards as sea level rises, resulting in a lowering or narrowing of habitat extent [Pontee, 2013]. As habitat extent deteriorates, their ability to provide effective storm protection to ports, harbours, marinas and other coastal and estuarine land uses is endangered. Mangroves, which play an equivalent protective role in tropical regions, are similarly exposed to a loss of surface sediment elevation as well as to increased sea surface temperatures and changes in precipitation and storminess [Ward et al., 2017]. As a consequence of the reduction or loss of this natural function, increased investment in flood or erosion defenses will be required in many areas.

Another issue with potentially significant economic consequences for navigation and navigation infrastructure concerns non-native (alien) species, particularly invasive alien species. As waters warm and other climate-related parameters change, alien species that were previously unable to survive if introduced (or to breed successfully if already present in low numbers) may begin to thrive. Some such species can cause physical damage and affect marine infrastructure integrity. Chinese mitten crabs [Rudnick et al., 2005], for example, burrow into earth embankments; so too may crayfish [Haubrock et al., 2019]. Molluscs such as piddocks and shipworms, may bore into piers and wharves. Other species foul or smother hard surfaces and equipment (e.g. carpet sea squirt, Natural Environment Research Council, 2010) as well as commercially important native species (e.g. slipper limpet fouling scallop beds [Chauvaud et al., 2001]). Problems may be particularly severe where there are no natural predators in the area subject to invasion.

It is widely considered that climate change will exacerbate invasive alien species' issues globally [Occhipinti-Ambrogi et al., 2010; Cottier-Cook et al., 2017 ; Chan et al., 2019], with potentially significant financial/economic implications. Many port and navigation operators will therefore need to take action to prevent or manage business-threatening invasions, for example by preparing and implementing marine biosecurity plans [PIANC WG 218, in press].

3.2.12 Changes in Ice Cover Conditions

Reduced ice cover (see Figure 3.9) would permit better access across Polar Regions and longer shipping seasons on the Great Lakes for multiple purposes, including locating, extracting and transporting resources, commercial fishing, recreation and tourism. Reduced ice cover also means longer open-water seasons, which may lead to increased wave intensity with more storm surges, and increased ocean swells. This in combination with the rise in air and ocean temperatures (leading to permafrost thaw), would increase the risk of coastal erosion.

Arctic sea ice has thinned, concurrent with a transition to younger ice. Between 1979 and 2018, the areal proportion of multi-year ice at least five years old has declined by approximately 90 % [IPCC SROCC, 2019]. This also means that ice cover is more prone to breaking up by ocean gravity waves, with production of more floe ice.

The Northwest Passage through Canada and the Northern Sea Route, north of Russia and Siberia, are both valued because they could significantly shorten ship transit times between Asia, Europe, and North America (see Figure 3.12).

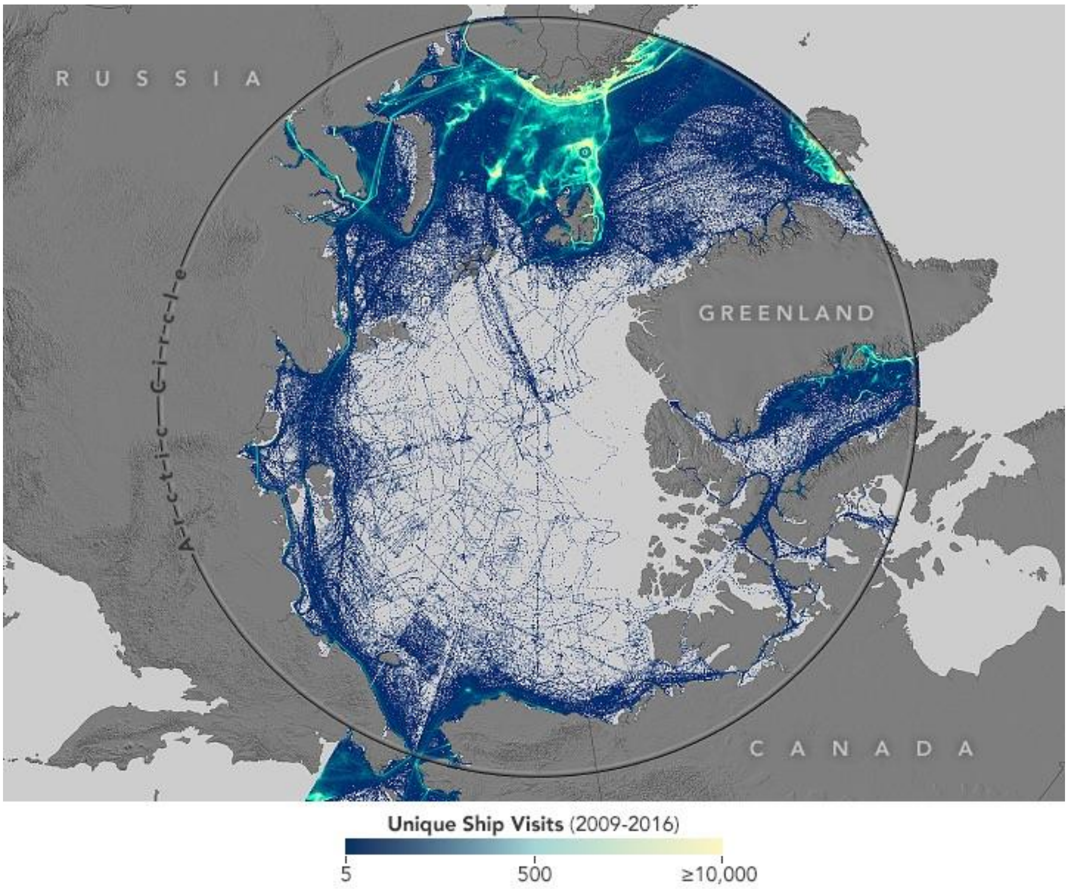


Figure 3.12: The map shows unique ship visits to Arctic waters between 1 September 2009 and 31 December 2016. Credit: NASA Earth Observatory (https://3kbo302xo3lg2i1rj8450xje-wpengine.netdna-ssl.com/wp-content/uploads/2018/04/Unique-Ship-Visits-Arctic.jpg)

If the Northwest Passage was open as a shipping route all year, there would be potential for reduced fuel consumption in shipping between Europe and Asia. If the Northeast Passage were open during summer, then sailing windows would be increased. The record melting in the Arctic during summer 2007 [Wadhams, 2012] and tied in 2019 [Yadav et al., 2020] gives an indication that these sailing routes will become accessible sooner than previously anticipated.

The transport of natural gas and oil along the Northern Sea Route (NSR) has seen rapid growth with cargo volume quadrupling between 2015-2018 to nearly 20 million tonnes. This leads to new economic growth. However, the scarcity of existing navigational infrastructure in the Arctic creates a significant gap in safety and environmental protection, which has led the U.S. Coast Guard to begin establishing a base at Barrow, Alaska[7]. There is also increasing development on the Russian side.

More freshwater in rivers could cause more ice to form at river outlets in the north, which can alter the seasonal salinity and chemistry in the estuaries, in addition to the timing or path of marine productivity and migration near rivers. Navigation and access through river outlets for shipping via rivers will also be determined by ice-open dates.

---

[7] **https://www.adn.com/alaska-news/article/coast-guard-sets-barrow-aviation-base-cover-arctic/2012/07/19/**

3.2.13 Changes in Icing

Icing of ship superstructures and ocean structures occurs when air temperatures are colder than the freezing point of seawater and wind speeds are above 8-10 m/s. Saline spray that is lofted and carried by the wind impacts bulkheads, decks, and rigging. Icing is a well-known hazard to traditional operations in northern waters. Icing in the ocean can be divided into two main categories: 1) Sea spray icing caused by wave-structure collision-generated sea spray; 2) Atmospheric icing caused by freezing rain or drizzle, freezing fog, or cloud droplets depositing on the superstructure. Sea spray icing is by far the dominant source for ice accretion on ships. The potential for ice accretion on vessels and offshore structures is directly related to the environmental conditions, i.e. wave height, wind speed and direction, air temperature, sea surface temperature and the freezing temperature of sea water. In the Arctic, prediction is hampered due to lack of good forecasts of these variable weather and ocean conditions. The modelling of wave-generated spray is complicated and challenging.

Infrastructure on land should also be considered with respect to heavy icing. Analysis and design measures need to account for regional changes in predicted wind, wave, and temperature. During the storm Narve, 12 January 2006, the gas production installations on the small island Melkoya in northern Norway experienced heavy sea spray icing. Predicted thickness was 12 cm cover, actual measured was more than 50 cm [Løset & Høyland, 2019].

4 INLAND NAVIGATION

As with maritime navigation, the climate-related drivers of change to inland navigation are meteorological variables outside the control of the navigation sector, such as temperature, precipitation, and storm intensity. The degree to which inland navigation is affected by direct effects like low water depends on the type of inland waterway and the nature and extent of water level management. Whereas the water level in canals and regulated rivers can typically be controlled assuming a sustainable water supply, the water level on-free flowing rivers and lakes depends on its discharge and hence on rainfall, snow or ice melt, etc. In 2018, the Rhine river revealed the types of effect extreme low water can have on national economies: the interruption in the logistics chains, not only for container transport, but also for chemicals, petroleum products, iron ores and other industrial raw materials, caused economic losses of almost 5 billion euros for German industrial output in 2018 [CCNR, 2019].

Where water levels are managed, however, there are also complex political, social, and environmental factors to be balanced when addressing water resources questions. Inland navigation is one user of water resources among others like water supply (industrial and household), flood damage reduction, power production (hydropower as well as conventional power plants) and irrigation. These needs are most often competing, and may be the subject of complex regulations and/or water allocation processes.

This chapter discusses drivers of change to inland navigation induced by global climate change, and the potential impacts of these changes on the inland navigation sector. Some possible responses to manage adverse impacts or enhance positive impacts are highlighted on Figure 4.1 and elaborated in Section 5.

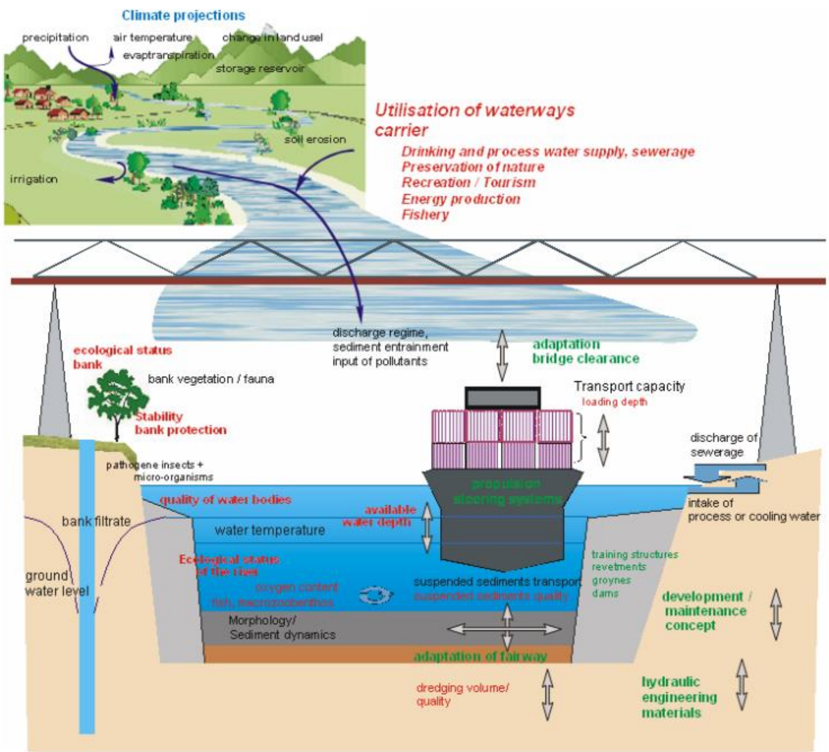


Figure 4.1: Links between drivers of change and potential impacts on inland navigation (courtesy of German Federal Institute of Hydrology).

4.1 Drivers of Change Relevant to Inland Navigation

IPCC AR5 (2014a) and AR 6 (2021) identified several climatological trends observed in the late 20th century and assessed the likelihood of future trends based on the emissions scenarios (RCPs). Some of these trends are summarised in Table 4-1 using the terminology described in Section 3.1. Such trends impact virtually all areas of the inland navigation sector, in cases where, as stated by the International Lake Ontario–St Lawrence River Study Board, two factors are critical to safe and efficient inland navigation: the available depth of water and the currents created by water flow[8].

Phenomenon and direction of trend	**Assessment that changes occurred (typically since 1950)**	**Likelihood of future changes based on RCP scenarios**		**Examples of relevance to navigation**
		Early-mid 21st Century	**Late 21st Century**	
Temperature				
Warmer and fewer cold days and nights over most land areas	Very Likely (decreased frequency of coldest days and nights, coldest 10 %)	Likely	Virtually certain (warming of the most extreme days and nights each year)	Form of precipitation (snow/rain); presence or absence of ice
Warmer and more frequent hot nights over most land areas	Very Likely (increased frequency of hot days and nights, hottest 10 %)	Likely	Virtually certain (warming of the most extreme days and nights each year)	Associated with precipitation quantities, rates of evapo-transpiration, drought
Warm spells/heat waves. Frequency increases over most land areas	Likely	Not assessed	Very Likely	Associated with precipitation quantities, rates of evapo-transpiration, drought, extreme heat; also impacts working conditions
Precipitation				
Heavy precipitation events. Frequency (or proportion) of total rainfall from intense rain increases over most areas	Likely over most land areas	Likely over many land areas	Very Likely over most land areas	Associated with precipitation quantities, high flow conditions, floods
Area affected by droughts increases	Likely in many regions since the 1970's	Low confidence	Likely	Associated with low flow conditions, droughts
Cyclones				
Increase in intense tropical cyclone activity	Likely in some regions since the 1970's	Low Confidence	Likely	Associated with storms, precipitation quantities, high winds

Table 4-1: Examples of trends and projections for extreme climatological and hydrological events (after Table SPM.1, IPCC (2014))

[8] http://www.losl.org/twg/navigation-e.html#2

The key drivers of change, directly influencing the navigation on inland waterways, are the meteorological parameters: air temperature and precipitation. These parameters determine the water temperature and water supply in the navigable river sections, which are discussed in more detail in Section 4.1.1 and Section 4.1.2. Such changes, especially in precipitation and hence water supply, will affect the occurrence of extreme hydrological conditions and may thus indirectly change the navigability of waterways, as described in Section 4.1.3. Since the river hydrology is interrelated with river morphology, the latter is an indirect driver of change to navigation, which is outlined in Section 4.1.4. Changes in ice cover, and ecological effects are covered in Sections 4.1.5 and 4.1.6 respectively.

4.1.1 Air and Water Temperature

The projected increases in air temperature discussed in Section 3.1.1 and Section 3.2.1 in the maritime navigation context, will also affect inland navigation – both directly and indirectly. The water temperature in navigable river sections depends on the air temperature. Global air temperature has risen by 0.85°C since the beginning of the 20th century. An accelerated increase in the annual mean air temperature of 0.2°C per decade (compared to an increase of 0.126°C per decade within the last 50 years [IPCC AR5, 2014a], is expected for most of the GHG emission scenarios within the next 20 years.

Based on the projected air temperature changes discussed in Section 3.1.1, the water temperature in rivers will rise by an approximately similar amount. With the rise of water temperature, especially in winter, freezing of rivers and channels in mid-latitudes (e.g. Germany, Poland, parts of the USA/Canada, China and Russia), will generally occur less frequently (see Section 4.1.5). There will also be consequences for aquatic biology (see Section 4.1.6). However, detailed studies of water temperature changes specific to navigable inland waterways are missing so far.

4.1.2 Precipitation

Precipitation is the predominant factor in water supply to navigable rivers. The annual trend of precipitation shows a large regional variability in the last century. Observed trends in annual precipitation for the period 1951-2010 (Figure 4.2) reflect the spatial variability of precipitation, which responds to atmospheric forcing of differing spatial resolution. Interannual variability remains high even in regions with pronounced trends (e.g. Central North America), but this is not always the case (e.g. Northern Asia).

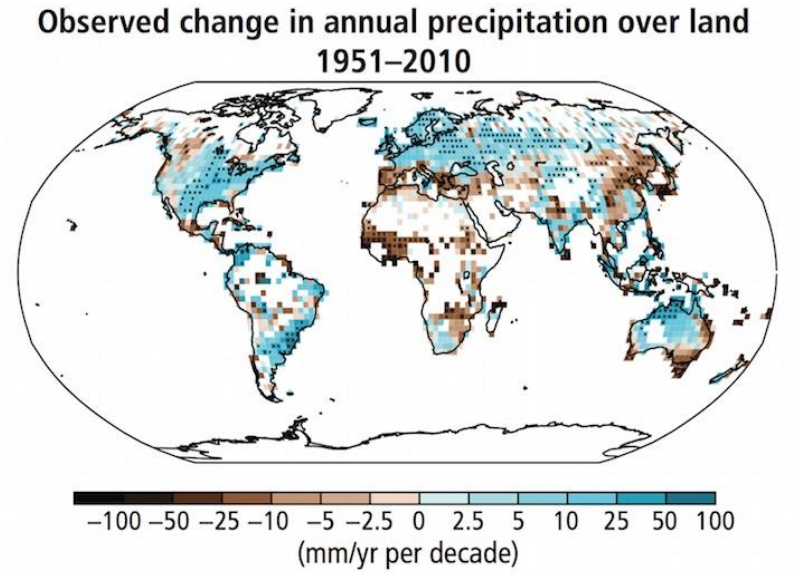


Figure 4.2: Trends in observed precipitation change, from 1951 to 2010 (reproduced from IPCC AR5, (2014a), Figure 1.1(e))

The change of annual precipitation expected in the future depends on the assumed scenario of the emission of greenhouse gases. While models predict regions of increasing annual precipitation with climate warming (Figure 3.8 and 4.3), substantial spatial and seasonal variations are also expected [IPCC AR6, 2021]. As previously presented in Sections 3.1.8 and 3.2.8, changes in precipitation will not be uniform. The high latitudes and the equatorial Pacific are likely to experience an increase in annual mean precipitation under the RCP8.5 scenario. In many mid-latitude and subtropical dry regions, mean precipitation will likely decrease, while in many mid-latitude wet regions, mean precipitation will likely increase under the RCP8.5 scenario (Figure 4.4).

Also of importance to waterborne transport, extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent.

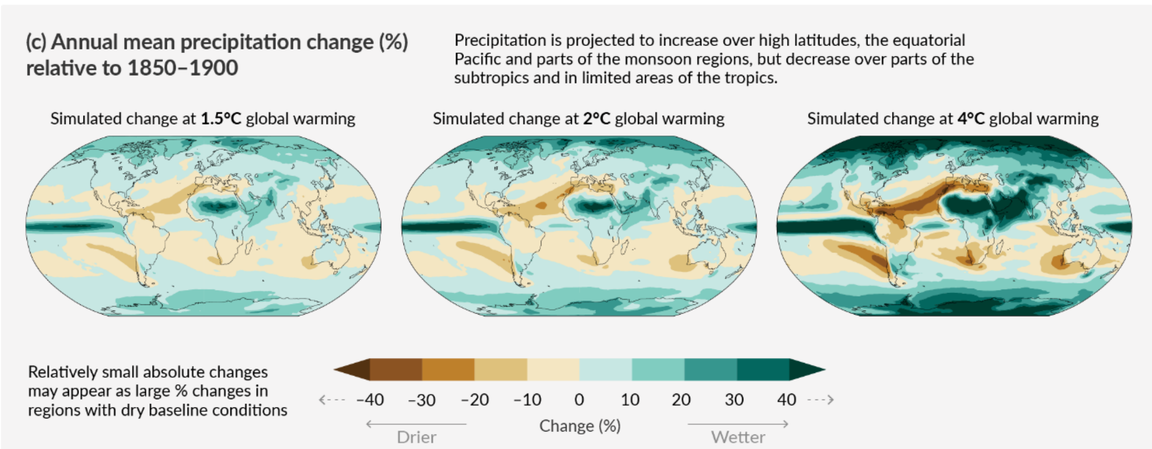


Figure 4.3: IPCC AR6 Figure SPM.5 – precipitation change at global warming levels of 1.5°C, 2°C and 4°C (20-year mean global surface temperature change relative to 1850-1900). Simulated changes correspond to Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model mean change at the corresponding global warming level. A high positive percentage changes in dry regions may correspond to small absolute changes.

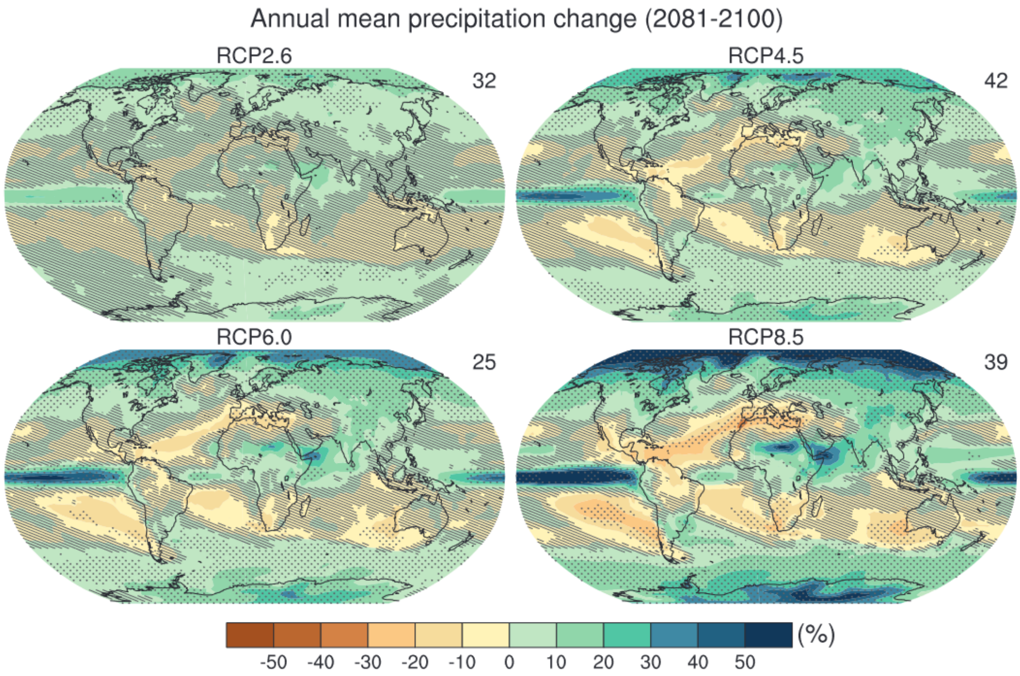


Figure 4.4: IPCC AR5 (2013) Figure TS.16 | Maps of multi-model results for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in 2081–2100 of average percent change in mean precipitation. Changes are shown relative to 1986–2005. The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. Hatching indicates regions where the multi- model mean signal is less than 1 standard deviation of internal variability. Stippling indicates regions where the multi- model mean signal is greater than 2 standard deviations of internal variability and where 90% of models agree on the sign of change.

In addition to the change in annual precipitation, the seasonal cycle of precipitation may change. In North America, northern Asia and northern Europe, precipitation is projected to increase in winter, while, especially in northern Europe, a reduction in summer precipitation is also expected. In parts of the United Kingdom, for example, a range of scenarios indicates that winter rainfall can be expected to increase by +10 % to +50 % whilst a reduction in total summer rainfall of -20 % to -70 % is possible [Met Office, 2021]. Furthermore, the frequency of heavy precipitation is increasing especially in North America and Asia. According to Figure 4.3, there is high uncertainty in projected precipitation change in Central Europe, Central Asia and Central United States.

Besides the annual cycle of precipitation, its form, i.e. rain or snow, significantly influences the water supply in navigable rivers and its annual cycle [Barnett et al., 2005]. Due to the increase of air temperature, the storage of water in a snow cover during winter and its release during summer melting is reduced [Nijssen et al., 2001]. For example, the resulting change in the annual cycle of discharge is already seen in the Rhine River in Europe, where it is reported that the mean discharges and baseflows may decrease in the summer months, with the potential for temporary impacts on navigation and logistics along some stretches. In winter the trends towards an increasing mean discharge will continue [FMTDI, 2015].

Finally, the increase in air temperature also influences the ratio of effective precipitation to total precipitation. Due to the increase in air temperature, an increase of evapotranspiration is anticipated, which will globally reduce the ratio of effective precipitation to total precipitation. However, detailed studies are needed to understand whether this will be an issue in a particular river catchment.

4.1.3 Extreme Hydrological Conditions

IPCC AR6 (2021) reports the paradoxical situation that warming climate increases the incidence of both floods and drought, but at different times and places. The extreme hydrological events with the greatest impact on the inland navigation sector are changes in seasonal precipitation; increased intensity of extreme rainfall; and increases in both high (or larger) and low (or smaller) discharges.

The change in the flow regime of rivers caused by the decreasing buffering of water in snow cover is expected to exacerbate extreme hydrological events in some catchments, with more floods in winter and more droughts in summer. However, only very few calculated results on future changes of the probability of extreme hydrological events can be found, e.g. for the River Meuse in Europe, a 10 % increase in the probability of river flooding is found. Compared to the estimates of the future mean discharge conditions, however, the prognosis of extreme hydrological events is more uncertain, e.g. for the River Meuse the uncertainty is four times higher than the expected effect of climate change [Booij, 2005].

4.1.4 River Morphology

River morphology reflects the supply and transport of sediments from source to sea in a catchment. In the event of climate change, both sediment supply and sediment transport are subject to change.

The change in river discharge, discussed in Sections 4.1.2 and 4.1.3, will alter the sediment supply into the rivers because of associated changes, for example in soil erosion. An increase in soil erosion is typically related to an increase of effective precipitation, although changes in land use are another important influence. For example, for the catchment of the River Rhine, estimates of the increase of soil erosion range from zero up to 38 % until 2050, depending on the scenario of the expected emission of greenhouse gases and of future land use [Asselman, 1997]. Furthermore, a recent study by the Federal Ministry of Transport and Digital Infrastructure in Germany [FMTDI, 2015] concluded that the choice of maintenance strategy can have a larger influence on the riverbed development and the sediment balance than the possible variation in discharge characteristics related to climate change.

Changes in precipitation will cause changes in river discharge which, along with the increasing probability of extreme hydrological events as discussed in Section 4.1.3 could cause changes in river channel and bank erosion, sedimentation and sediment transport. Although there is considerable literature on past changes in flow in various rivers, whether caused by human influences or natural climatic variability, and associated changes in morphology, there is very little literature on possible future channel changes. This may be attributed to a lack of physically based models of river channel form and sediment transport, in turn resulting in little confidence in estimates of the effect of climate change on river channels [IPCC AR6, 2021]. The prediction of changes in sediment transport also shows a great dependence on the expected scenario of greenhouse gas emission. The uncertainty of this prediction is even larger when considering different scenarios of land use change, which could ultimately result in a decrease of total annual sediment load [FMTDI, 2015]. Dahl et al. (2018) modelled two adjacent watersheds in the northern United States and found that even the same emissions scenario would likely result in increased sediment yield and dredging in one watershed, but decreases in the other, due to projected land use in each watershed.

4.1.5 Changes in Ice Cover

IPCC SROCC (2019) concluded that there is only limited evidence of changes in lake and river ice specifically in the mountains, indicating a trend, but not universally, towards shorter lake ice cover duration consistent with increased water temperature. The lack of a clear overall global trend, and the need for site-specific investigations to understand conditions locally, is illustrated by the examples in Table 4-2.

Region/water body type	Reference	Period investigated	Main findings
Tibetan Plateau lakes	Cai et al. (2019) Du et al. (2017)	2000-2017 2002-2015	Shorter duration ice cover on 40/58 lakes and 43/71 lakes respectively but large interannual variability meant statistically significant trends on only a few lakes.
Austrian lakes	Kainz et al. (2017) Niedrist et al. (2018)	1921-2015 1972-2015	Significant trend towards later freeze and earlier ice break-up but also significant interannual variability.
Canadian rivers	Rokaya et al. (2018) in IPCC, 2019	1903-2015	Highly variable trends in timing and magnitude of river ice jams.
USA lakes	U.S EPA, 2020	1850-2015 1984-2015	Trend towards shorter ice period; later first freeze apparent from 1850 but less uniformity in trend for thaw dates.
Europe: Finland lake Danube river	European Environment Agency[9]	1833-2011 1876-2011	Overall, average duration of ice cover has shortened at a mean rate of 12 days per century. Icing typically occurring nearly six days later with ice break-up around six days earlier.

Table 4-2: A list of examples to illustrate the lack of a clear global trend

The United States Environmental Protection Agency (EPA) has long-term indicators for the development of ice cover for nine U.S. lakes, which indicate a shorter ice period than previously in those lakes [U.S EPA, 2020]. Figure 4.4 and Figure 4.5 show the first freeze and thaw

[9] **https://www.eea.europa.eu/data-and-maps/indicators/lake-and-river-ice-cover-1**/assessment and Centre for Economic Development, Transport and the Environment of North Savo, Finland

dates respectively for these lakes. While the trend for later first freeze dates is apparent starting in 1850 for all nine lakes, there is less uniformity in trends for the thaw dates: many of the thaw dates cycles of earlier and then later trends are within the 1984-2015 period.

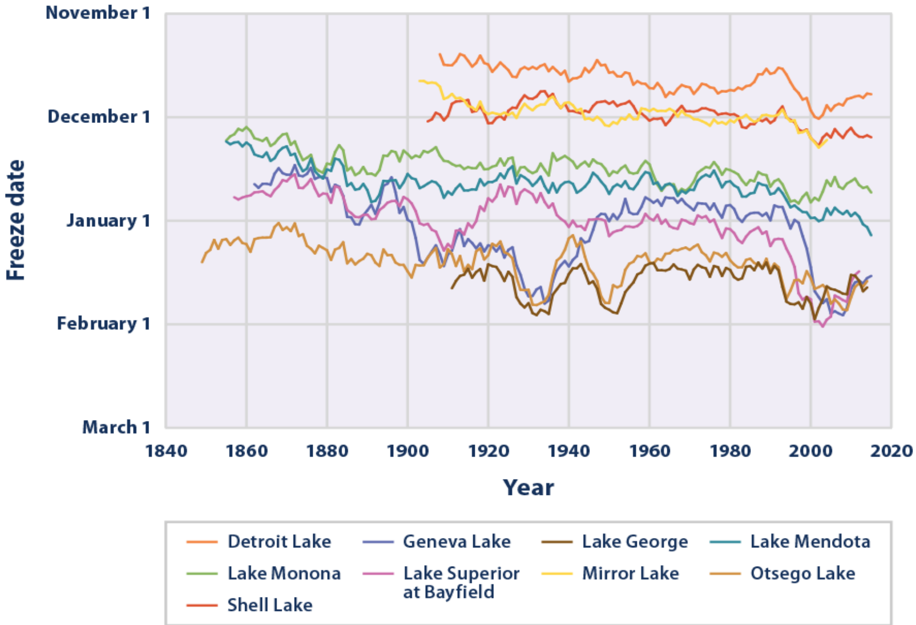


Figure 4.4: The first freeze date for selected U.S. lakes from 1850-2015 (copied from U.S EPA (2020))

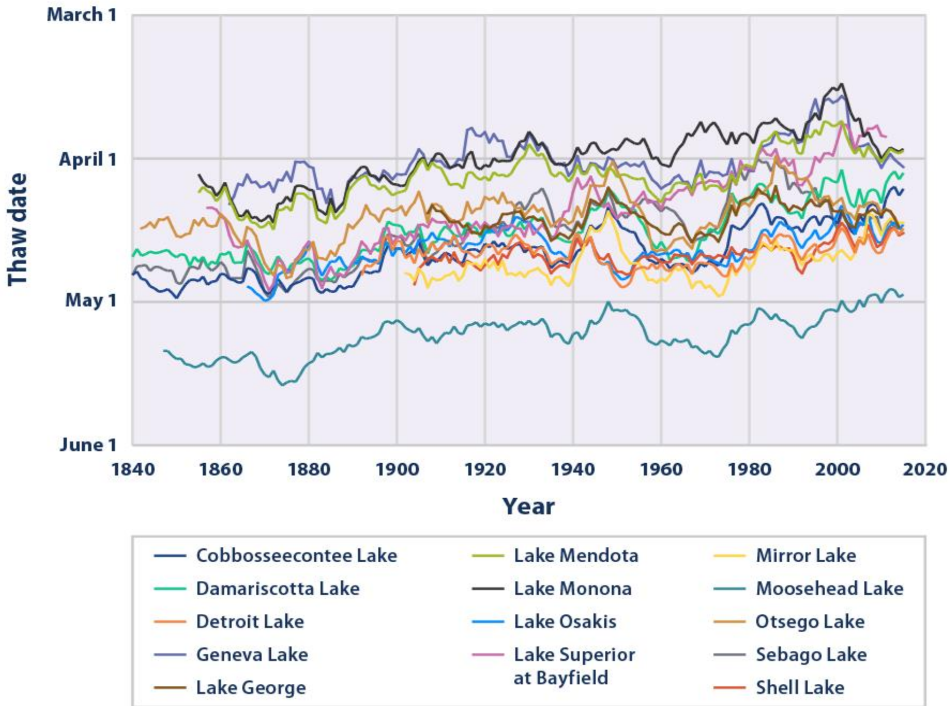


Figure 4.5: Date of ice thaw for selected U.S. lakes from 1840-2015 (copied from U.S EPA (2020))

Similar developments can also be seen in Europe according to European Environment Agency (EEA). These long-term statistics point out a trend towards later freeze-up and earlier break-up dates in some European lakes and rivers. For instance, it is estimated that the ice-covered period in Lake Kallavesi in Finland has shortened by nearly a month since the monitoring started in 1834. On average, it has been estimated that the duration of ice cover in the northern hemisphere has shortened at a mean rate of 12 days per century over the last 150-200 years, resulting from a 5.8 day later ice cover and a 6.5 day earlier ice break-up on average.

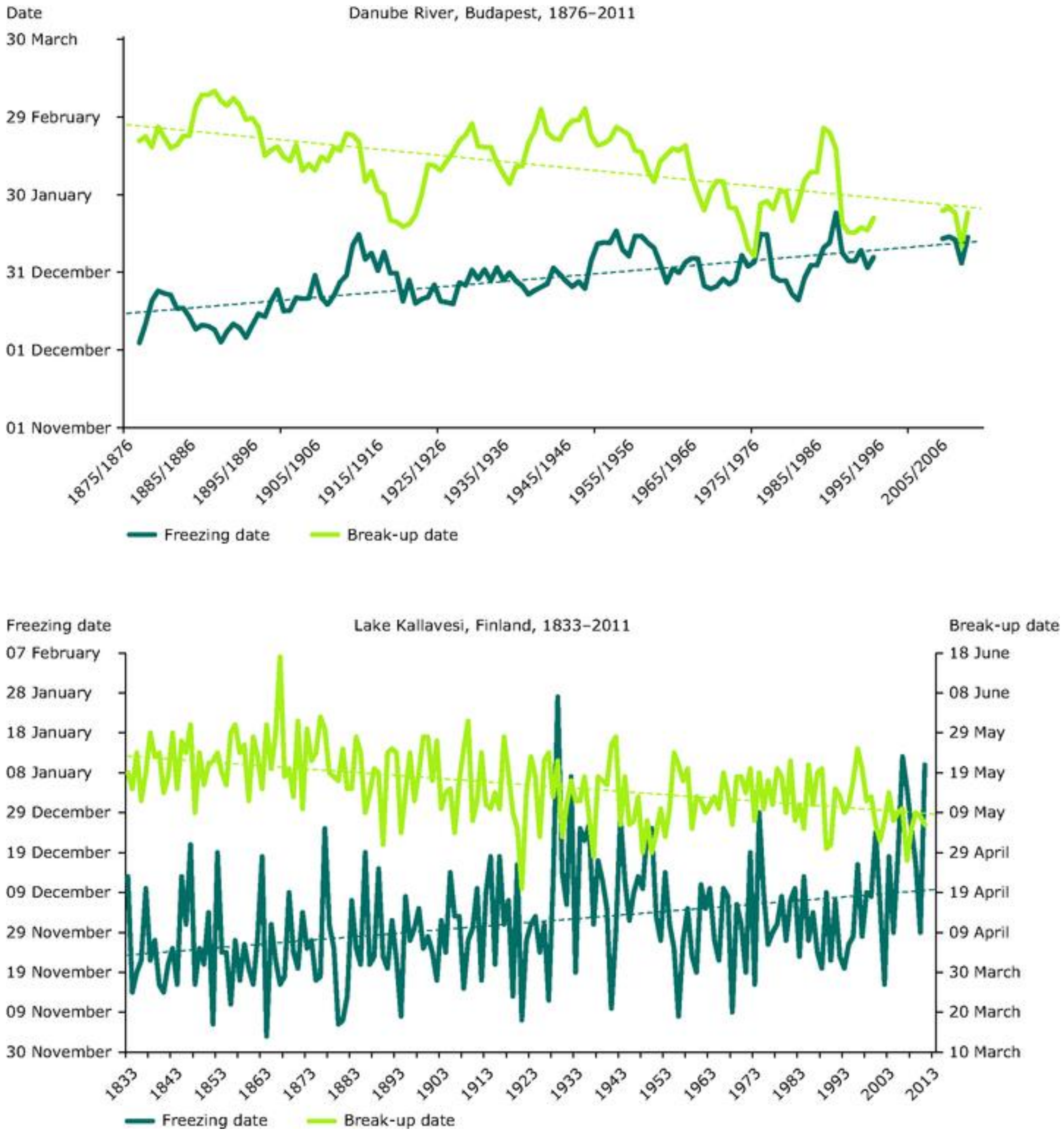


Figure 4.6: Freezing and break-up dates of Lake Kallavesi (Finland) and River Danube (Budapest, Hungary)[10]

[10] Figure are copied from **https://www.eea.europa.eu/data-and-maps/indicators/lake-and-river-ice-cover-1/assessment** and Centre for Economic Development, Transport and the Environment of North Savo, Finland)

4.1.6 Ecological Effects

Changes in water temperature will directly and indirectly affect aquatic ecology in several different ways including through changes in evaporation, oxygenation, stratification, nutrient levels, growth rates and the overall suitability of habitats for both native and non-native species. Some changes in ecological characteristics will impact on navigation interests [Fenoglio et al., 2010].

Increased water temperature will lead to increased evaporation (e.g. in the late autumn and winter). In summer, higher temperatures will tend to cause an intensification of oxygen depletion in rivers due to enhanced biological activity in many regions [Lindenschmidt et al., 2018]. Increases in air temperature, changes in precipitation and evaporation can all lead to habitat and species changes – for example desiccation associated with changes in seasonal rainfall or increases in the frequency of droughts/heatwaves can impact on the survivability of characteristic riverbank vegetation species [PLA, 2015].

In lower river reaches, as discussed in Section 3.1.9 there may be changes in salinity and saltwater intrusion due to rising sea levels; changes in stratification or mixing; and/or precipitation changes. Such changes will affect the characteristic biology in impacted river reaches.

River ice plays an important role influencing in-stream habitat for fish, invertebrates, and aquatic plants. Changing ice regimes influence the behaviour and biological response of aquatic biota thereby affecting their growth, survival, and reproduction [Prowse et al., 2011]. Such changes in river ice regimes have meaningful biological consequences as they determine stratification conditions that affect the entire freshwater food web. One such consequence is earlier algae bloom times at the base of the food web [Hannah, 2015].

Surface ice creates habitats that shelter fish, so reduced ice cover will lead to a loss of suitable winter habitat. An increased number of winter warm spells that lead to mid-winter ice break-up may impact aquatic habitat availability. Changes in ice cover can also impact fish migrations. Movement of anadromous fish to overwintering habitats occurring prior to river ice formation as well as local movements between habitats occurring after ice formation can be impacted. This could lead to that habitat being less preferred due to lack of surface ice cover. Changes in ice-cover duration and break-up timing can alter river flow regimes, thereby influencing fish migratory routes and the timing of fish runs [Prowse et al., 2011]. Indeed, water temperature changes at all latitudes can impact on fish and other migratory aquatic species, not only affecting migratory routes and timing, but impacting on habitat suitability and leading to range and distribution changes as species shift permanently to areas where conditions are more favourable.

Higher water temperatures will impact more widely on both vegetation growth rates and habitat suitability for temperature-sensitive species. Warming typically stimulates the growth of both native and non-native aquatic plants (macrophytes), including waterweed species [Zhang et al., 2019]. The growing season may also be extended. Canadian waterweed (Elodea canadensis), Egeria densa (Brazilian waterweed) and Curly waterweed (Lagarosiphon major) are examples of non-native species of concern in European waterways as water temperatures increase [Silveira et al., 2017].

4.2 Potential Impact on Inland Navigation

Climate change will result in a number of general impacts on navigation and inland port operations as well as on related infrastructure. These are summarised in Table 4-2 (adapted from PIANC WG 178 (2020)), where the ticks indicate the climate parameter or process associated with potential impacts to navigation infrastructure or operations. Section 4.2 elaborates on these and the other drivers of change relevant to inland navigation discussed in Section 4.1.

Parameter or process >> **Impact susceptibility**	**Air temperature**	**Water temperature**	**Precipitation**	**Storminess**
Flooding due to overwhelmed drainage systems or high groundwater levels			✓	✓
Overtopping due to high water levels			✓	✓
High in-channel flow velocities			✓	✓
Low river flow conditions, drought or reduced water supply	✓		✓	
Changes in bathymetry, or sediment or debris transport			✓	✓
River bed or bank erosion			✓	✓
Damage to breakwaters or other port structures				✓
Fog or other reduced visibility issues	✓	✓	✓	
Wind speed, strength, direction, duration	✓			✓
Interruptions to sea and/or land side supply chains	✓		✓	✓
Extreme cold, ice or icing	✓	✓		
Extreme heat or humidity	✓			
Changes in water chemistry		✓		
Changes in biological character	✓	✓	✓	

Table 4-3: Examples of typical relevant parameters and processes based on impact susceptibility

4.2.1 Air and Water Temperature

In addition to the gradual changes in air and water temperatures, it is widely predicted that heatwaves frequency will increase (Section 3.1.1). Rising temperatures will not only have consequential effects for seasonal precipitation, wind, storms, etc. they will also have direct effect on certain types of waterway assets or activities.

Without adaptation, increases in maximum (or minimum) air temperatures or high humidity levels could compromise the health and safety of port or waterway personnel working outside, in offices or storage facilities, or operating equipment. High temperatures or humidity levels can also adversely impact on the handling or storage of sensitive cargo; or operating limits for plant and equipment may be exceeded. Heatwaves (where temperatures exceed a defined threshold for a number of days) can cause problems for road pavements, for rail tracks and overhead wires or for lock or bridge mechanisms, and hence for transport of cargos by any mode.

Changes in water temperature are expected to affect navigation due to biological or chemical changes as well as indirectly through regulations to protect and enhance riverine and estuarine ecosystems. Warmer water temperatures, resulting in an increased occurrence of oxygen deficits for the same nutrient loading, will adversely impact these ecosystems. If oxygen deficits are compensated by discharging water over spill weirs, the water depth in some navigable rivers could be reduced.

Water temperature changes can affect both native and non-native species, with consequences for navigational safety, infrastructure integrity or operational efficiency, or port and waterway users' commercial interests. These potential biology-related changes are elaborated in Section 4.2.6.

4.2.2 Precipitation

Climate drivers in the form of increases and decreases in total precipitation, changes in the form and quantity of seasonal precipitation and increases of intensity of extreme rainfall will cause a range of impacts to inland navigation. Increased total winter rainfall, more intense summer rainfall, or less snow cover and hence snowmelt contributing to a reduction in water supply in springtime could all affect navigability. Associated increased and decreased water levels and velocities may in turn affect sedimentation processes leading to bank failure, local scour, or changes in locations of aggradation and degradation. Changes in water levels that impact the movement of sediment, and hence channel maintenance activities, will require increased or reduced dredging, depending on location-specific impacts.

Changes in water level and velocity can impact manoeuvrability and the operational efficiency of inland navigation. Higher water levels may restrict barge loading heights to ensure safe air clearances below critical bridge deck elevations; low water levels may restrict barge loading tonnages to maintain safe under-keel clearance. Navigation structures may experience loadings different from design loading, affecting stability and resiliency. Long-term higher or lower water levels could require modifications to existing ports and mooring areas or may reduce their potential for expansion.

Changes in the timing of seasonal high water and seasonal low water may impact shipping and maintenance schedules. These issues are already being observed in the North American Great Lakes, where falling lake levels due to changes in precipitation reduces ship clearance in channels and harbours and increases demand for dredging [Kling et al., 2003].

Insofar as the port estate and its surroundings are concerned, changes in precipitation characteristics may also lead to an increase in the risk of surface water or ground water flooding (see Section 3.2.8). Ensuring adequate capacity, upgrading and maintaining drainage systems will become important requirements for some inland ports.

4.2.3 Extreme Hydrological Conditions

The occurrence of more extreme floods and droughts will exacerbate impacts identified in Section 4.1.3. For example, in August 2022, the Rhine River reached its lowest point ever measured by the Ministry of Infrastructure and Water Management of the Netherlands. Inland navigation was strongly disturbed leading to higher prices for bulk good and fuel. In the meantime, discussions about the low water challenges facing the Rhine[11] had concluded there is no one-size-fits-all solution, rather a range of actions needs to be taken rapidly regarding adaptation of fleet, infrastructure, logistics and storage concepts, as well as implementation of digital tools, in order to ensure the reliability of inland navigation and to avoid a permanent shift to other transport modes.

4.2.4 River Morphology

Changes in sediment load will cause changes in riverbed and/or bank erosion or accretion (river dune development), as well as changes in floodplain sedimentation, and will therefore potentially require an adaptation of sediment management protocols. For example, changes in the quantity or frequency of dredging may be required to maintain safe navigable depths.

Changes in morphology may also impact on riverine habitats and species, and hence on navigation operations, as discussed in Section 4.2.6.

4.2.5 Changes in Ice Cover

Although many climate trends indicate shorter periods of ice cover with associated benefits for ice-free access, a high degree of variability in local climatic conditions is still expected to cause ice impacts to inland navigation in many years. Warmer early winter air temperatures, followed by a rapid decrease in air temperature, can result several cycles of ice formation during winter months. This will result in increased occurrence of freeze up jamming. For example, the early winter of 2006-2007 was relatively warm in the continental United States, with the result that few ice covers were formed. When temperatures dropped in late January, the combination of ice-free rivers and high discharge resulted in significant ice production which impacted navigation along the Mississippi River (Figure 4.7). While reducing the period of ice cover, earlier mechanical breakup due to rainfall events can coincide with higher than normal ice strength, resulting in midwinter ice jams that freeze in place or jams that occur in different locations than expected.

Elsewhere however, including in the Great Lakes, the decreased duration of ice cover may be beneficial, resulting in extended navigation seasons.

---

[11] https://www.ccr-zkr.org/files/documents/workshops/wrshp261119/ien20_06en.pdf

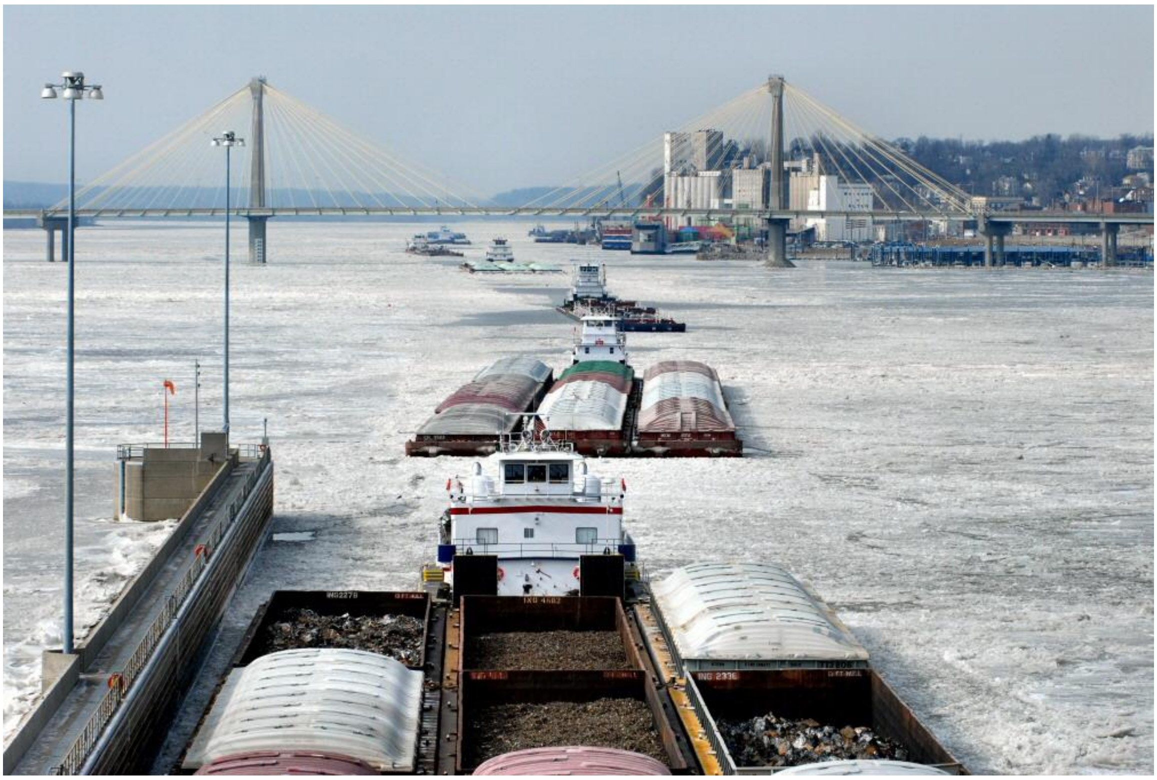


Figure 4.7: Tows delayed during ice conditions, Melvin Price Locks and Dam, Mississippi River, February 2007; ice build-up in the lock caused one tow to become stuck, temporarily shutting down the lock; later, width restrictions were implemented (photo by Russell Elliott courtesy of US Army Corps of Engineers)

4.2.6 Fresh Water Ecology

Water temperature changes can directly and indirectly affect both native and non-native species, with consequences for navigational safety, infrastructure integrity, operational efficiency or port and waterway users' commercial interests.

In riparian zones, vegetation can play an engineering role, for example a dense root mat can contribute to bank stability. Desiccation may lead to problems including species death, erosion and bank collapse. Suitable alternative (e.g. drought-tolerant) species may therefore need to be identified and planted in order to help maintain structural integrity [IWAC, 2009].

Section 4.1.5 notes that changes in ice-cover duration and break-up timing are among the climate-induced changes that can impact on species' migratory routes and timing as well as leading to changes in these species' supporting habitats. Section 4.1.1 explains that water temperature is more generally likely to increase leading to changes in characteristic ecology. Where changes in habitat suitability result in range changes (i.e. species shift permanently to areas where conditions are more favourable), this may impact on the viability of socio-economic and recreational activities such as fishing and wildlife watching, with implications for related navigation and navigation infrastructure provisions. It may also lead to the de-designation of existing sites or the new designation of protected areas supporting certain species, in turn potentially resulting in additional or changed constraints on waterway maintenance and/or new waterway development activities.

Increased growth rates of native vegetation or invasive aquatic plants can block waterways, obstruct boat passage and pose a hazard to safety of navigation particularly in canals and slow-flowing rivers. They can also clog intakes and sometimes cause damage to boat engines and propellors. Warming water temperatures are likely to increase maintenance requirements and therefore costs (e.g. cutting regimes), particularly on smaller waterways and those used for recreation. Where the invasive species involved are not native to the local environment, there are also potential biodiversity and/or liability issues.

Warmer water results in an increased occurrence of oxygen deficits for the same nutrient loading, will adversely impact freshwater ecosystems. As noted in Section 4.2.1, there may be a competing interest between managing oxygen deficits and managing water depth in navigable rivers. Changes in salinity or saline intrusion may similarly affect the characteristic ecology of a water body, with potential implications for the navigation.

5 RESPONSES TO CLIMATE CHANGE

The previous sections explain how and why changes in temperature are linked to changes in sea level, wind and wave conditions, ice conditions in polar regions, precipitation, storm intensity, extreme heat and other variables. Whilst the rate and extent of change in most variables will depend on the success of the Paris Agreement in reducing global greenhouse gas emissions, some changes have already taken place and others are effectively locked-in. If potentially significant disruption to maritime and inland navigation infrastructure and operations is to be minimised, action will be needed to strengthen resilience and, where appropriate, adapt.

The exact responses required will vary from one location to another, and will depend on such variables as local/regional rates of change in relevant parameters; exposure; the availability of resources; and the range of potential adaptation options (including relocation) available. According to the World Bank, the overall net benefits of investing in resilient infrastructure in developing countries could amount to $ 4.2 trillion over the lifetime of new infrastructure – a $ 4 benefit for each dollar invested in resilience [UNCTAD, 2021, citing Hallegatte et al., 2019]. Many other studies similarly demonstrate that investing in climate-resilience makes good economic sense – as illustrated by [Hanson et al., 2011] which examined climate impacts on port cities. However, a multitude of factors will determine the cost-effectiveness of specific options on a local basis.

Some adaptation measures can be implemented at a relatively small marginal cost (e.g. measures such as risk and vulnerability assessments informing early warning systems or the preparation of disaster response plans), but others may be expensive in terms of investment or operating costs or both. There are not only legal or technical, but also economic limits to adaptation responses [Renner and Bialonski, 2003]. In some cases, it may be necessary to accept the increased risk and put contingency plans in place. In others, transformational change such as relocation of assets or facilities, or modal shift, may be necessary.

PIANC WG 178 (2020) and PIANC PTG CC Technical Note No.1 (2022) provide, respectively, detailed guidance on the conceptual development and evaluation of adaptation and resilience options for designers, managers and operators of navigation infrastructure, and advice on managing uncertainties. The WG 178 guidance introduces a four-stage methodological framework, assisting the reader in understanding the background information needed for informed decision-making; the availability of climate data and the use of climate change scenarios; climate change vulnerability and risk assessments; and identifying/evaluating possible responses (see Figure 5.1).

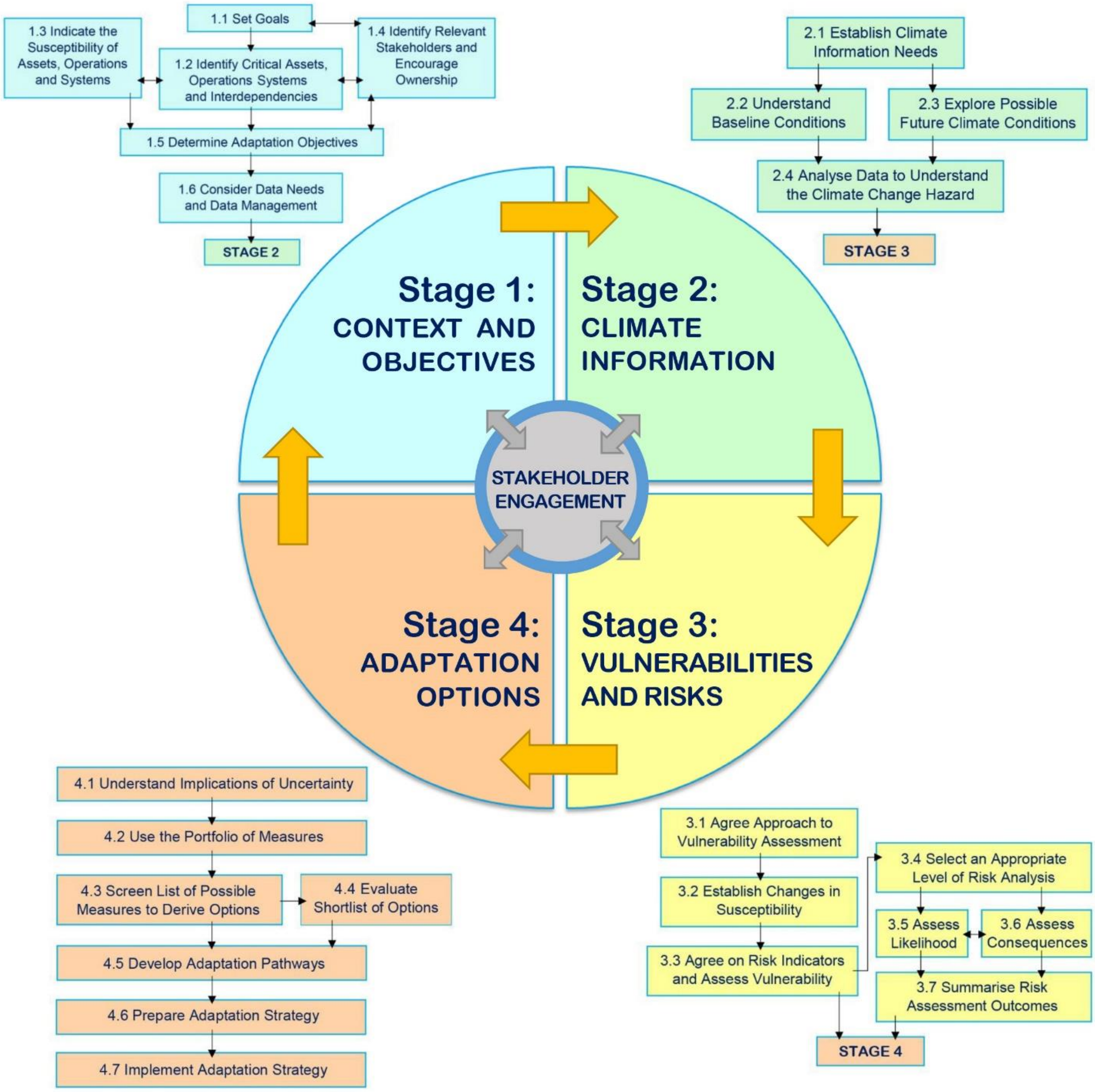


Figure 5.1: The four stages in the climate adaptation planning process

Insofar as existing port and waterway infrastructure and operations are concerned, the WG 178 report also presents a portfolio of potential adaptation measures, categorised in line with the IPCC AR5 report [IPCC, 2013] according to whether they are physical, social or institutional. These are presented in Table 5.1 below.

Physical	… including structural, engineered, technological, systems and service-based interventions. This category of measures covers hard and soft engineering measures, nature-based solutions, maintenance activities and new products.
Social	… people-based, including operational, management, educational, information-related and behavioural measures. Awareness-raising, training, early warning, incident response, contingency planning, operational modifications and data collection are examples from this category.
Institutional	… including governance, economics, law, regulation, policies and programmes. This category covers legal and financial incentives and penalties, mapping and zoning, spatial planning and the role of design or building standards.

Table 5.1, taken from PIANC WG 178 (2020), illustrates a range of generic measures to strengthen resilience and adapt port and waterway assets and operations. This guidance document also contains an annexed series of hazard-specific measures' tables (e.g. in relation to flooding, extreme heat or cold, high winds, high or low flow conditions, and so on).

Physical measures **Structures, systems, technologies, services**	**Social measures** **People, behaviour, operations, information**	**Institutional measures** **Governance, economics, regulation, policy**
Prioritise maintenance to maximise operational resilience and improve adaptive capacity	Undertake climate change risk assessment, prepare risk maps	Prepare strategic level climate change adaptation strategies
Install real-time monitoring infrastructure	Prepare and raise awareness of contingency, emergency or disaster response plans	Review and revise relevant codes of practice, standards, specifications or guidelines to accommodate changing conditions
Use Cloud (back-up) for data storage to reduce physical risks	Introduce and regularly review warning systems	Review health and safety requirements and revise if needed
Relocate vulnerable assets and equipment out of high-risk areas	Prioritise asset inspection	Introduce penalties for non-compliance with standards
Revert to phased array for radar	Educate workforce, stakeholders, local communities	Require zoning of assets, operations or activities based on risk
Invest in redundancy, temporary infrastructure or other physical back-up provision for critical assets (including power and water supply)	Liaise and coordinate with utilities and other service providers; develop information-sharing protocols	Use local regulations (e.g. byelaws) to reduce risks, especially in multi-use locations
Reinforce, raise, strengthen or otherwise protect or modify critical assets	Improve (or instigate) monitoring, record keeping and data management, consider cybersecurity issues	Policies to encourage relocation out of high-risk areas
Install or develop new, responsive or demountable infrastructure or equipment	Undertake trend analysis or forecasting	Collaborate with land-use planning systems e.g. to introduce set back or buffer areas
Install warning equipment	Develop revised operational protocols; modify working practices as conditions change	Limit new infrastructure development in high-risk areas
Nominate or provide physical sanctuaries	Introduce and implement adaptive management procedures, base operations or working arrangements on monitoring outputs	Identify, secure and coordinate alternative transport routes or modes
Increase storage capacity	Allow for flexibility and responsiveness in programming (increase operational hours, modify staffing rotas, vessel scheduling, lock operation, etc.)	Promote reduced insurance premiums if improved resilience is demonstrated
Install multi-modal equipment	Be prepared to revert to traditional, low tech ways of operating if needed (binoculars, telephone, paper charts, two-way radios, etc.)	Set up contingency or disaster response fund
Apply nature-based solutions, Working with Nature, soft engineering		Introduce and enforce build-back-better or build-out-of-harm's-way policy
Install treatment or reception facilities		
Incorporate flexibility in new or replacement infrastructure design		

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

	Revert to traditional, low tech, ways of operating; ensure binoculars, telephone, paper charts, two-way radios are available Ensure availability of transport and accommodation for personnel during an incident Temporarily or permanently restrict activities in high-risk areas Nominate safe routes and areas, identify diversions Identify and exploit interconnectivity and intermodal options to maintain business continuity during events Provide training on new tools, codes of practice, procedures or protocols, ensure importance of redundancy is understood Facilitate technology transfer	Improve legal protection for vulnerable habitats with risk reduction role (e.g. absorbing wave energy, providing erosion protection) Provide grants or incentives e.g. for development or maintenance of resilient infrastructure Research and develop novel tools and methods

Table 5-1: Generic measures for strengthening resilience or adapting assets, operations or systems [PIANC, 2020]

6 PORT AND WATERWAY CONTRIBUTIONS TO REDUCING GREENHOUSE GAS EMISSIONS

With over 80 % of global merchandise trade by volume and more than 70 % by value being seaborne [UNCTAD, 2017], ports and maritime transport facilities constitute key nodes in global supply chains. They are vital to global production processes that rely heavily on manufacturing, outsourcing and low-cost shipping. As noted in Section 1.2, international shipping is responsible for approximately 2 % of the total anthropogenic emission of greenhouse gases.

Compared to emissions from international shipping, GHG emissions from inland waterway vessels and from port and waterway infrastructure and activities are relatively small. Port and waterway operators nonetheless have an important role to play, not only in reducing emissions from their own assets and operations, but also in facilitating the reduction of GHG emissions from vessels.

In order to explore what actions can be taken to reduce GHG emissions from port and waterways, PIANC WG 188 (2019) was tasked to investigate the carbon footprint of activities related to development, maintenance and operation of navigation channels and port infrastructure including the management of dredged material. Life-cycle analysis (LCA) and other assessment methods supported this investigation and provided insights into opportunities for improved carbon management.

The resulting guidance emphasises how developing a carbon management framework and taking proactive steps to effectively manage carbon will help those responsible for port and navigation infrastructure:

- comply with emerging regulatory requirements,
- respond to general stakeholder and public pressure to reduce environmental burdens,
- take a leadership role in carbon management practices,
- address the UN Sustainable Development Goals,
- drive innovation and investment while influencing future practice and regulation
- cut costs; including through efforts to reduce energy consumption.

In addition, WG 188 (2019) draws attention to several unique opportunities to reduce and offset emissions from waterways navigation infrastructure development, including through dredging and the beneficial use of dredged sediments, which need to be considered in any carbon management framework for this sector.

The WG 188 guidance describes the important considerations when developing a carbon management framework and describes how emissions can be quantified; it presents a series of good practice case studies; and explores the financial aspects of carbon reduction measures. Overall, it enables the user to manage, influence and prepare reports for a navigation infrastructure project or a port with both land-side and water-side considerations over the whole lifecycle from design to construction to operations/maintenance and end-of-life considerations (see Figure 6.1)

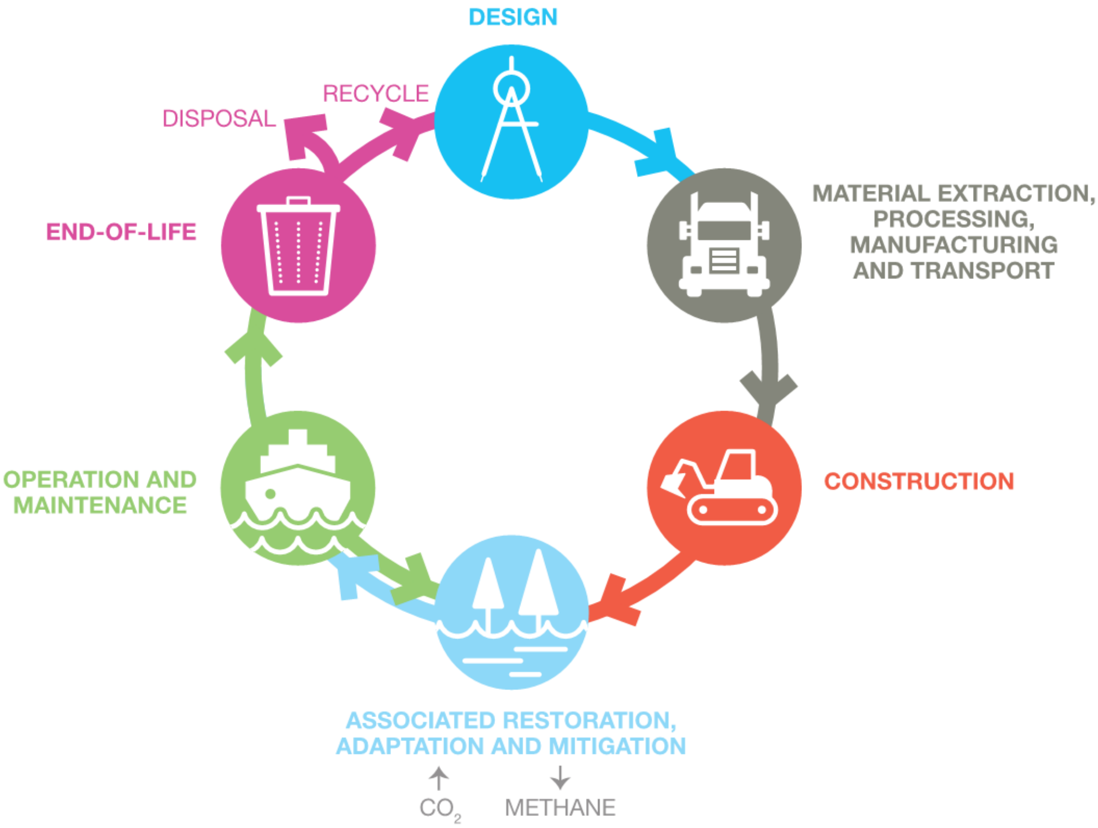


Figure 6.1: WG 188 Carbon Management Life-cycle for Ports and Navigation Infrastructure and Projects

Implemented frameworks at ports and navigational infrastructure are presented as case studies in an appendix to help broaden the navigation community's understanding of the carbon footprint and sequestration potential of port and navigation infrastructure and activities. These case studies also present best practices used to address the carbon footprint of navigation channel development and maintenance projects which can differ based on location and context-specific factors; for example, some strategies may rely more on operational changes while others may seek built or natural infrastructure solutions.

Port and waterway organisations interested in taking action to reduce their GHG emissions are directed to PIANC WG 188 (2019) publication on 'Carbon Management for Port and Navigation Infrastructure'.

7 CONCLUSIONS

Climate change is already affecting many ports and waterways' infrastructure and operations. To facilitate understanding of how much and how quickly the climate is likely to change, and the potential consequences for sea levels, precipitation characteristics, wind and wave conditions and other relevant variables, this update of the 2008 PIANC TG 3 report provides an overview of the climate science. The update focuses on the drivers of importance to the maritime and inland sectors respectively, exploring the nature of the physical changes expected according to the latest publications of the IPCC, the projections regarding their possible magnitude and extent, and how such changes might impact on navigation infrastructure and operations.

This report, together with the following PIANC publications, provide a suite of sector-specific guidance that will enable the navigation community to explore opportunities, shape polices, and prepare for the adaptation and mitigation challenges climate change is already bringing:

- PIANC WG 188 (2019): "Carbon Management for Port and Navigation Infrastructure".
- PIANC WG 175 (2019): "A Practical Guide to Environmental Risk Management (ERM) for Navigation Infrastructure Projects".
- PIANC WG 178 (2020): "Climate Change Adaptation Planning for Ports and Inland Waterways".
- PIANC TG 193 (2020): "Resilience of the Maritime and Inland Waterborne Transport System".
- PIANC WG 195 (2021): "An Introduction to Applying Ecosystem Services for Waterborne Transport Infrastructure Projects".
- PIANC WG 203 (2021): "Sustainable Inland Waterways: A Guide for Inland Waterway Managers on Social and Environmental Impacts".
- PIANC PTG CC Technical Note 1 (2022): "Managing Climate Change Uncertainties in Selecting, Designing and Evaluating Options for Resilient Navigation Infrastructure".

Adaptation involves preparing strategies, making modifications, or taking other actions that adapt our current infrastructure and operations to account for and accommodate the changing climate. Mitigation, on the other hand, refers to activities that minimize greenhouse gas emissions, reducing contributions to global warming, which is the major driver of climate change. According to IPCC AR6 (2021), although many impacts can be avoided, reduced or delayed by mitigation, and while some adaptation is currently underway to address observed and projected climate change, we are at a critical time in which action on climate change is imperative to avoid catastrophic global temperature change of more than 1.5°C [IPCC SR15, 2018]. Both mitigation and adaptation are therefore required to reduce vulnerability and address the consequences associated with climate change for all transportation sectors, including waterborne transportation.

8 REFERENCES

Asselman, N. E. M. (1997): "Suspended Sediment in the River Rhine: The Impact of Climate Change on Erosion, Transport, and Deposition ('Suspensief sediment transport in de Rijn: het effect van klimaatveranderingen op erosie, transport en sedimentatie')".

Barnett, T.P., Adam, J.C. & Lettenmaier, D.P. (2005): "Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions", Nature, 438(7066), 303-309.

Booij, M.J. (2005): "Impact of Climate Change on River Flooding Assessed with Different Spatial Model Resolutions", Journal of Hydrology, 303(1-4), 176-198.

Bruno, J.F., Bates, A.E., Cacciapaglia, C., Pike, E.P., Amstrup, S.C., Van Hooidonk, R. & Aronson, R.B. (2018): "Climate Change Threatens the World's Marine Protected Areas", Nature Climate Change, 8(6), 499-503.

Cai, Y., Ke, C.Q., Li, X., Zhang, G., Duan, Z. & Lee, H. (2019): "Variations of Lake Ice Phenology on the Tibetan Plateau from 2001 to 2017 Based on MODIS Data", Journal of Geophysical Research: Atmospheres, 124(2), 825-843.

Caldwell, H., Quinn, K.A., Meunier, J., Suhrbier, J. & Grenzeback, L. (2002): "Impacts of Global Climate Change on Freight", Proceedings, Federal Research Partnership Workshop "The Potential Impacts of Climate Change on Transportation", U.S. Department of Transportation Center for Climate Change and Environmental Forecasting, p. 3-32.

Calfas, M. (2021): "Practical Climate Change Adaptation Solutions for Ports", [Online], Available at: **https://www.maritimeuk.org/imh-2021/imh-events/practical-climate-change-adaptation-challenges-and-good-practice-solutions-ports/**.

CCNR (2019): "Annual Report 2019, Inland Navigation in Europe", Market Observation.

Chan, F.T., Stanislawczyk, K., Sneekes, A.C., Dvoretsky, A., Gollasch, S., Minchin, D., David, M., Jelmert, A., Albretsen, J. & Bailey, S.A. (2019): "Climate Change Opens New Frontiers for Marine Species in the Arctic: Current Trends and Future Invasion Risks", Global Change Biology, 25(1), 25-38.

Chauvaud, L., Thouzeau, G. & Grall, J. (2001): "Scallops and Slipper Limpets: Witnesses and Actors of Chronic Changes in an N-Enriched Coastal Ecosystem", Oceanis, 27, 215-238.

Cottier-Cook, E.J., Beveridge, C., Bishop, J.D.D., Brodie, J., Clarke, P.F., Epstein, G., Jenkins, S.R., Johns, D.G., Loxton, J., MacLeod, A., Maggs, C., Minchin, D., Mineur, F., Sewell, J. and Wood, C.A. (2017): "Non-Native Species: Decadal Review of the Impacts of Climate Change on Non-Native Species", Marine Climate Change Impacts Partnership, UK.

Dahl, T.A., Kendall, A.D. & Hyndman, D.W. (2018): "Impacts of Projected Climate Change on Sediment Yield and Dredging Costs", Hydrological Processes, 32(9), 1223-1234.

Danielson, R.E., Zhang, M. & Perrie, W.A. (2020): "Possible Impacts of Climate Change on Fog in the Arctic and Subpolar North Atlantic", Advances in Statistical Climatology, Meteorology and Oceanography, 6(1), 31-43.

Davis, A.J., Jenkinson, L.S., Lawton, J.H., Shorrocks, B. & Wood, S. (1998): "Making Mistakes When Predicting Shifts in Species Range in Response to Global Warming", Nature, 391(6669), 783-786.

Dibike, Y., Prowse, T., Bonsal, B., Rham, L. D. & Saloranta, T. (2012): "Simulation of North American Lake-Ice Cover Characteristics under Contemporary and Future Climate Conditions", International Journal of Climatology, 32(5), 695-709.

Du, J., Kimball, J.S., Duguay, C., Kim, Y. & Watts, J.D. (2017): "Satellite Microwave Assessment of Northern Hemisphere Lake Ice Phenology from 2002 to 2015", The Cryosphere, 11(1), 47-63.

Engelhard, G.H., Righton, D.A. & Pinnegar, J.K. (2014): "Climate Change and Fishing: A Century of Shifting Distribution in North Sea Cod", Global change biology, 20(8), 2473-2483.

Federal Ministry of Transport and Digital Infrastructure (FMTDI) (2015): "The Metropolitan Region Rhine-Neckar: A Case Study of Cooperative Federalism in the Field of Railroad Infrastructure".

Fenoglio, S., Bo, T., Cucco, M., Mercalli, L. & Malacarne, G. (2010): "Effects of Global Climate Change on Freshwater Biota: A Review with Special Emphasis on the Italian Situation", Italian Journal of Zoology, 77(4), 374-383.

Flather, R.A., Baker, T.F., Woodworth, P.L., Vassie, L.M. & Blackman, D.L. (2001): "Integrated Effects of Climate Change on Coastal Extreme Sea Levels", Proudman Oceanographic Laboratory Internal Document No. 140. 20pp.

Gasser, T., Guivarch, C., Tachiiri, K., Jones, C.D. & Ciais, P. (2015): "Negative Emissions Physically Needed to Keep Global Warming Below 20C", Nature communications.

Ghanooni-Bagha, M., YekeFallah, M.R. & Shayanfar, M.A. (2020): "Durability of RC Structures Against Carbonation-Induced Corrosion under the Impact of Climate Change", KSCE Journal of Civil Engineering, 24, 131-142.

Hallegatte, S., Rentschler, J. & Rozenberg, J. (2019): "Lifelines: The Resilient Infrastructure Opportunity", World Bank Publications.

Hannah, D.M. & Garner, G. (2015): "River Water Temperature in the United Kingdom: Changes over the 20th Century and Possible Changes over the 21st Century", Progress in Physical Geography, 39(1), 68-92.

Hannah, L., Midgley, G., Andelman, S., Araújo, M., Hughes, G., Martinez-Meyer, E., Pearson, R. & Williams, P. (2007): "Protected Area Needs in a Changing Climate", Frontiers in Ecology and the Environment, 5(3), 131-138.

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C. & Chateau, J. (2011): "A Global Ranking of Port Cities with High Exposure to Climate Extremes", Climatic change, 104, 89-111.

Haubrock, P.J., Inghilesi, A.F., Mazza, G., Bendoni, M., Solari, L. & Tricarico, E. (2019): "Burrowing Activity of Procambarus Clarkii on Levees: Analysing Behaviour and Burrow Structure", Wetlands Ecology and Management, 27, 497-511.

Haugen, J.E. & Iversen, T. (2008): "Response in Extremes of Daily Precipitation and Wind from a Downscaled Multi-Model Ensemble of Anthropogenic Global Climate Change Scenarios", Tellus A: Dynamic Meteorology and Oceanography, 60(3), 411-426.

Heimhuber, H., Glamore, W., Bishop, M., Dominguez, G., Scanes, P. & Ataupah, J. (2019): "Climate Change in Estuaries – State of the Science and Guidelines for Assessment", [Online], Available at: **https://estuaries.unsw. edu.au/climatechange**.

Hemer, M.A., Fan, Y., Mori, N., Semedo, A. & Wang, X.L. (2013): "Projected Changes in Wave Climate from a Multi-Model Ensemble", Nature climate change, 3(5), 471-476.

High North News (2019): "Container Shipping Is Coming to the Arctic along Russia's Northern Sea Route", Online], Available at: **https://www.highnorthnews.com/en/container-shipping-coming-arctic-along-russias-northern-sea-route**, accessed on 26-02-2023.

Hulme, M., Jenkins, G.J., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G. & Hill, S. (2002): "Climate Change Scenarios for the UK: The UKCIP02 Scientific Report", Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK. 120pp.

Ibáñez, I., Clark, J.S., Dietze, M.C., Feeley, K., Hersh, M., LaDeau, S., McBride, A., Welch, N.E. & Wolosin, M.S. (2006): "Predicting Biodiversity Change: Outside the Climate Envelope, Beyond the Species-Area Curve", Ecology, 87(8), 1896-1906.

Inland Waterways Advisory Council (IWAC) (2009): "Climate Change Mitigation and Adaptation Implications for Inland Waterways".

IPCC AR4 (2007): "IPCC Fourth Assessment Report (AR4)", Climate change, 374.

IPCC AR5 (2013): "Climate Change 2013: The Physical Science Basis", Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC AR5 (2014a): "Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part A: Global and Sectoral Aspects", Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, US.

IPCC AR5 (2014b): "Climate Change 2014: Impacts, Adaptation, and Vulnerability, Part B: Regional Aspects", Working Group II Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, US.

IPCC AR5 (2014d): "Mitigation of Climate Change", Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, US.

IPCC AR6 (2021): "Summary for Policymakers. Climate Change 2021: The Physical Science Basis", Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.

IPCC SR15 (2018): "Summary for Policymakers". *In:* "Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty", Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24, [Online], Available at: **https://doi.org/10.1017/9781009157940.001.**

IPCC SROCC (2019): "IPCC Special Report on the Ocean and Cryosphere in a Changing Climate", Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp.

Izaguirre, C., Losada, I.J., Camus, P., Vigh, J.L. & Stenek, V. (2021): "Climate Change Risk to Global Port Operations", Nature Climate Change, 11(1), 14-20.

Kainz, M.J., Ptacnik, R., Rasconi, S. & Hager, H.H. (2017): "Irregular Changes in Lake Surface Water Temperature and Ice Cover in Subalpine Lake Lunz, Austria", Inland Waters, 7(1), 27-33.

Kling G.W., Hayhoe K., Johnson B., Magnuson J.J., Polasky S., Robinson S.K., Shuter B.J., Wander M.M., Wuebbles D.J., Zak D.R., Lindroth R.L., Moser S.C. & Wilson M.L. (2003): "Confronting Climate Change in the Great Lakes Region: Impacts on our Communities and Ecosystems", Union of Concerned Scientists, Cambridge, Massachusetts, and the Ecological Society of America, Washington, D.C.

Lindsey, R. (2018): "No Save Haven for Coral from the Combined Impacts of Warming and Ocean Acidification, [Online], Available at: **https://www.climate.gov/news-features/featured-images/no-safe-haven-coral-combined-impacts-warming-and-ocean-acidification**.

McEvoy, D., & Mullett, J. (2013): "Enhancing the Resilience of Seaports to a Changing Climate: Research Synthesis and Implications for Policy and Practice (Vol. 11, No. 18)", National Climate Change Adaptation Research Facility (NCCARF).

Met Office (2019): "UK Climate Projections, Headline Findings and Future Temperature Change".

Met Office (2021): "Climate Change Projections Over Land", [Online], Available at: **https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/summaries/climate-change-projections-over-land**, accessed on 26-02-2023.

Natural Environment Research Council (2010): "Invasive Sea Squirts Spotted in Scotland, [Online], Available at: **https://webarchive.nationalarchives.gov.uk/ukgwa/20220204090141/https://nerc.ukri.org/planetearth/stories/653/**, accessed 26-02-2023.

Niedrist, G.H., Psenner, R. & Sommaruga, R. (2018): "Climate Warming Increases Vertical and Seasonal Water Temperature Differences and Inter-Annual Variability in a Mountain Lake", Climatic Change, 151, 473-490.

Nijssen, B., O'Donnell, G.M., Hamlet, A.F. & Lettenmaier, D.P. (2001): "Hydrologic Sensitivity of Global Rivers to Climate Change", Climatic change, 50, 143-175.

Occhipinti-Ambrogi, A. & Galil, B. (2010): "Marine Alien Species as an Aspect of Global Change", Advances in Oceanography and Limnology, 1(1), 199-218.

Peirson, W.L., Shand, T., Ruprecht, J.E., Guerry, N., Evans, J., Cox, R. & Hassan, M. (2014): "Quantifying Climate Change and Determining Future Coastal Design Storms for Eastern australia", Coastal Engineering Proceedings, (34), 26-26.

PIANC PTG CC (2022): "Managing Climate Change Uncertainties in Selecting, Designing and Evaluating Options for Resilient Navigation Infrastructure".

PIANC TG 193 (2020): "Resilience of the Maritime and Inland Waterborne Transport System".

PIANC TG 3 (2008): "Climate Change and Navigation – Waterborne Transport, Ports and Waterways: A Review of Climate Change Drivers, Impacts, Responses and Mitigation".

PIANC WG 175 (2019): "A Practical Guide to Environmental Risk Management (ERM) for Navigation Infrastructure Projects".

PIANC WG 178 (2020): "Climate Change Adaptation Planning for Ports and Inland Waterways".

PIANC WG 188 (2019): "Carbon Management for Port and Navigation Infrastructure".

PIANC WG 195 (2021): "An Introduction to Applying Ecosystem Services for Waterborne Transport Infrastructure Projects".

PIANC WG 203 (2021): "Sustainable Inland Waterways: A Guide for Inland Waterway Managers on Social and Environmental Impacts".

PIANC WG 218 (in Press): "The Implications of Invasive Alien Species for Waterborne Transport Infrastructure".

Pinsky, M.L., Selden, R.L. & Kitchel, Z.J. (2020): "Climate-Driven Shifts in Marine Species Ranges: Scaling from Organisms to Communities", Annual review of marine science, 12, 153-179.

PLA (2015): "Adapting to Climate Change", Update Report to the Secretary of State, December 2015, Port of London Authority, London, UK, [Online], Available at: **https://www.gov.uk/government/publications/climate-adaptation-reporting-second-round-port-of-london-authority**.

Poloczanska, E.S. (2013): "Global Imprint of Climate Change on Marine Life", Nat Clim Change. 2013; 3: 919-25, Largest assembly and analysis of global impacts of climate on marine biota.

Poloczanska, E.S., Burrows, M.T., Brown, C.J., García Molinos, J., Halpern, B. S., Hoegh-Guldberg, O. & Sydeman, W.J. (2016): "Responses of Marine Organisms to Climate Change Across Oceans", Front Mar Sci 3: 62.

Pontee, N. (2013): "Defining Coastal Squeeze: A Discussion", Ocean & coastal management, 84, 204-207.

Port of London Authority (2015): "Adapting to Climate Change", Update Report to the Secretary of State, [Online], Available at: **https://pla.co.uk/Environment/Environmental-Reports-and-Strategic-Documents**.

Prowse, T., Alfredsen, K., Beltaos, S., Bonsal, B.R., Bowden, W.B., Duguay, C.R., Korhola, A., McNamara, J., Vincent, W.F., Vuglinsky, V. & Walter Anthony, K.M. (2011): "Effects of Changes in Arctic Lake and River Ice", Ambio, 40, 63-74.

Pyke, C.R., Andelman, S.J. & Midgley, G. (2005): "Identifying Priority Areas for Bioclimatic Representation under Climate Change: A Case Study for Proteaceae in the Cape Floristic Region, South Africa", Biological Conservation, 125(1), 1-9.

Renner, V. & Bialonski, W. (2004): "Technische und wirtschaftliche Konzepte für flussangepasste Binnenschiffe", Duisburg, Versuchsanstalt für Binnenschiffbau eV.

Robins, P.E., Skov, M.W., Lewis, M.J., Giménez, L., Davies, A.G., Malham, S.K. & Jago, C.F. (2016): "Impact of Climate Change on UK Estuaries: A Review of Past Trends and Potential Projections", Estuarine, Coastal and Shelf Science, 169, 119-135.

Rokaya, P., Budhathoki, S. & Lindenschmidt, K.E. (2018): "Trends in the Timing and Magnitude of Ice-Jam Floods in Canada", Scientific Reports, 8(1), 5834.

Rudnick, D.A., Chan, V. & Resh, V.H. (2005): "Morphology and Impacts of the Burrows of the Chinese Mitten Crab, Eriocheir sinensis H. Milne Edwards (Decapoda, Grapsoidea), in South San Francisco Bay, California, USA", Crustaceana, 787-807.

Silveira, M.J. & Thiébaut, G. (2017): "Impact of Climate Warming on Plant Growth Varied According to the Season", Limnologica, 65, 4-9.

SLOCAT (2021): "Tracking Trends in a Time of Change: The Need for Radical Action Towards Sustainable Transport Decarbonisation, Transport and Climate Change Global Status Report", 2nd edition, [Online], Available at: **https://tcc-gsr.com/global-overview/global-transport-and-climate-change/.**

Thoresen, C.A. (2010): "Port Designer's Handbook", pp. 175-188, London, UK: Thomas Telford.

U.S. EPA (2020): "Climate Change Indicators: Lake Ice", [Online], Available at: **https://www.epa.gov/climate-indicators/climate-change-indicators-lake-ice.**

UNCTAD (2017): "Port Industry Survey on Climate Change Impacts and Adaptation", *In:* Asariotis, R., Benamara, H. & Mohos-Naray, V.: "Division on Technology and Logistics", UNCTAD Research Paper No. 18. UNCTAD/SER.RP/2017/18/Rev.1.

UNCTAD (2021): "Climate Change Impacts on Seaports: A Growing Threat to Sustainable Trade and Development", [Online], Available at: **https://unctad.org/news/climate-change-impacts-seaports-growing-threat-sustainable-trade-and-development**, accessed 26-02-2023.

UNFCCC (2018): "Paris Climate Change Conference", November 2015, UNFCCC.

United Nations (1987): "Montreal Protocol on Substances that Deplete the Ozone Layer", Washington, DC: US Government Printing Office, 26, 128-136.

United Nations (1998): "The Kyoto Protocol to the United Nations Framework Convention on Climate Change", American Journal of International Law, 92(2), 315-331.

United Nations Climate Change (UNCC) (2018): "Initial IMO Strategy for Reducing Shipping Emissions Set for Adoption", [Online], Available at: **https://unfccc.int/news/initial-imo-strategy-for-reducing-shipping-emissions-set-for-adoption** accessed on 26-02-2023.

USGCRP (2018): "Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program", Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018.

Wadhams, P. (2012): "Arctic Ice Cover, Ice Thickness and Tipping Points", Ambio, 41, 23-33.

Wahr, J., & Zhong, S. (2013): "Computations of the Viscoelastic Response of a 3-D Compressible Earth to Surface Loading: An Application to Glacial Isostatic Adjustment in Antarctica and Canada", Geophysical Journal International, 192(2), 557-572.

Walther, G.R., Post, E., Convey, P., Menzel, A., Parmesan, C., Beebee, T.J., Fromentin, J.M., Hoegh-Guldberg, O. & Bairlein, F., (2002): "Ecological Responses to Recent Climate Change", Nature, 416(6879), 389-395.

Ward, R., Friess, D., Day, R. & Mackenzie, R. (2016): "Impacts of Climate Change on Global Mangrove Ecosystems: A Regional Comparison", Ecosyst. Health Sustain, 2, 1-25.

World Meteorological Organization (WMO) and United Nations Environmental Program (UNEP) (2005): "Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties", WMO/UNEP.

Yadav, J., Kumar, A. & Mohan, R. (2020): "Dramatic Decline of Arctic Sea Ice Linked to Global Warming", Natural Hazards, 103, 2617-2621.

Yang, X., Pavelsky, T.M. & Allen, G.H. (2020): "The Past and Future of Global River Ice", Nature, 577(7788), 69-73.

Zhang, P., Grutters, B.M., Van Leeuwen, C.H., Xu, J., Petruzzella, A., Van den Berg, R.F. & Bakker, E.S. (2019): "Effects of Rising Temperature on the Growth, Stoichiometry, and Palatability of Aquatic Plants", Frontiers in plant science, 9, 1947.

PIANC HQ: Boulevard du Roi Albert II 20 B. 3 | 1000 Brussels | Belgium

http://www.pianc.org | VAT BE 408-287-945 | ISBN 978-2-87223-030-3

Cover picture:
Weir System near Hagestein the Netherlands.
Picture provided by (C) Rijkswaterstaat: 313174