PIANC

EnviCom - Task Group 3
Climate Change and Navigation

Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation

"Navigation, Ports, Waterways"
"Navigation, Ports, Voies Navigables"

Contents

Front cover photograph by BfG, Department M2, Mr Helmut Jakobs, showing navigation during extremely low discharge in the river Rhine on 27 July 2006

Report of PIANC EnviCom Task Group 3: Climate change and navigation

Task group members

Members of the group and their sources represent a broad cross-section of pertinent disciplines, including climate change specialists (meteorologists and forecasters), hydrology experts (water balance and discharge specialists), oceanographers, hydraulic engineers, infrastructure and forward planning experts in the field of maritime and inland navigation.

Members:
Hans Moser, Federal Institute of Hydrology, Germany (chairman)
Peter J. Hawkes, HR Wallingford, United Kingdom (secretary)
Øivind A. Arntsen, Norwegian University of Science and Technology, Norway
Pierre Gaufres, National Centre for Maritime and River Studies, France
Stephan Mai, Federal Institute of Hydrology, Germany
Gernot Pauli, Central Commission for the Navigation on River Rhine, France
Kathleen D. White, US Army Corps of Engineers, USA

Corresponding members:
Susan Blackwell, Ports Australia
James J. Corbett jr., University of Delaware, USA
Karin De Schepper, Inland Navigation Europe, Belgium
Guido Dumon, Flemish Government Coastal Division, Belgium
Leticia Maria Greyling, South Africa
Harald Köthe, Federal Ministry of Transport, Germany
Marcos Garcia Sotillo, Puertos del Estado, Spain
Takeshi Suzuki, National Institute for Land and Infrastructure Management, Japan

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Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation

Summary

The main goal for EnviCom Task Group 3 “Climate Change and Navigation” was to discuss the climate change related issues for the navigation sector, and how to understand and to deal with the knowledge about climate change and the various projected scenarios.

The assumptions, definitions and findings of the 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007) represent a peer-reviewed body of knowledge that identifies changes in climate and projected future changes. Projections for 2100 suggest a global mean sea level rise of a few decimetres and a greater frequency and intensity of extreme weather events. Even if emissions of greenhouse gases (especially carbon dioxide CO_2) stop today, these changes would continue for many decades and in the case of the sea level for centuries.

This report reviews climate change impacts on maritime and inland navigation including sea level rise, wind conditions, wave action, tidal and surge propagation and range, ocean circulation, storms, coastal hydrodynamics, sea chemistry, environmentally protected areas, ice conditions, icing, water supply and quality in inland rivers, extreme hydrological conditions, and coastal, estuarine and river morphology. Potential adaptation and mitigation responses are identified.

Navigation contributions to greenhouse gas (GHG) emissions are discussed, along with opportunities for navigation to contribute both to overall decreases in anthropogenic GHG, and, through use of alternative fuels, to decreases in other pollutants.

1 The starting point for this review

1.1 Global climate change

Significant changes in climate and their impacts are visible regionally, and are expected to become more pronounced in the next decades. Since the industrial age a global average temperature increase of about 0.6° C has occurred (Figure 1.1, top). The assumptions, definitions and findings of the 4th assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007) are taken as the basis for this report. Nevertheless, we take into account that there are inherent uncertainties in climate predictions, which become much wider when translated into the potential impacts on navigation. Projections for 2100 suggest that temperature will have risen by between 0.6 to 4° C above 1990 levels (Figure 1.1, bottom).

Due to the continued melting of polar ice and mountain glaciers, and the expansion of the warmer sea water, the sea level is projected to rise. Projections for 2100 suggest a global mean sea level rise of a few decimetres. Generally a greater frequency and intensity of extreme weather events is expected. Even if emissions of greenhouse gases stop today, these changes would continue for many decades and in the case of the sea level for centuries.

1.2 Contributions to greenhouse gas emission

It is estimated that about 4 % of global greenhouse gas (GHG) emission is due to anthropogenic causes, whereas the main emissions come from the seas (40 %), the vegetation (27 %) and the soil (27 %). Of the anthropogenic emission, transportation and traffic is responsible for about 23 % of energy-related GHG emissions (Kahn Ribeiro et al., 2007) and to this part navigation contributes less than 10 % (Kahn Ribeiro et al., 2007; Fugelstvedt et al., 2008, and references therein). Although navigation is not a main driving force to increase climate change caused by GHG emissions, the navigation sector should evaluate the possibilities to contribute to a reduction of anthropogenic GHG emissions to emphasize navigation as an environ¬mentally sound mode of transportation. Moreover, this should be of particular concern for the navigation sector itself, since both aviation and shipping emissions are excluded from national emission targets and the Kyoto Protocol.

1.3 Climate change impacts and responses

Climate change has a real impact on ecosystems, biodiversity, 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 happen and about the vulnerability of natural and anthropogenic systems on Earth. Strategies and policies are in force or in preparation to minimise the anthropogenic influence on enforced climate change (Montreal Protocol, Kyoto Protocol). Their goal is to adapt to unavoidable changes, to moderate damage and/or to realise opportunities associated with climate change. Against this background it is necessary and timely to consider the vulnerability of navigation, and to develop adaptation strategies in order for navigation to be prepared for climate change.

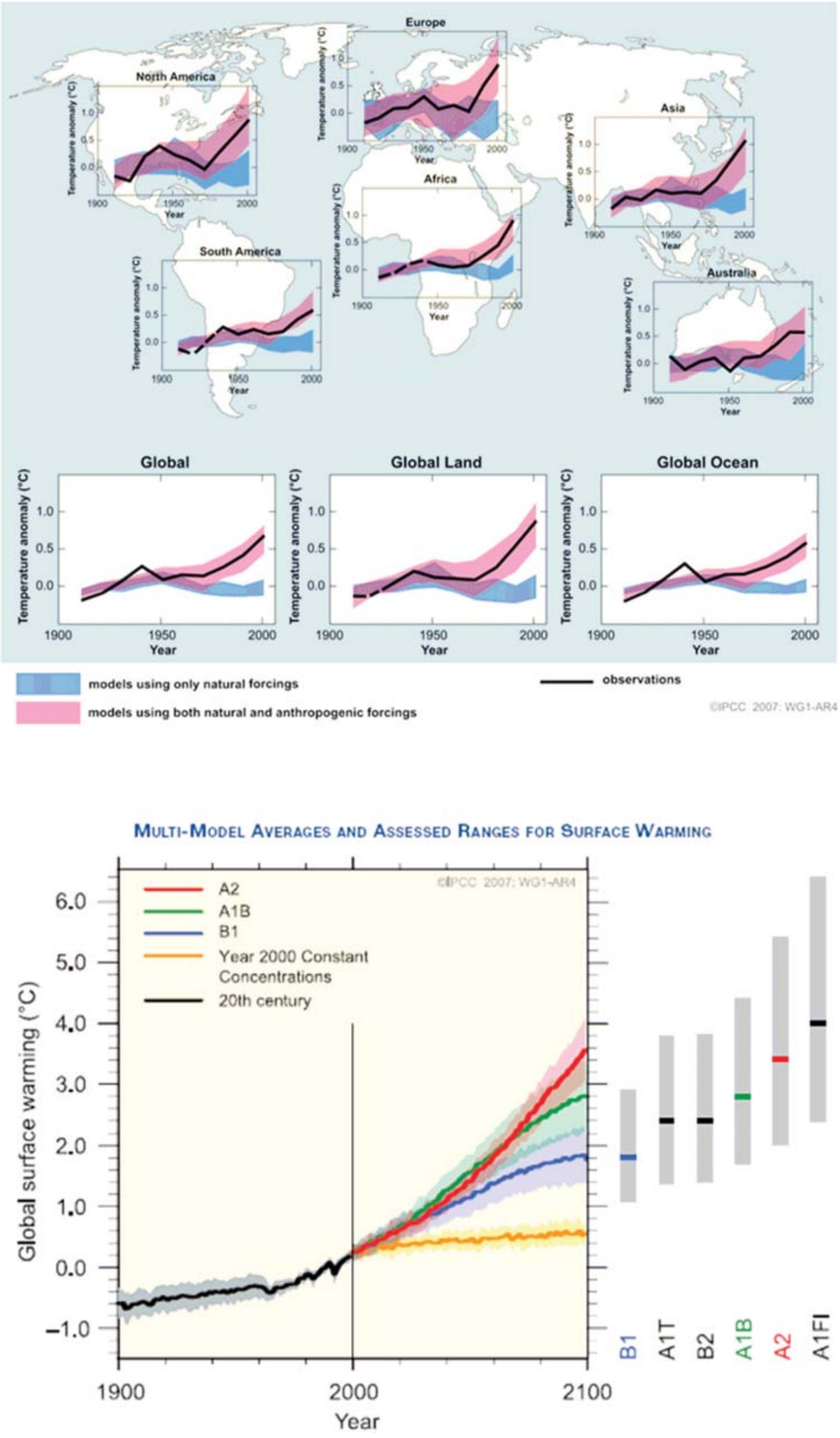


Figure 1.1: Observed (top) and predicted (bottom) change in temperature due to climate change (reproduced from Figures 4 and 5 of AR4, SPM, IPCC, 2007d)

2 Need and approach

2.1 Need

IPCC takes the global lead on assessing and summarising information on past and future climate change. Individual countries or industries then focus on their particular interests, with the aim of providing specific guidance on climate change issues for actual use within that country or industry. For example, in Britain, the United Kingdom Climate Impacts Programme organises and reports in more detail for UK interests, whilst keeping faith with IPCC approaches and conclusions. PIANC's responsibility is to the special interests of the navigation sector, focussing on climate change issues relevant to navigation and ports.

IPCC updated all of its reports and recommendations during 2007. As PIANC is a global organisation providing guidance for sustainable waterborne transport, ports and waterways, it is timely for PIANC to update its position and recommendations regarding climate change. At present, EnviCom Task Group 3 is the only PIANC group looking specifically at climate change. It will take a broad look at all aspects of potential interest to navigation and ports, and will recommend specialist Working Groups to prepare detailed guidance on aspects of greatest interest to the industry.

For inland navigation the consequences of climate change could be a question of reliability or even of fundamental existence. A small change in the level of water in rivers and ports, for example due to a change in the seasonal pattern of rainfall, may affect the number of days per year that waterways can be used without restriction. For industries using navigation as the primary mode of transportation for their goods, climate change is a fundamental question for the future location of their production facilities.

Maritime navigation is sensitive to storminess and wind/wave conditions, and also to sea level in ports. The industry needs to be prepared to adapt sea waterways and sea ports, infrastructure and facilities, as well as the ships and navigational equipment, to be able to continue to operate successfully in future.

Polar navigation is also sensitive to the spatial and seasonal distribution of solid and floating ice, which in turn is sensitive to climate change.

2.2 Terms of reference

The mission statement for PIANC is "The global organisation providing guidance for sustainable waterborne transport, ports and waterways".

The main goal of EnviCom Task Group 3 was to discuss the climate change related issues, and to produce, within about one year, a report for the navigation sector on how to understand and to deal with the knowledge about climate change and the various projected scenarios. This 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.

The report informs PIANC on how navigation may be affected by climate change and in what fields actions have to be taken to develop adaptation strategies and investments in a pro-active way. The report provides a common and basic platform for all PIANC commissions to build up their work plans regarding climate change. The report includes the following matters:

1. Identification of the relevance of climate change for maritime and inland navigation and a summary of the realistic impact scenarios (e.g. environmental, technical, economic, political) by documenting the existing uncertainties with the use of climate models. The report shows potential impacts on navigation, distinguishing between maritime and inland navigation.

2. Summary of examples where climate change already creates problems for navigation.

3. Discussion on how the navigation sector could contribute to reduce climate change impacts (e.g. reduction of CO_2 emissions and alternative fuel concepts). Support navigation as an environmentally sound and sustainable mode of transportation.

4. Discussion of climate impacts and responses to prepare the navigation sector for the projected climate scenarios with the aim of adapting navigation infrastructure, equipment and daily practice for future sustainability.

2.3 Review of pertinent literature

Although large-scale climatic processes are driven by the ocean-atmosphere exchange system, very few studies are available on maritime impacts compared to continental impacts due to shorter data series and fewer human consequences. Coastal issues, port vulnerability and low lying coastal areas are better documented and studied as well as hydrologic evolution of some large river basins. Thus impacts on navigation have to be deduced from research undertaken in specific fields (e.g. coastal risks, water supply, nuclear plant protection) and more generally from IPCC Working Group 2 reports. The schematic shown in Figure 2.1 depicts some potential climate change impacts on navigation.

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

IPCC has introduced several global climate change scenarios, from which projections are made, from which potential impacts and responses can be identified. Commonly used scenarios include the A2 scenario (rapid increase in the emission of greenhouse gases), the B2 scenario (among the moderate scenarios), and the A1B scenario (intermediate between the others but closest to the B2 scenario) (IPCC, 2000).

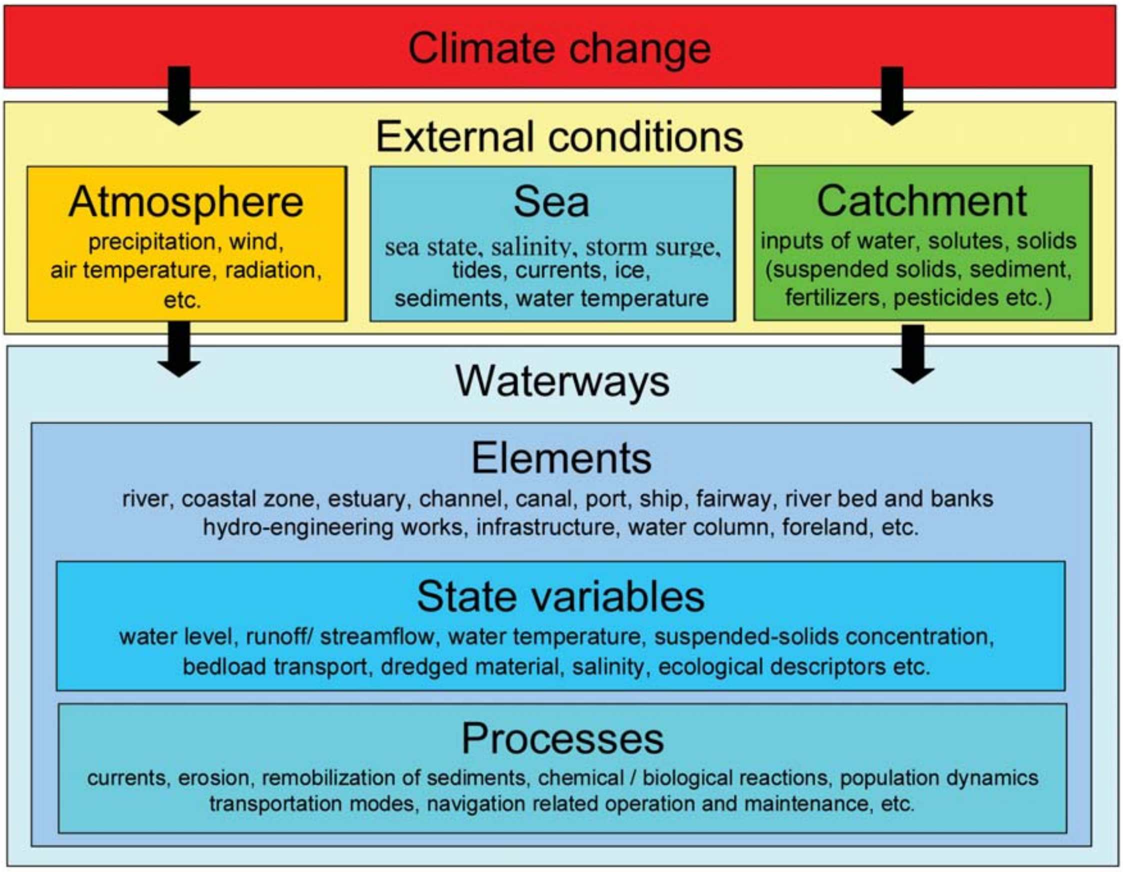


Figure 2.1: Schematization of climate change influencing the use of waterways (after BMVBS, 2007)

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 (IPCC, 2007a, 2007b, 2007c, 2007d). In this process, they have drawn a careful distinction between levels of confidence in scientific understanding (e.g. Table 2.1) and the likelihoods of specific results (e.g. Table 2.2). In view of the international peer review of IPCC uncertainty guidance, this Task Group has adopted the same terminology in its discussion of climate impacts.

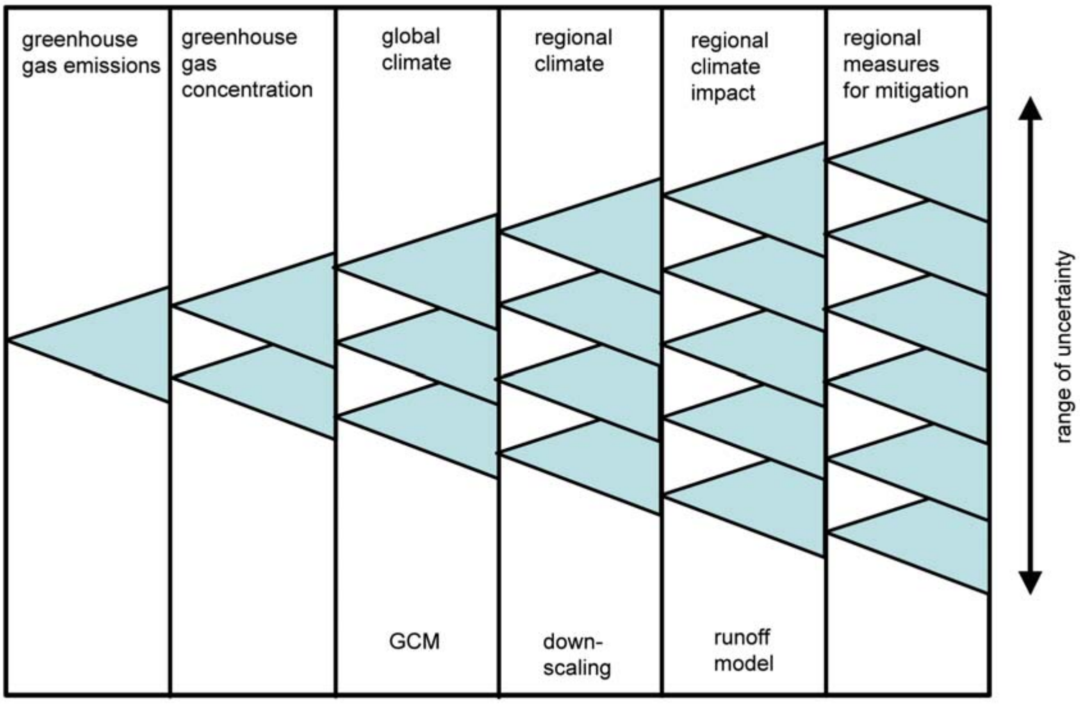
Table 2.1: Standard terms used to define levels of confidence (from IPCC, 2007)

Confidence terminology	***Degree of confidence in being correct***
Very high confidence	*At least 9 out of 10 chance*
High confidence	*About 8 out of 10 chance*
Medium confidence	*About 5 out of 10 chance*
Low confidence (only used for areas of major concern and where a risk-based perspective is justified)	*About 2 out of 10 chance*
Very low confidence (only used for areas of major concern and where a risk-based perspective is justified)	*Less than 1 out of 10 chance*

Table 2.2: Standard terms used to define the likelihood of an outcome or result where this can be estimated probabilistically (from IPCC, 2007)

Likelihood terminology	***Likelihood of the occurrence/ outcome***
Virtually certain	*> 99 % probability*
Extremely likely	*> 95 % probability*
Very likely	*> 90 % probability*
Likely	*> 66 % probability*
More likely than not	*> 50 % probability*
About as likely as not	*33 to 66 % probability*
Unlikely	*< 33 % probability*
Very unlikely	*< 10 % probability*
Extremely unlikely	*< 5 % probability*
Exceptionally unlikely	*< 1 % probability*

The navigation community should work with the climate researchers to incorporate and to understand the propagation of uncertainty from greenhouse gas forcing, through climatological variables, to navigation related variables (Figure 2.2, top) when considering impacts, responses, vulnerabilities, and opportunities. Thus, for example, complexity and uncertainty may be inversely related to spatial scale (Figure 2.2, bottom) but proportional to scientific understanding of processes.



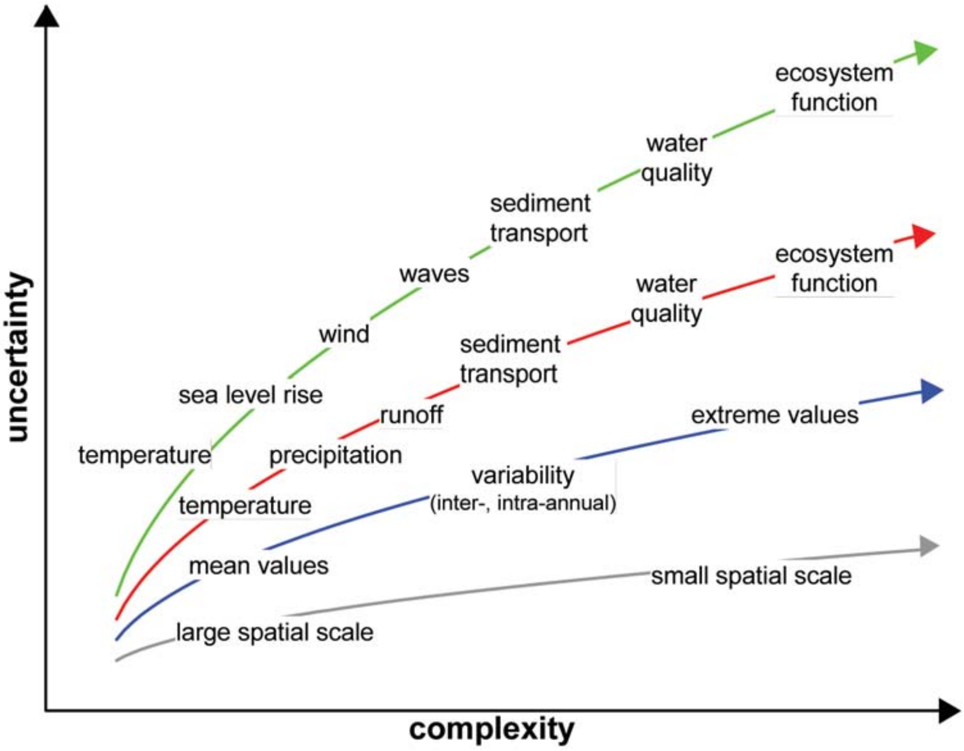


Figure 2.2: Illustrations of the spread of uncertainties: (top) from greenhouse gas forcing to navigation; (bottom) a red curve representing inland navigation issues and a green curve representing maritime navigation issues

Figure 2.3 (reproduced from IPCC, 2007d) shows that there are differences in uncertainty between the scenarios as well. The figure shows projected surface temperature changes for the early and late 21st century relative to the period 1980 1999. The central and right panels show the Atmosphere-Ocean coupled General Circulation Model (AOGCM) average projections for the B1 (top), A1B (middle) and A2 (bottom) SRES scenarios, averaged over the decades 2020 2029 (centre) and 2090 2099 (right). The left panels show corresponding uncertainties as the relative probabilities of estimated global average warming from several different AOGCM and Earth System Model of Intermediate Complexity studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore the difference in the number of curves shown in the left-hand panels is due only to differences in the availability of results.

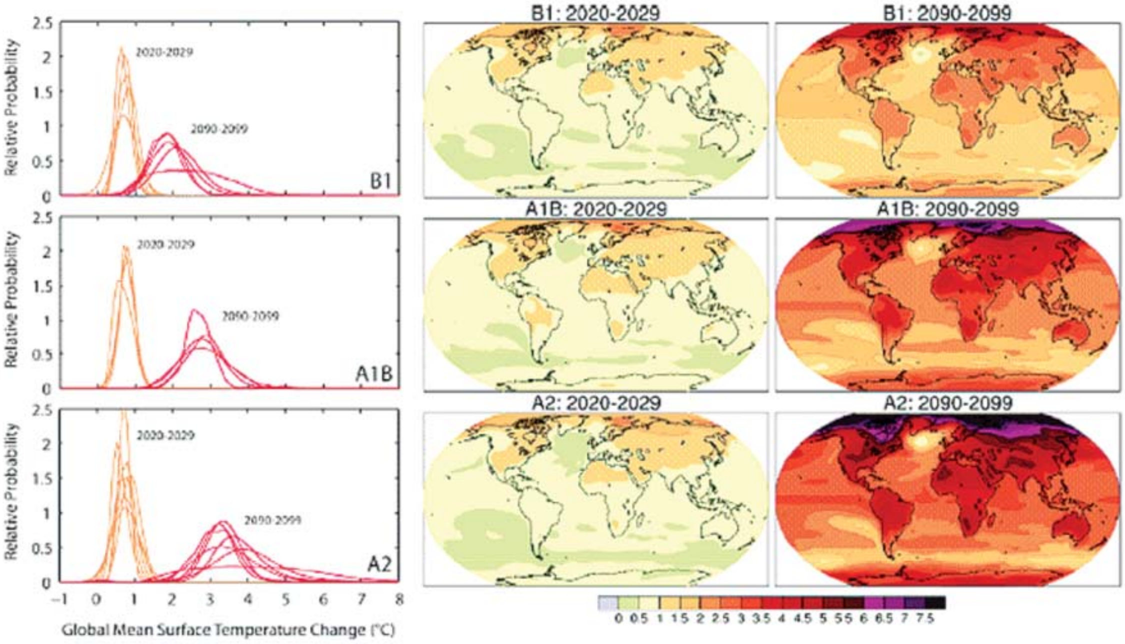


Figure 2.3: Projected surface temperature changes for the early and late 21st century relative to the period 1980 1999, illustrating uncertainties between models and between scenarios (reproduced from IPCC, 2007d)

3 Maritime navigation

3.1 Drivers of change relevant to navigation

Most of the drivers discussed in this section are metocean variables such as wind, waves, sea level and ice. Some are more complex geographical response variables such as ocean circulation and estuarine morphology. One is the complex political response variable of designated environmentally protected areas. The common features of these drivers are that they are outside the control of the navigation sector, might be subject to climate change, and might have impacts upon navigation.

3.1.1 Sea level

IPCC (Bindoff et al., 2007) concludes that global mean sea level rose at an average rate of about 1.7 ± 0.5 mm/year during the twentieth century and that the rate has been slightly higher over the period 1961 to 2003. Climate model projections (IPCC, 2007d) suggest that the global average rate of rise over the twenty first century will be 2 5 mm/year, implying that mean sea level will be 0.2 0.5 m higher in 2100 than in 2000 (see Figure 3.1. However, these figures primarily relate to the thermal expansion of the oceans, excluding rapid dynamic changes such as melting of the Antarctic and Greenland ice sheets. The additional sea level rise corresponding to historical rates of melting would increase mean sea level rise to 0.2 0.6 m by 2100. Some researchers (e.g. Horton et al., 2008) would argue that this under-estimates the effect of ice melt and that we could be looking at 1 m increase by the end of the century if not more.

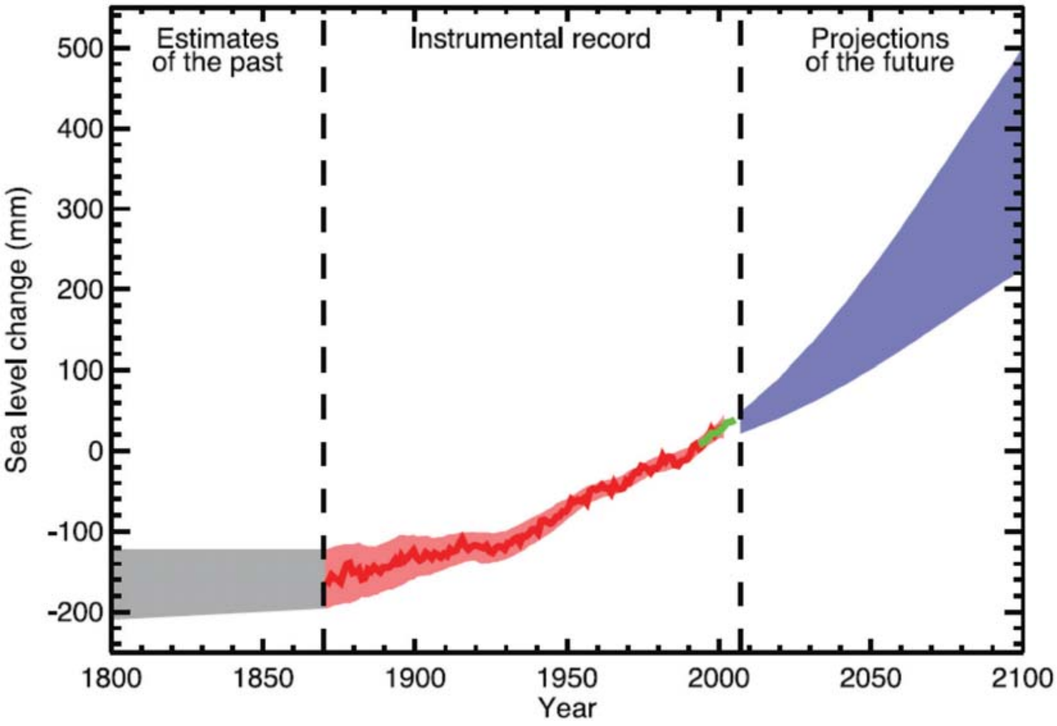


Figure 3.1: Observed and projected (SRES A1B scenario) sea level rise (reproduced from IPCC, Bindoff et al., 2007)

In combination with other factors, like subsidence and glacial isostatic adjustment, 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, 2007a) due to changes in ocean density distribution (steric sea level rise). In upper Canada, glacial rebound is almost a metre a century (see Figure 3.2) meaning that the land is rising faster than the sea level.

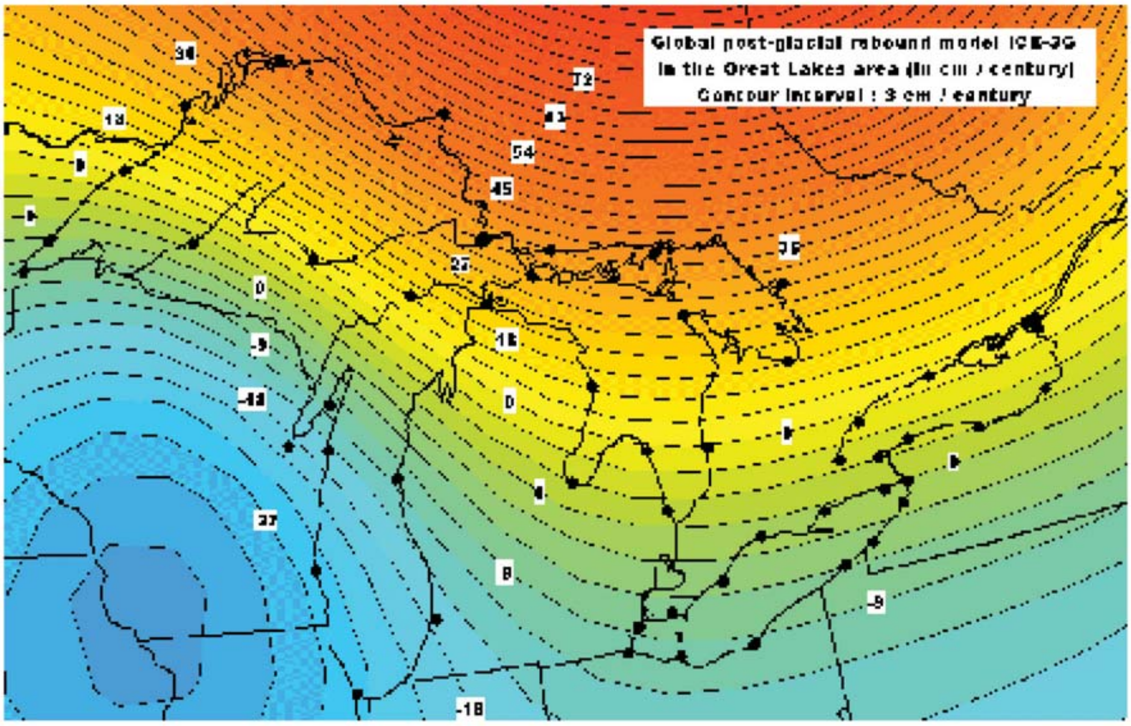


Figure 3.2: Postglacial rebound in the Great Lakes area, shown as contours of centimetres per century (diagram provided by John Kangas)

Figure 3.3 (reproduced from IPCC, 2001) illustrates the view that, even if CO_2 emission is reduced and atmospheric concentrations stabilize, surface air temperature will continue to rise slowly for a century or more. Consequently, thermal expansion of the oceans would continue long after CO_2 emission is reduced, and melting of ice sheets would continue to contribute to sea level rise for many centuries. Figure 3.3 is a generic illustration for stabilization at any level between 450 and 1,000 ppm, and therefore has no units on the response axis. Responses to stabilization trajectories in this range show broadly similar time courses, but the impacts become progressively larger at higher concentrations of CO_2.

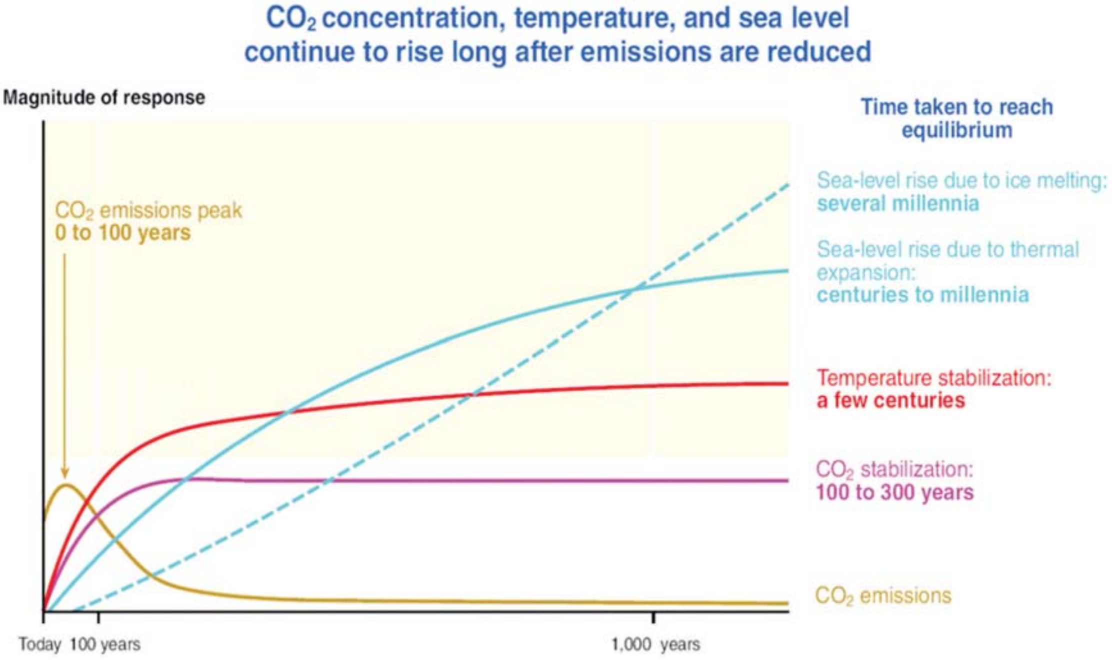


Figure 3.3: Illustration of temperature rise and sea level rise continuing long after reduction of CO_2 emission to a neutral level (reproduced from IPCC, 2001)

In the absence of more specific information, a sensible precautionary allowance would be to assume that mean (and by inference extreme) sea level will increase by 5 mm/year from now on (reflecting the upper range given in the previous paragraph). However, for port and coastal defence design where sea level is critical, and where long term land level change may also be relevant, site specific review would be necessary.

3.1.2 Wind conditions

Wind conditions could be affected by temperature and other climate changes in a number of aspects. The seasonal distribution of wind speeds and directions, and the frequency, pathways and/or durations of storms and hurricanes could change.

IPCC (2007) has little to say on wind conditions, and previous future climate change projections have tended to show only small changes in wind conditions, but with quite high uncertainty. 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, however, it would not be sensible to design for any specific change in wind conditions, rather to be aware that they could change, and to look at recent data from time to time when operations dependent upon wind are being reviewed.

3.1.3 Wave action

Waves could be affected by climate change in a number of 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 hurricanes 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.

IPCC (Trenberth et al., 2007) reports a statistically significant trend of increasing annual mean and winter mean significant wave height (H_s) for the mid-latitudinal North Atlantic and North Pacific, western subtropical South Atlantic, eastern equatorial Indian Ocean, and the East China and South China Seas. It also reports statistically significant decreases in H_s for western Pacific tropics, the Tasman Sea and the south Indian Ocean. Similar trends are found for the 99 % extreme H_s with a maximum increase of winter extreme H_s of 0.4 m per decade in the North Atlantic. The worsening of wave conditions in the north-eastern North Atlantic is most likely connected to a northward displacement of the storm tracks, with decreasing wave heights in the southern North Atlantic (IPCC 2007a). Regional analyses become important, for example in Norway it is anticipated that during winter the storm tracks will be more to the south than now (Debenard and Røed, 2008).

3.1.4 Tide and surge propagation and range

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 also demonstrates (Hulme et al., 2002) that plausible changes in surge propagation due to storms tracking differently around the UK could have a significant impact (over and above that directly due to mean sea level rise) on extreme sea level. Even just around the British Isles, 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. Therefore, without site specific studies, it seems not worth making any specific allowance for changes in tide and surge propagation and range.

3.1.5 Ocean circulations and coastal hydrodynamics

Ocean circulations could be affected by climate change, and these effects could be either gradual or sudden.

For example, it is very likely that the Atlantic Ocean Meridional Overturning Circulation (MOC) will slow down during the course of the 21st century. For three emission scenarios used, if MOC weakens in most models, it is very unlikely MOC will undergo a large abrupt transition as a collapse (IPCC, 2007d).

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

3.1.6 Coastal and estuarine morphology

Climate change impact on coastal morphology is 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 beach drift, and hence coastal and estuarine morphology, are disproportionately sensitive to small changes in wave height, period or direction. Erosion of low lying beaches and saltmarshes is affected by changes in waves or sea levels. These sensitivities could only be quantified through detailed site specific modelling. ACIA (2004) states that thawing permafrost weakens coastal lands, adding to the vulnerability of arctic coastlines.

3.1.7 Storm events

There is considerable inter annual and inter decadal difference in storm activity. IPCC (Meehl, 2007) notes that there is observational evidence for an increase of intense cyclone activity in the North Atlantic since 1970, but uncertainty about whether this represents a continuing trend or just natural variability. It would be possible to quantify changes by continued analysis of climate model time series results, but these changes would vary from one location to another and would be sensitive to details of the climate model used. IPCC (Meehl, 2007) tentatively reports a reduced number of tropical cyclones, but with a higher average intensity, although projections vary between climate models.

3.1.8 Sea chemistry

Ocean salinity changes are an indirect but potentially sensitive indicator for detecting changes in precipitation, evaporation, river runoff and ice melt. Bindoff et al. (2007) report large-scale, coherent trends in ocean salinity for the period 1955 to 1998 consistent with changes in precipitation resulting in water transport in the atmosphere from low latitudes to high latitudes and from the Atlantic to the Pacific. These trends result in a global freshening of water in subpolar latitudes and the Pacific. Increasing salinity is noted in shallower tropical and subtropical oceans and large areas of the Atlantic and Indian Oceans. Bindoff et al. (2007) also report that ocean biogeochemistry is changing, largely due to an increase in total inorganic carbon by 118 ± 19 gigatonnes (GtC) over the period 1750 to 1994. This has impacted pH and dissolved oxygen (decreasing trends), and has resulted in a shift in the distribution of carbon species (CO_2, carbonate and bicarbonate). These changes in turn impact nutrient cycling and primary productivity. 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).

3.1.9 Designated environmentally protected areas

Regulations regarding environmentally protected areas vary from country to country, but in general, they are considered to be areas reserved for the lasting protection of the natural or cultural resources within the designated boundaries. Once designated, environmentally protected areas have fixed boundaries. However, climate change can lead to shifts in the distribution of suitable habitat and environmental conditions for a species or community (Pyke et al., 2004), with the result that protected species may move from protected areas to new, more suitable areas.

3.1.10 Ice conditions

About 10 % of the Earth's surface is permanently covered by ice. IPCC (Lemke et al., 2007) conclude that the volume and extent of ice (and snow cover) on the Earth is decreasing, and that this trend will continue. Plots of freeze up and break-up dates for several rivers and lakes suggest that the number of navigation days lost to ice has decreased steadily and significantly (about 15 days for the examples given) since 1845.

Recent observations show that changes in ice cover in the Arctic Ocean are occurring more rapidly than previously known. The Northeast Passage is predicted to be ice free for about two months during 2008. Under several different IPCC (2007) scenarios, large parts of the Arctic Ocean are expected no longer to have permanent ice cover by 2100 (Figure 3.4). There is a lot more information on observed and expected changes in ice and snow, including regional variations, in Chapter 4 of IPCC (Lemke et al., 2007). ACIA (2004, 2005) gives detailed information for the Arctic.

3.1.11 Icing

Icing of ship superstructures and ocean structures occurs when air temperatures are colder than the freezing point of sea water. 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, such as sailing and sealing. Icing in the ocean can be divided into two main categories. Sea spray icing is caused by wave-structure collision-generated sea spray. Atmospheric icing is 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.

Ryerson (1991) reports that air temperatures for 117 observed trawler icing events average 8.1 °C, with most (67 %) occurring between 3.5 and 12.6 °C. Ryerson and Gow (2000) cited Soviet studies showing that icing events are rare at temperatures above 3.0 °C, and Japanese research found that severe icing occurs between 6.0 and 8.1 °C. Spray is carried further over ship superstructures in high relative winds, and ice accretion occurs most rapidly when ships sail into the wind and seas are high. Overland (1990) presents a method to predict 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 (http://polar.ncep.noaa.gov/marine.meteorology/vessel.icing/).

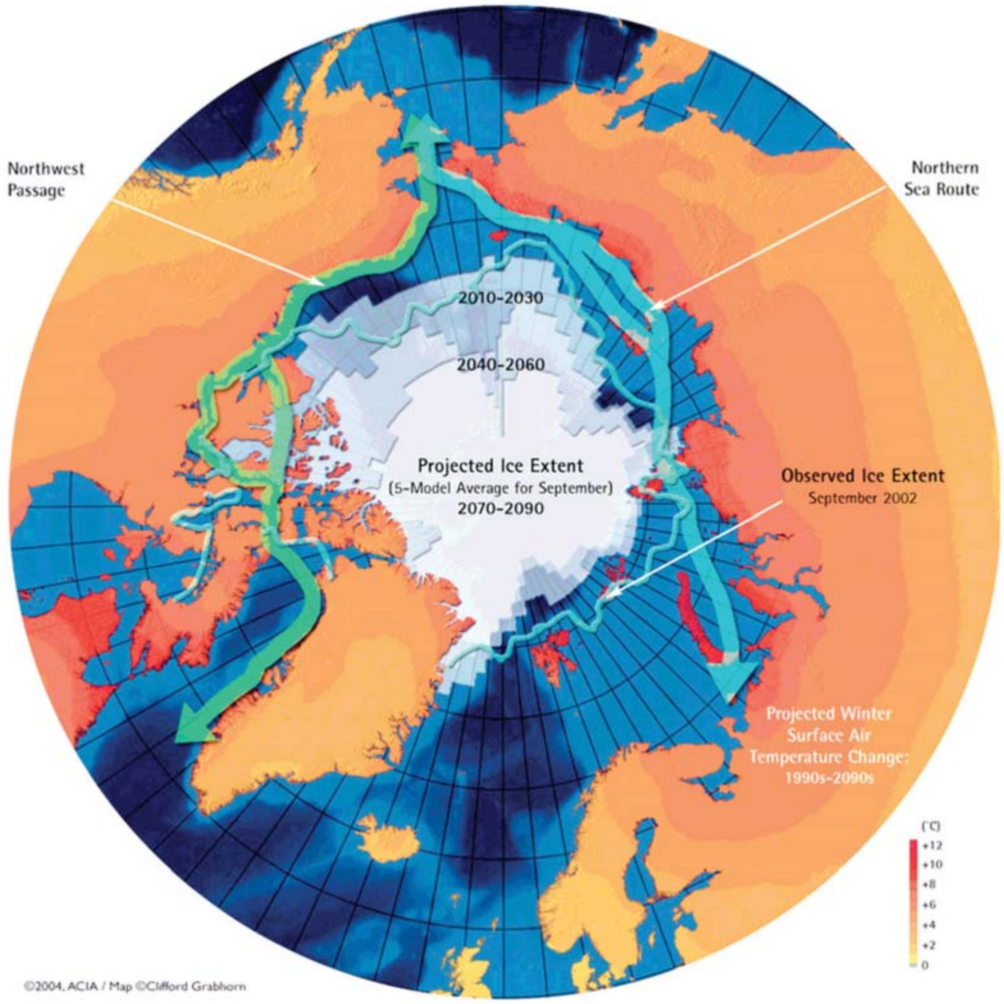


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Figure 3.4: Observed and projected Arctic sea ice extent (reproduced from ACIA, 2004, 2005)

IPCC (2007d) reports that model projections show fewer mid-latitude storms and a poleward shift of the storm tracks, particularly notable in the Southern Hemisphere. 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 icing.

3.2 Potential impacts on navigation

Climate change will result in number of general impacts on navigation and harbour operations as well as on related infrastructure. These are summarised in Table 3.1, where the letter "x" indicates which changes might have impacts on which navigation related sectors. For this purpose, the table distinguishes between Port, Coastal, Offshore and Vessels, as these tend to involve different groups of people within the navigation industry, and as they might be investigated by different future PIANC Working Groups on climate change. The same information is expanded upon in the remainder of Section 3.2, with potential impacts being sorted into the same categories used in Section 3.1 for the drivers of change.

Table 3.1: Drivers and impacts on maritime navigation

Drivers	**Potential impact**	**Port**	**Coastal area**	**Offshore structure**	**Vessels**
Increase in power and reach of storm surge, coastal flooding, spray zone and erosion patterns	Degradation, failure and replacement	x	x		
	Changed dredging requirements	x			
Change in magnitude and duration of storm surges and incidents of water over sea wall structures	Low land flooding	x	x		
Wave attack at a higher water level reducing the energy loss of breaking	Increased vulnerability of structures	x	x	x	
Changes in frequency, duration and intensity of storms	Permanent loss of sand offshore and onshore	x	x	x	
	Degradation of structures	x	x	x	
	Loss of viable industrial land (port enlargements)	x	x		
	Retreat of coastal landscapes		x		
	Problems in manoeuvring				x
	Reduced regularity of the port	x			x
	Reduced capacity of natural systems to recover		x		
Change in the sea level range (and other sea state parameters)	Degradation of materials over time	x	x	x	
	Exposure of decks of wharfs and jetties (corrosion)	x		x	
Ice and icing	Access to Polar Regions (NW and NE Passages open all year)				x
	More freshwater in rivers, giving more ice at river outlets in the north				x
	Reduced ice cover will increase bio-production in Polar Regions, so northward relocation of fish				x
	Change in sea spray affecting icing				x

3.2.1 Increase of the global mean sea level and storm surges

Mean sea level has increased in the recent past, and will continue to rise in the future, possibly at an accelerated rate. For navigation purposes, high and 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 surge behaviour, associated with weather conditions, means that this is not necessarily the case.

Although sea level rise would have no direct impact on navigation itself, it 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 ships and bridges; the elevation at which wave forces attack a structure will increase, potentially increasing the vulnerability of the structure. It may also increase the exposure of decks of wharfs and piers; it may increase 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.

An increase in the absolute levels of low and extreme low sea levels would allow greater underkeel clearance for vessels, and possibly reduce the need for dredging in low sedimentation areas.

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

3.2.2 Change in wind conditions

The proportion of winds with speeds above 15 m/s is projected to increase in northern areas. In addition to the obvious potential to produce higher waves, an increase in wind speed would also have some direct effects on navigation. Preferred shipping routes may change. Manoeuvring through curved narrow sailing channels would be more difficult. 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 impacts include reduced calm weather window time at high risk (e.g. oil and gas) terminals, increased berthing time for ships at terminals, and delayed departure time for ships at terminals, any or all of which may necessitate larger areas for anchoring of waiting vessels.

3.2.3 Evolution of wave action

Offshore loading and unloading operations are wave height dependent, for example buoy loading ships require $H_s < 4.5$ 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.

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

Changes in wave climate might affect ship routing and port operations. As well as affecting large vessels, any change in wave action may affect local (small boat) fishing fleets and floating aquaculture plants.

3.2.4 Evolution of tidal propagation and range

Although tidal range may be significant in some estuary and river locations, generally only minor changes are expected, relative to the effects of changes in mean sea level, wind and waves that would be considered anyway.

3.2.5 Changes in ocean circulations and coastal hydrodynamics

Although a change in ocean circulation could affect navigation, any direct impact would be small and uncertain and so probably not worth considering, at least until there is a firmer projection of any circulation change. Changes in coastal hydrodynamics could, locally, cause large impacts on navigation, but these would be very different from one site to another. These might include narrowing or widening (or even opening or closing) of channels, changed dredging requirements, erosion or accretion of beaches protecting port structures and/or changed current velocities.

3.2.6 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 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. For example, ACIA (2004) reports that the risk of flooding in coastal wetlands is projected to increase, with impacts on society and natural ecosystems. 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 hypothetical changes in morphology as a guide to whether more detailed studies may be needed. In arctic regions land-based navigation infrastructure may be destabilized as permafrost melts (ACIA, 2004).

3.2.7 Changes in storm events

This type of change may show itself through the overall distribution of wind or wave or rainfall conditions, or perhaps through the seasonal or spatial distribution of storm occurrence.

Changes in storm duration and/or frequency may lead to decreased regularity of ports, increased downtime and the requirement for more storage capacity at container terminals for use in times of closure. Changes in the frequency, duration and/or intensity of storm events may 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 viable land.

Other impacts might include changes in visibility due to more 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.

3.2.8 Changes in sea chemistry

Saltier and warmer water, as expected in the tropics, may lead to increased corrosion and deterioration of port structures and vessels. Less salty and warmer water in the higher latitudes may contribute to increased sea level there. Fish migration may adapt to changes in salinity and temperature, and to changes in phosphates and nitrates, requiring corresponding adaptation by fishing vessels.

3.2.9 Relocation of designated environmentally protected areas

Predicting species or ecosystem response in the face of climate is complex (e.g. Davis et al., 1998); thus, detailed studies may be required to assess changes to environmentally protected areas. Ibanez 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 conditions may advocate for relocation of environmentally protected areas, with potential opportunities for the navigation industry in some places and potential problems in others.

3.2.10 Changes in ice conditions

Reduced ice cover (see Figure 3.4) would permit better access to 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 sea ice is likely to allow increased offshore extraction of oil and gas, although increasing ice movement could hinder some operations (ACIA, 2004). If the Northwest Passage were 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 (NSIDC, 2007) gives an indication that these sailing routes can be accessible sooner than previously anticipated. A Danish shipping company (Jensen A., personal communication) has ordered ten container vessels capable of crossing the Arctic, between Europe and Asia, during the summer season.

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.

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.

Production of zoo plankton would increase in polar areas due to reduced ice cover, tending to cause relocation of fish from south to north, tending to cause a shift of commercial fisheries to the north. Defining protected areas based on previous estimates of sustainable catch limits will not be directly applicable in these newly opened areas.

3.2.11 Icing

Icing increases the weight and raises the centre of gravity of ships, lowering freeboard and reducing stability, a potentially catastrophic problem, particularly for smaller vessels such as fishing trawlers. Icing also affects personnel and equipment operations, emergency evacuation procedures and communications.

Icing of ships would be affected by temperature change, with a potential benefit for navigation in Polar Regions. Structures at the coast at high latitudes may have more sea spray during winter. Light from navigation installations could be reduced by additional sea spray icing.

3.3 Responses

Discussion in Sections 3.1 and 3.2 of climate drivers and impacts on maritime navigation indicates that changes in sea level and storm intensity, combined with changes to land-based infrastructure and ice conditions in Polar Regions, will require responses related to maritime navigation infrastructure and operations. Table 3.2 presents potential responses to climate change impacts. Exact responses will vary from one country to another, depending on such variables as overall exposure, wealth and alternative locations available. Nicholls et al. (2007) examine climate impacts on port cities in terms of population and assets exposed (Figure 3.5). They conclude that there are potentially very large benefits available from global, regional and/or local adaptation and mitigation strategies.

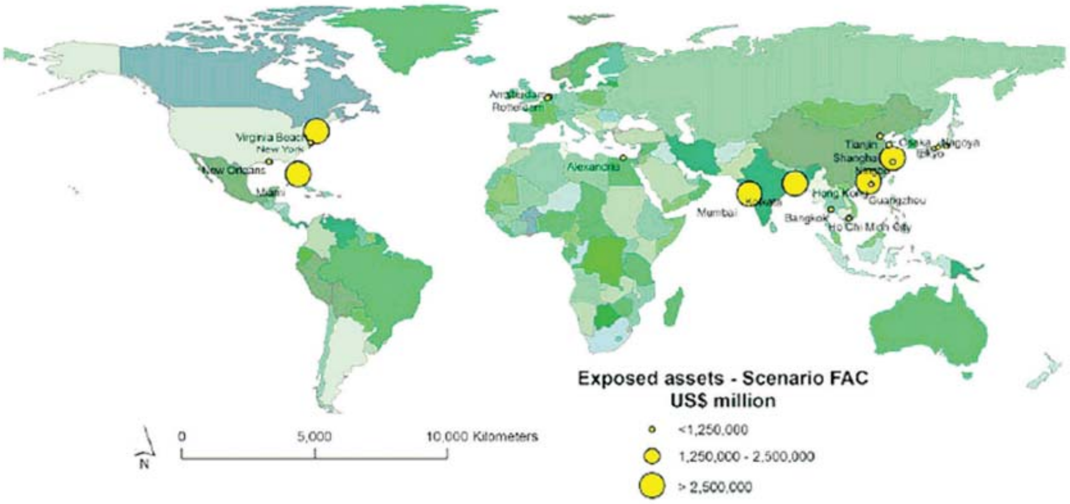


Figure 3.5: Nicholls et al. (2007) identified the top 20 port cities with exposed assets under future climate (2070) and socioeconomic change scenarios (OECD source)

Table 3.2: Range of responses of navigation to possible future climate change

Area of intervention	**Response (measures)**
Maritime infrastructure design	Redevelopment of wharf fendering (to barrier ships at dock)
	Increase of quay levels, sea wall structures and connected area behind to overcome increased frequency of overtopping and low land flooding
	Lowest point in buildings placed at a higher level
	Revision of ship tunnel dimensions
	Relocation or strengthening of less protected marinas for pleasure boats
	Stronger and higher salt water erosion resistant bridges needed
	Overtopping and stability of breakwaters: crest height and armour unit block size increased; possible reorientation
	Restrictions on existing port developments, and limitations on location of new ports
	In the absence of site-specific guidance, a sensible allowance for sea level rise is 5 mm/yr
	A sensible response to possible future wave condition change is to check that design and operability are not seriously affected by a blanket 10 % increase in offshore wave heights (plus 5% increase in wave periods to maintain the same wave steepness): Defra (2006)
	For nearshore wave conditions affected by wave breaking, change in sea level (and hence water depth) is another consideration: apply the 10% precautionary increase in deep water wave height, and then break the waves to the limit determined by the water depth at any particular location
	A reasonable test of sensitivity to possible future wind condition change is to check that design and operability are not seriously affected by a blanket 10 % increase in wind speeds: Defra (2006)
	Communities and industrial facilities in coastal zones may already be threatened or forced to relocate, while others face increasing risks and costs
	Rebuilding or new design elements of land-based Arctic infrastructure may be required by melting permafrost: ACIA (2004)
Maritime infrastructure operation and maintenance	Increased maintenance and replacement costs of port, coastal and sea platform infrastructure
	Increased maintenance due to increased storm surge damage to coastal protection infrastructure, seawalls, dunes, breakwaters etc.
	More sedimentation at river outlets, increasing dredging need
Maritime navigation practice	Adapting to fish migration, changes in fishing fleet design and harbour location
	Fishing fleet needs bigger boats to maintain activity if wave height increases, or else the work time is changed
	Change in beach erosion may require new or changed beach nourishment
	More frequent moist and cold air requires more compact and airtight equipment to avoid condensation problems
	Pilot meeting places may need to be altered
	Terminals for smaller passenger boats may need to be relocated; use of "quieter" parts of the coastline

Area of intervention	**Response (measures)**
	New mapping of new ice free areas in the Polar Region
	Account for more sea spray icing on navigation installations and structures
	Lift-on lift-off replaced by roll-on roll-off: Caldwell et al. (2002)
Vessel operation	More submerged reefs that need to be marked for avoidance
	Relocation of navigation fairways to less exposed areas; increased need for protected transportation channels
	Increased waiting time requiring larger areas for anchoring of vessels (vacant area is often very limited)
Vessel design	Use of different fuel or less fuel; reduced emissions
	Higher waves may require stronger ship design
Ecological	Relocation of fish farming plants to less exposed areas
	Changed designation of environmentally protected areas
Risk communication	Increasing shipping to reduce greenhouse gas emissions
	A potential problem for the public perception of navigation activities may arise due to difficulties in distinguishing between climate change effects and navigation-induced effects

4 Inland navigation

Like 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 inland navigation sector has more capability to respond to these drivers than the maritime sector, since in most countries adequate water resources infrastructure exists to modify run-off from precipitation. At the same time, complex political, social, and environmental factors govern the balance of water resources requirements for navigation against competing needs for water supply, flood damage reduction, hydropower, and irrigation.

This chapter discusses drivers of change to inland navigation induced by global climate change, the potential impacts of these drivers to the inland navigation sector, and possible responses that will mitigate adverse impacts or enhance positive impacts (Figure 4.1).

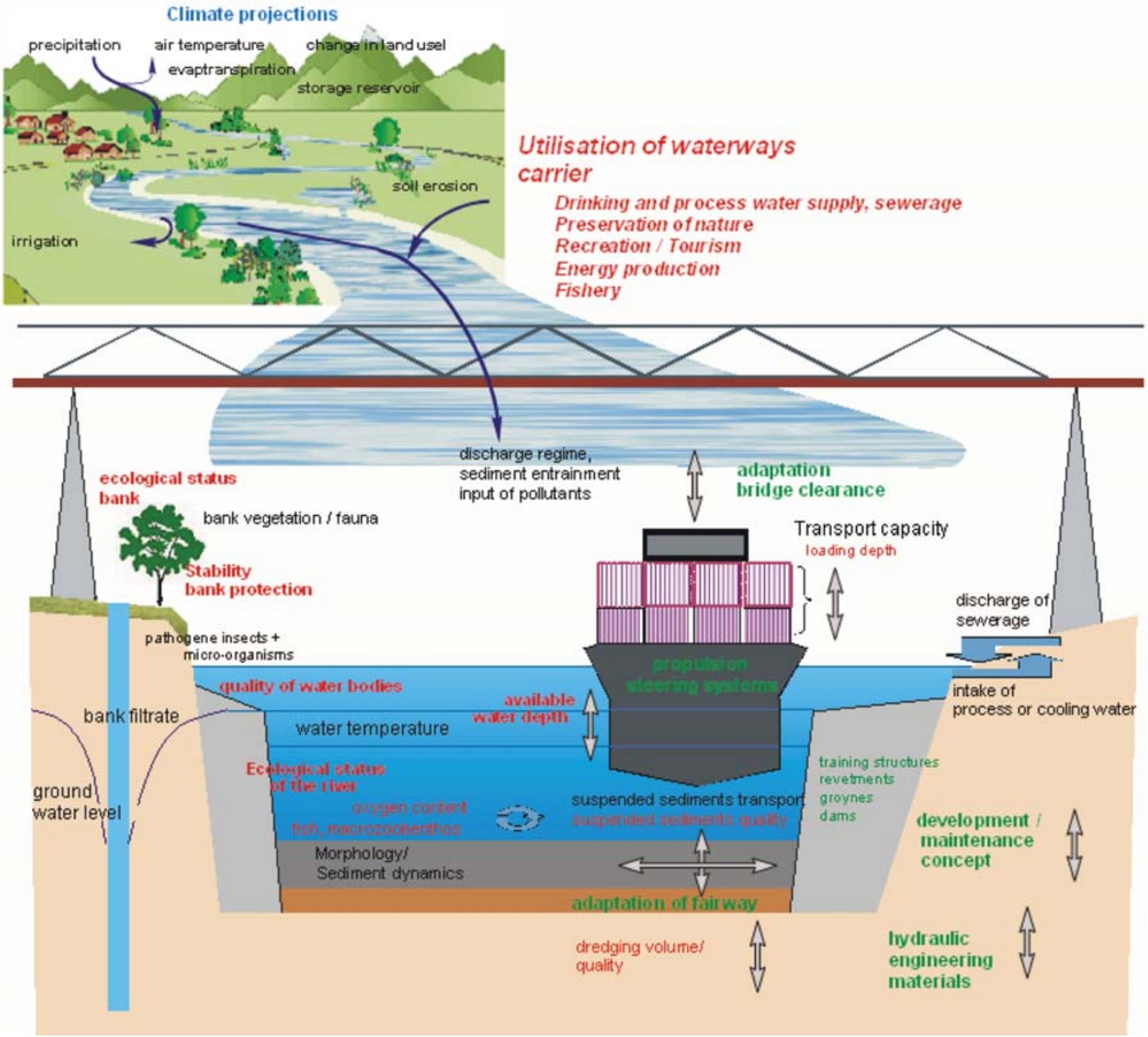


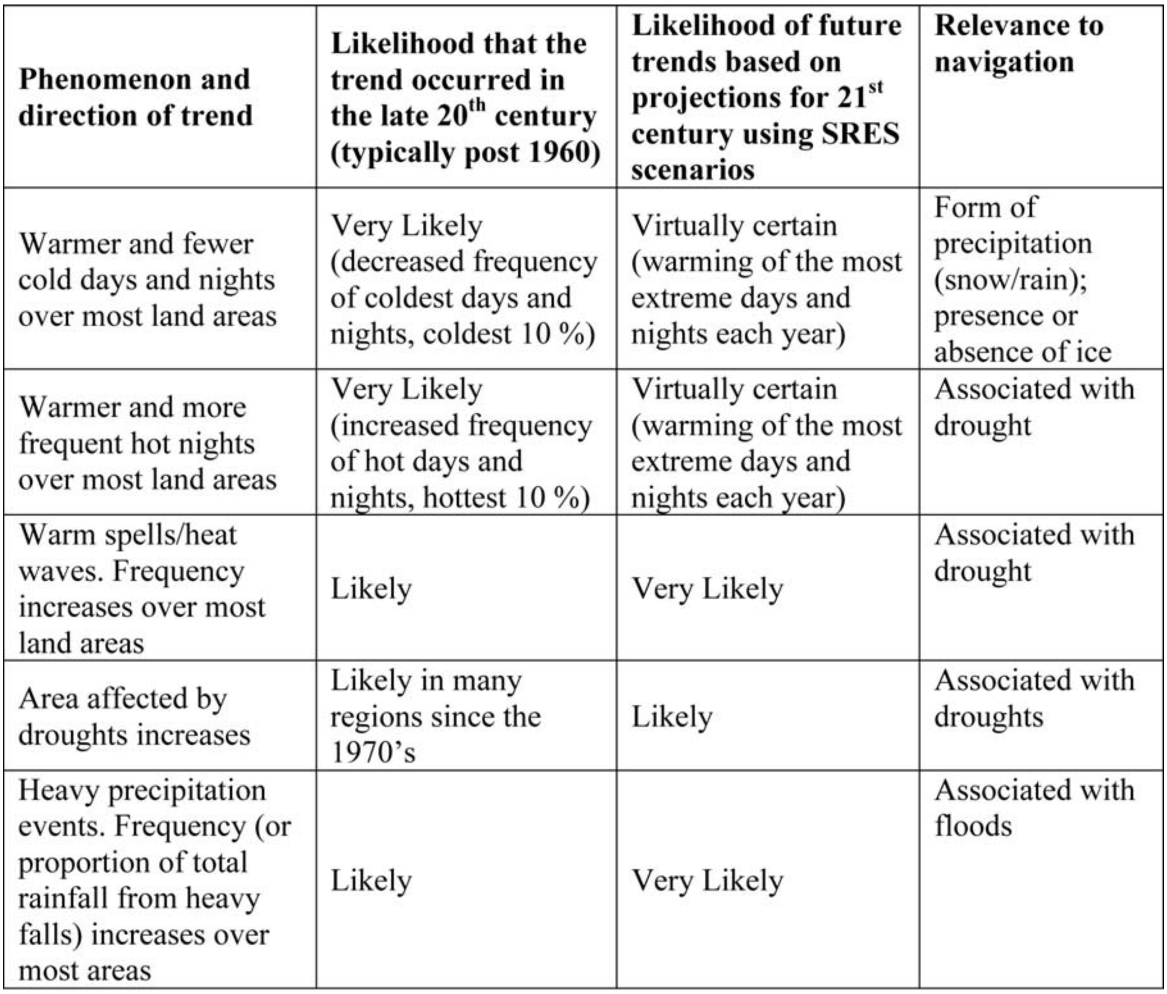
Figure 4.1: Links between drivers of change and potential impacts on inland navigation (courtesy of Federal Institute of Hydrology)

4.1 Drivers of change relevant to navigation

IPCC (2007d) identifies several climatological trends observed in the late 20th century and assesses the likelihood of future trends based on emissions scenarios (SRES) reported in IPCC (2000). These trends are summarized in Table 4.1 using the terminology of Tables 2.1 and 2.2.

These trends impact virtually all areas of the inland navigation sector, if, as stated by International Lake Ontario – St Lawrence River Study Board, the two factors critical to safe and efficient inland navigation are the available depth of water and the currents created by water flow (http://www.losl.org/twg/navigation-e.html#2).

Table 4.1: Trends and projections for extreme climatological and hydrological events (after Table SPM.2, IPCC, 2007d)



Phenomenon and direction of trend	**Likelihood that the trend occurred in the late 20th century (typically post 1960)**	**Likelihood of future trends based on projections for 21st century using SRES scenarios**	**Relevance to navigation**
Warmer and fewer cold days and nights over most land areas	Very Likely (decreased frequency of coldest days and nights, coldest 10 %)	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 %)	Virtually certain (warming of the most extreme days and nights each year)	Associated with drought
Warm spells/heat waves. Frequency increases over most land areas	Likely	Very Likely	Associated with drought
Area affected by droughts increases	Likely in many regions since the 1970's	Likely	Associated with droughts
Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas	Likely	Very Likely	Associated with floods

The key drivers of change, directly influencing the navigation on inland waterways, are the meteorological parameters: precipitation and air temperature. These parameters determine the water supply and the water temperature in the navigable river sections, which are discussed in more detail in Sections 4.1.1 and 4.1.2. The changes, especially in the water supply, will alter the occurrence of extreme hydrological conditions and thus will 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.

4.1.1 Water supply in the navigable river sections/waterways

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 1900-2005 (Figure 4.2) reflect the spatial variability of precipitation, which responds to atmospheric forcings of differing spatial and temporal 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).

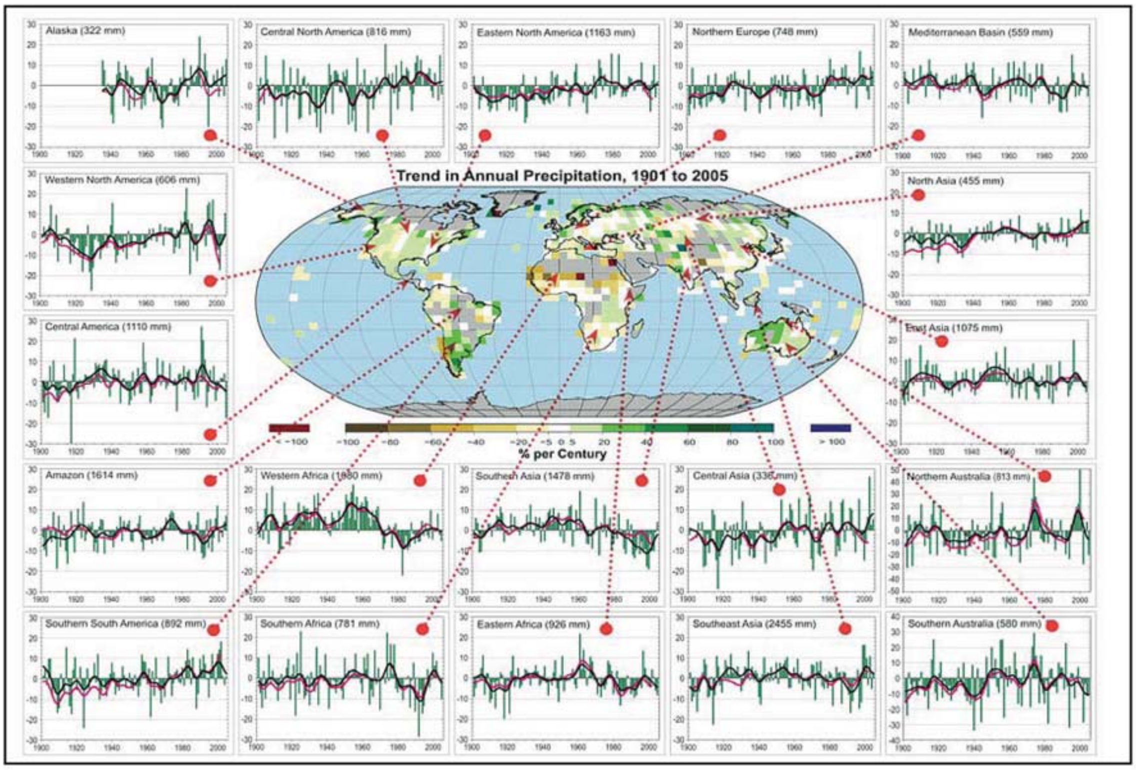


Figure 4.2: Trends in annual precipitation for 1900 to 2005
(reproduced from IPCC, Trenberth et al., 2007, AR4 WG1, Figure 3.14)

The change of annual precipitation expected in the future depends on the assumed scenario of the emission of greenhouse gases. While models predict increasing annual precipitation with climate warming, substantial spatial and seasonal variations are also expected (Meehl et al., 2007).

Figure 4.3 indicates that increases in precipitation are expected at high latitudes in winter

(December-January-February) and summer (June-July-August), while the mid-latitudes and tropics show mixed results. Regionally, precipitation has exhibited changes in seasonal trends, especially in the tropics, which shows a dry season and a monsoon season.

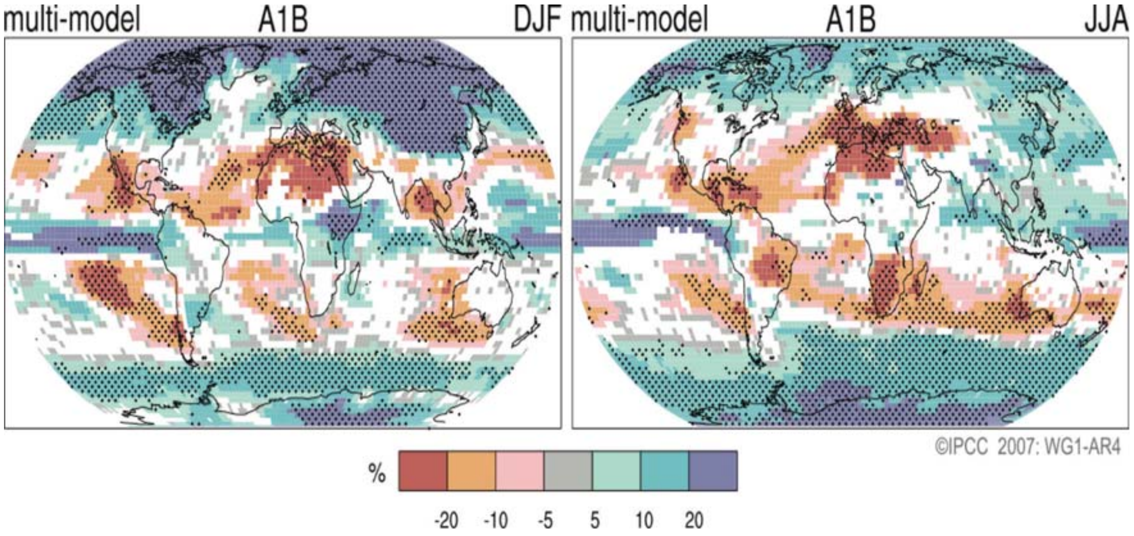


Figure 4.3: Predicted changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999, for December to February (left) and June to August (right); white areas are where less than 66 % of the models agree in the sign of the change and stippled areas are where more than 90 % of the models agree in the sign of the change (reproduced from IPCC, Meehl et al., 2007, AR4 WG1, Figure 10.9)

In addition to the change in annual precipitation, the seasonal cycle of precipitation may change. It seems that in North America, northern Asia and northern Europe the precipitation will increase in winter, while, especially in northern Europe, a slight reduction of precipitation in summer is expected. In addition to that, the frequency of heavy precipitation is increasing especially in North America and Asia. According to Figure 4.3, there is high uncertainty (white area) 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, which is discussed in more detail in Section 4.1.2, 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 River Rhine. 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 for each river catchment are needed here.

4.1.2 Water temperature

The water temperature in navigable river sections depends on the air temperature. 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, 2007) is expected for most of the emission scenarios of greenhouse gases within the next 20 years. 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, will occur less often. However, detailed studies for inland waterways are missing so far. Increased water temperature will lead to increased evaporation in the late fall and winter. In summer, higher temperatures will tend to cause an intensification of oxygen depletion in rivers due to enhanced biological activity. Since oxygen deficits are often compensated by discharging water over spillweirs, the water depth in navigable rivers is reduced. Further impacts are given in Section 4.2.

4.1.3 Extreme hydrological conditions

Several trends identified in Table 4.1 are indicative of an increase in extreme weather. IPCC (2007a) predicts that it is virtually certain that there will be warming of the most extreme days and nights each year over most land areas; very likely that the frequency of heat waves and heavy precipitation will increase over most areas; and likely that drought, and intense tropical cyclone activity will increase. Caused by this intensification of precipitation, and less precipitation stored as snow (see Section 4.1.1), more extreme hydrological events have to be expected. IPCC (2007a) 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 and increases in both larger and smaller discharges.

The change in the flow regime of rivers caused by the decreasing buffering of water in snow cover is expected to enhance extreme hydrological events 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 a 10 % increase in the probability of river flooding is found. Compared to the estimates of the future mean discharge conditions, 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, 2004).

4.1.4 River morphology

The morphology reflects the supply and transport of sediments in rivers. In the event of climate change, both sediment supply and sediment transport are subject to change.

The change in water quantity, described in Section 4.1.1, will alter the sediment entrainment into the rivers because of changes in soil erosion. An increase in soil erosion is related to an increase of effective precipitation. 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).

Changes in water quantity will cause changes in river discharge; especially, the probability of extreme hydrological events will increase, as discussed in Section 4.1.3. This could cause changes in river channel 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 on possible future channel changes. This may be attributed to a lack of physically based models of river channel form and sediment transport, resulting in little confidence in estimates of the effect of climate change on river channels (IPCC, 2001). Besides that, the prediction of changes in sediment transport shows a great dependence on the expected scenario of greenhouse gas emission. For example, for the River Rhine at Rees, the prediction of the increase in total annual sediment load varies from zero up to 37 % (Asselman, 1997). The uncertainty of this prediction is even larger when also considering different scenarios of land use change – even a decrease of total annual sediment load may then be possible.

The changes in sediment load will cause changes in river bed erosion, river dune development as well as in floodplain sedimentation, and therefore will require an adaptation of sediment management, i.e. dredging or artificial sediment supply.

4.1.5 Changes in ice cover

Observations indicate that river ice covers exhibit regional variations. A trend to later ice cover formation was reported by Magnuson et al. (2000) for selected rivers globally (Figure 4.4). On the other hand, rivers in Siberia (Smith, 2000; Ginzburg and Soldatova, 1996) and New England (Dudley and Hodgkins, 2002; Hodgkins et al., 2003, 2005) exhibit both earlier and later freeze up. Earlier ice cover break up was reported in Canada (Zhang et al.), Alaska (Keyser et al., 2000; Sagarin and Micheli, 2001), New England (Hodgkins et al., 2003, 2005), and Finland (Kajander, 1995). The duration of North American Great Lakes ice covers is decreasing as freeze up occurs later and break up occurs earlier (see Figure 4.5 from Kling et al., 2003). In a study of Finnish lakes and rivers, Korhonen (2005) noted that in general, freeze up is later and break up is earlier at many sites during the last few decades, but that statistically significant trends are usually only found where records exist since the late 1800s.

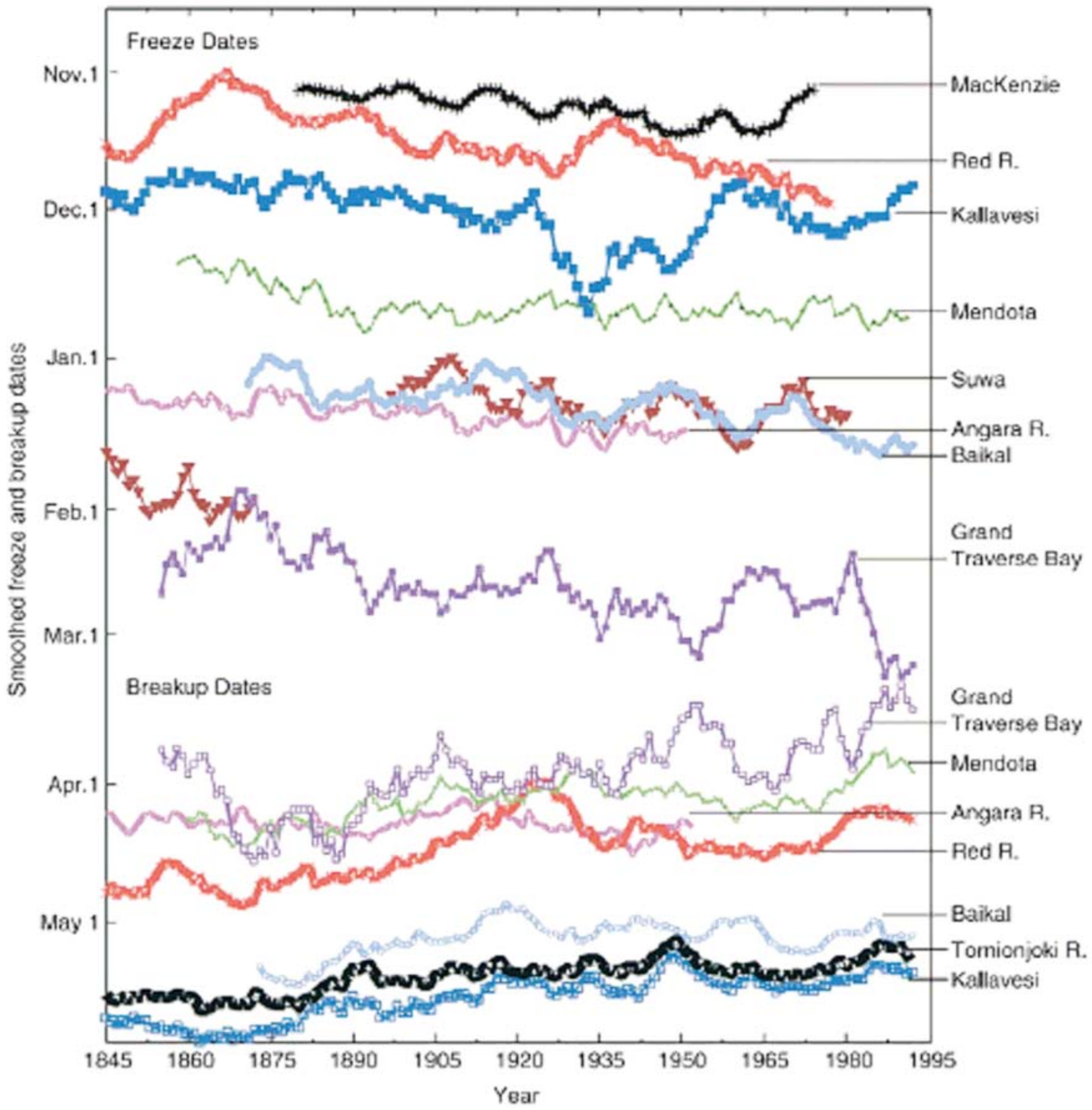


Figure 4.4: Time series of freeze-up and break up dates from several northern lakes and rivers in the US, dates smoothed with a 10 year moving average (reproduced from IPCC, AR4, WG1, Figure 4.5; original from Magnuson et al., 2000)

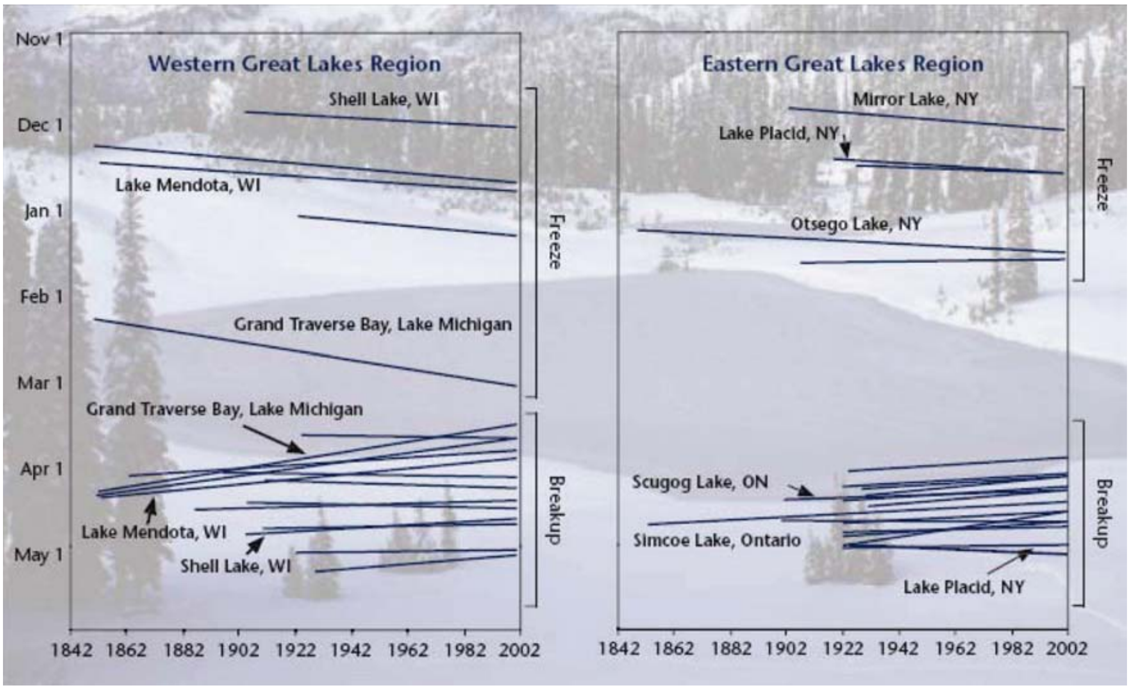


Figure 4.5: Observed changes in lake ice cover freeze up and break up for the North American Great Lakes (reproduced from Kling et al., 2003)

4.2 Potential impacts on navigation

Climate change effects due to temperature, precipitation, and sea level rise have and will continue to impact inland navigation primarily in terms of water depth and velocity, resulting in changes in sedimentation and the presence and absence of ice. General areas of impact are listed in Table 4.2.

Table 4.2: Drivers and impacts to inland navigation

Drivers	**Impacts**	**Rivers, channels, canals, lakes**	**Locks, dams, and infrastructure**	**Operational control**	**Vessels**
Water supply: increased precipitation Extreme conditions: more extreme floods	Increased water level and velocity	x	x	x	x
	Changes in sedimentation processes (bank failure, local scour, locations of aggradation and degradation)	x	x	x	
	Manoeuvrability		x		x
	Increased loads on structures		x		
	Decreased development land area available		x		
	Reduced regularity of the port		x	x	
	Reduced capacity of natural systems to recover	x			
Water supply: decreased precipitation Extreme conditions: more extreme droughts	Decreased water level and velocity	x	x	x	x
	Reduced regularity of the port		x	x	
	Changes in sedimentation processes (locations of aggradation and degradation)	x	x	x	
	Reduced capacity of natural systems to recover	x			
Water supply: changes in form and quantity of seasonal precipitation	Change in timing of seasonal high water and seasonal low water	x	x	x	x
	Changes in sedimentation processes (locations of aggradation and degradation)	x	x	x	x
Water temperature increases	Ecosystem impacts affecting habitat	x		x	
	Oxygen depletion	x		x	
	Reduced capacity of natural systems to recover	x			
River morphology	Changes in sedimentation processes (locations of aggradation and degradation)	x	x	x	x
	Ecosystem impacts affecting habitat and lifecycle				
	Reduced capacity of natural systems to recover	x			
Changes in ice cover	Shorter duration of river ice	x	x	x	x
	Changes in locations of ice jams	x	x	x	

4.2.1 Water supply in the navigable river sections/waterways

Climate drivers in the form of increases and decreases in precipitation and changes in form and quantity of seasonal precipitation will cause a range of impacts to inland navigation (see Figures 4.6 and 4.7).

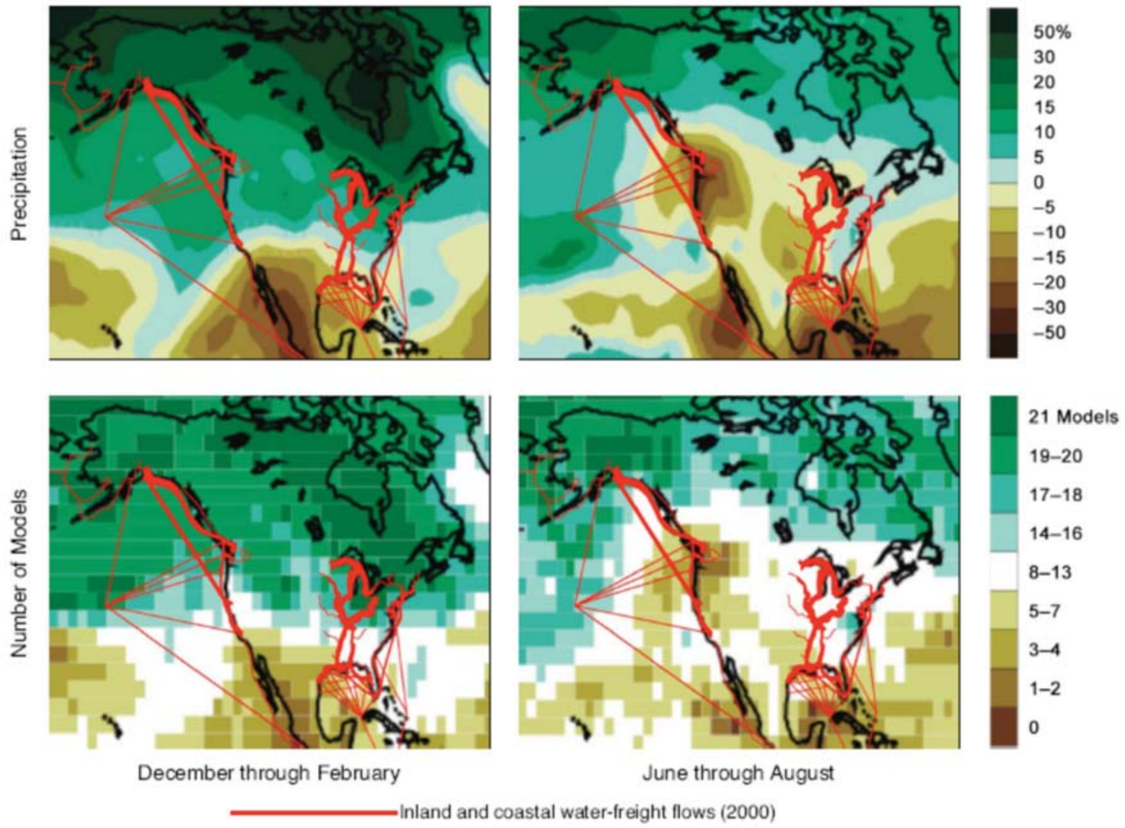


Figure 4.6: Precipitation changes over North America from the MMD A1B simulations: (top row) annual mean, DJF and JJA fractional change in precipitation from 1980 1999 to 2080 2099, averaged over 21 models; (bottom row) number of models out of 21 that project increases in precipitation (after IPCC, 2007d, Figure 11.12), superimposed over map of navigation from DOT freight analysis

These include increased and decreased water level and velocity, and resultant changes in sedimentation processes such as bank failure, local scour, and locations of aggradation and degradation. Changes in water levels that impact the movement of sediment, and hence channel maintenance activities, will require increased or decreased dredging, depending on the locations and specific impacts.

Changes in water level and velocity can also impact manoeuvrability and operational efficiency of navigation structures. Navigation structures may also experience loadings different from design loading, affecting stability and resiliency. Higher water levels could require modifications to existing ports and mooring areas or 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).

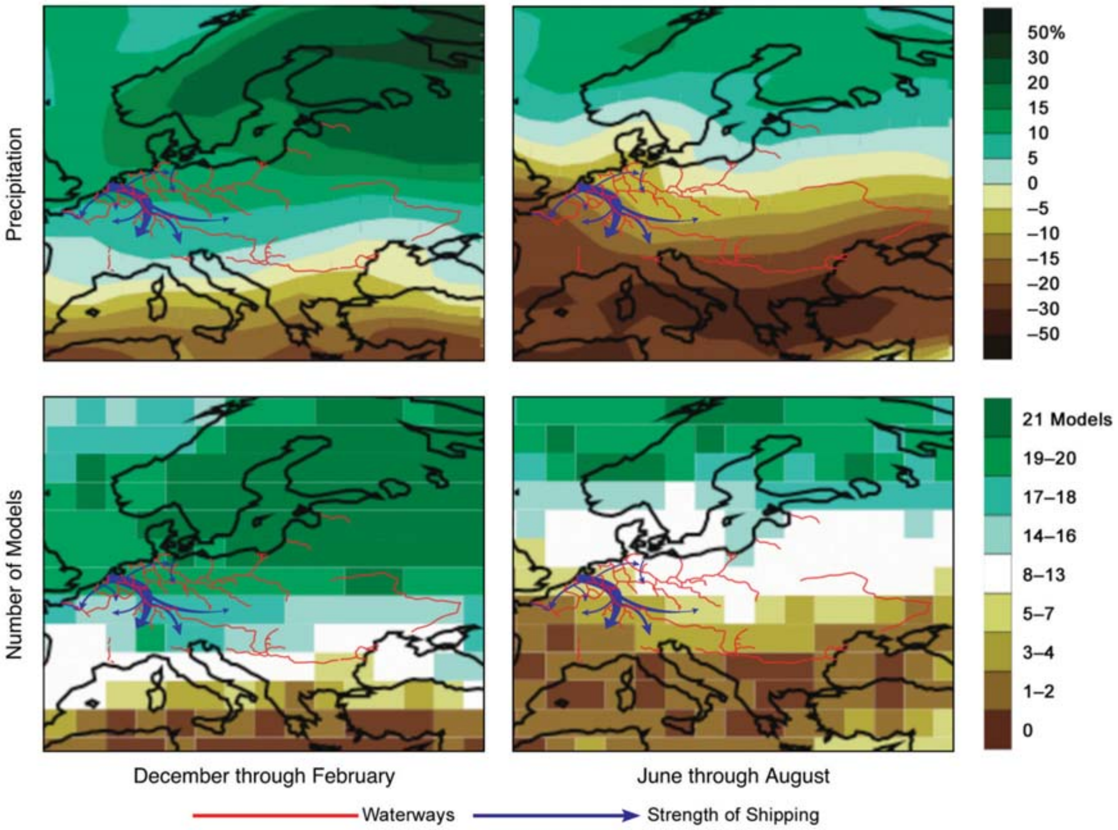


Figure 4.7: Precipitation changes over Europe from the MMD A1B simulations: (top row) annual mean, DJF and JJA fractional change in precipitation from 1980 1999 to 2080 2099, averaged over 21 models; (bottom row) number of models out of 21 that project increases in precipitation (after IPCC, 2007d, Figure 11.5), superimposed over map of main inland navigation routes

4.2.2 Water temperature

Changes in water temperature are expected to affect navigation primarily 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. Since oxygen deficits are often compensated by discharging water over spillweirs, the water depth in navigable rivers could be reduced.

4.2.3 Extreme hydrological conditions

The occurrence of more extreme floods and droughts will exacerbate impacts identified in Section 4.2.1. Increased flood levels may result in the need for re engineering infrastructure design (Caldwell et al., 2002). For example, Figure 4.8 depicts the changes to a dredged basin of the barrage at the River Rhine after a single extreme event. The large changes were caused by the suspended load transported from Switzerland due to the large summer flood in 2005.

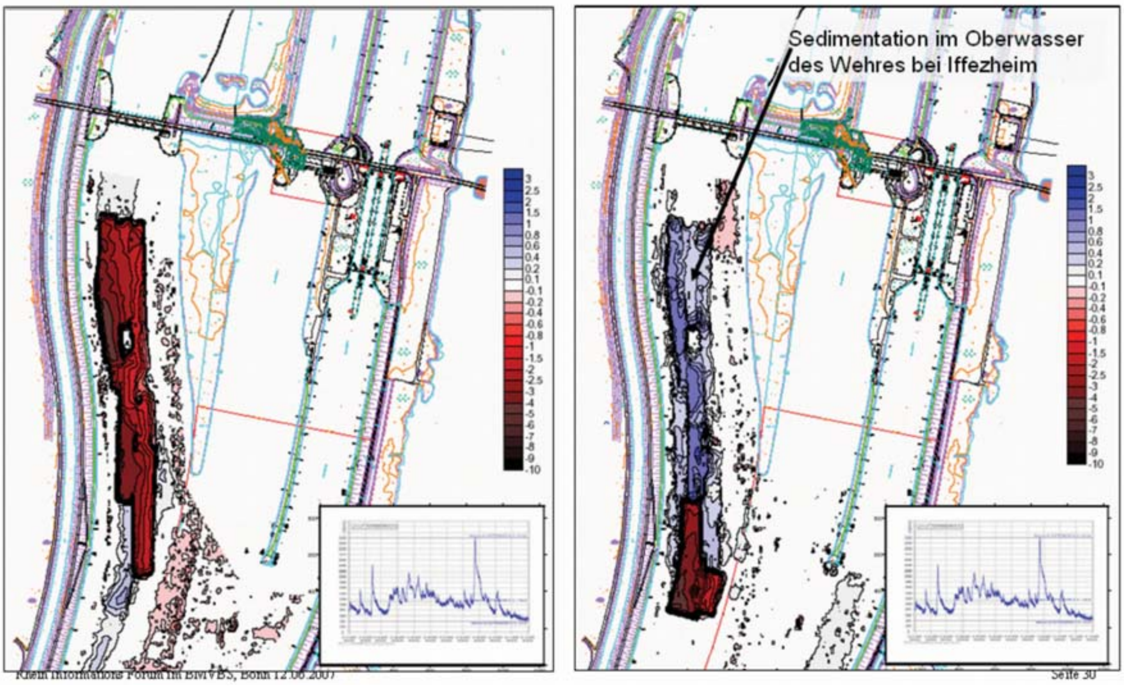


Figure 4.8: Changes to a dredged basin at a barrage in the River Rhine after an extreme high water in August 2005 (left: bathymetry before the extreme discharge, right: bathymetry after the extreme discharge, inset diagram: suspended load) (courtesy of Federal Institute of Hydrology, Germany)

4.2.4 River morphology

The changes in sediment load will cause changes in river bed erosion and river dune development, as well as changes in floodplain sedimentation, and therefore will require an adaptation of sediment management, i.e. dredging or artificial sediment supply. Changing erosion, scour, and sedimentation patterns will also impact ecosystem structure and functioning.

4.2.5 Changes in ice cover

Although climate trends indicate shorter periods of ice cover, 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 in thicker or rougher than normal ice cover formation or 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 4.9). While reducing the period of ice cover, earlier break up 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. In the Great Lakes, decreased duration of ice cover may be beneficial, resulting in extended navigation seasons.

Figure 4.9: 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)

4.3 Responses

Discussion in Sections 4.1 and 4.2 of climate drivers and impacts indicates that rivers, channels, canals, and infrastructure will be impacted most by observed and expected climate changes, followed by navigation system operations and vessels. Impacts to rivers, channels and canals may be mitigated through changes in operational control of flow or by modifications to channel maintenance. Because water supply for inland navigation is intimately connected to and competing with other water users such as domestic water supply, industrial and agricultural demand, and ecosystem requirements, operational changes to water control will require legal and environmental analyses. However, control of water flow to improve navigation may well be in line with the principles for flood mitigation (IKSR, 1998). Similarly, changes to existing maintenance practices such as channel and bank stabilization and dredging, will also require legal and environmental analyses before proceeding. Navigation system operation may benefit from increased use of automation, queuing procedures and the application of River Information Services (PIANC, 2002).

Extension of the time range of water level forecasts, increased data sharing regar-ding unexpected hazardous conditions or conditions requiring restrictions, and lessons learned from response successes and failures, should also improve system operation in the face of climate changes. Impacts to infrastructure will require analysis of existing structures and potentially re engineering to meet expected loadings under various climate change scenarios.

Impacts of climate change relevant to inland navigation, such as low water levels or floods, are well known phenomena in many parts of the world. The users of the navigation systems and the operators of the vessels try to respond to these phenomena in a way that assures the reliability of inland navigation. Thus, possible responses of the inland navigation sectors to the impact of climate change are already known and often applied (Middelkoop and van Deursen, 1999). Changes in transport management and operation of the vessels are short term responses addressing situations, when navigation is inhibited for a short period of time. If navigation conditions are altered over longer periods of time, adaptation of the fleet and new vessels of different design seem to be inevitable. Waterway users sometimes have to respond, when the providers of the waterway cannot take action. Caldwell et al. (2002) addressed impacts in the US Great Lakes, Mississippi River and the St. Lawrence Seaway and noted that decreased water levels in the absence of increasing authorized dredged channel depths may require either light loading of current vessels or use of vessels with decreased draft.

Table 4.3 summarizes possible responses by inland navigation to climate change impacts. Some of these responses require additional investment and/or cause higher operational costs. In other words, there are not only legal or technical, but also economic limits to these responses (Renner and Bialonski, 2003). Obviously, there is a portfolio of responses and in order for inland navigation to make the best choices of adaptation to climate change, the costs and benefits of the individual measures/responses should be known.

Table 4.3: Possible responses of inland navigation to climate change impacts

Area of intervention	**Response (measures)**	**Additional information**
Waterway design and maintenance	Creation of water storage facilities	(Upstream) reservoirs needed for flood mitigation could also be used to improve navigation
	Deepening of channels instead of widening	
Waterway operation	Managing water flow	Store water in times of high water flow, release water in times of low flow
	Improving forecast of water level	Better information, further ahead, could optimise the use of vessel capacity for given conditions, and reduce uncertainty margins
	Improved queuing procedures	Decision support systems and automation of queuing could help to overcome capacity restrictions of waterway infrastructure
	Implementation of River Information Services (RIS)	RIS in general support safe and efficient navigation
	Providing up-to-date electronic charts of fairway with water depth information	Better information to optimise use of vessels in given conditions, and reduce uncertainty margins
Transport management	Chartering of additional vessels	
	Increasing daily operation times of vessels	
	Cooperation with other modes of transport	Contractual arrangements with road and rail transport can be made for times of reduced navigability
	Increased storage of goods	
Vessel operation	Employing sophisticated Inland ECDIS (Electronic chart display and information system)	Provision of all necessary and always up-to-date information, better to utilize given navigation possibilities
Vessel design	Reduction of weight	Using alternative design or materials, installing lighter equipment
	Increasing width	Wider vessels need less draught

5 Mitigation – Navigation contributions to reduction of greenhouse gas emissions

In 2004, transport caused some 23 % of the world's energy-related greenhouse gas (GHG) emissions (International Energy Agency, 2006). Transport's GHG emissions have increased at a faster rate than other energy using sectors, with freight transport growing even faster than passenger transport. Even though some 90 % of global merchandise is transported by sea, navigation currently seems to count for less than 10 % of transport GHG emissions (Kahn Ribeiro et al., 2007).

The contribution of navigation to global warming is still highly debated. Studies by the Institute of Atmospheric Physics of the German Aerospace Centre, DLR, and by the College of Marine and Earth Studies of the University of Delaware, USA, conclude that emissions from maritime navigation count for 2.7 % of all anthropogenic CO_2 emissions. Further studies by DLR reveal the aerosols from ship emissions causing a cooling of the Earth's atmosphere that far outweighs the warming effects of their GHG emissions.

That makes GHG emissions from navigation appear small compared to road transport or other human activities. However, with the world maritime fleet growing steadily and with inland navigation's substantial modal share in some of the growth regions of the world such as China, navigation's share of GHG emissions may increase by as much as 75 % in the next 20 years (Vidal, 2007).

Transport affects people in many ways: it enables economic growth and creates social benefits; at the same time it has negative impacts on people's health, the economy and the environment (WBCST, 2007). Thus transportation's GHG emissions will be only one aspect of future transport development and must be addressed in the context of sustainable transport.

5.1 Technical, operational and transport management measures for mitigation of GHG emissions from navigation

Numerous measures for the reduction of GHG emissions from navigation have been identified – and are already implemented in many cases. The most comprehensive study so far seems to have been undertaken by the International Maritime Organisation (IMO). The study identified significant potential for emission reduction by technical measures, which can be easily implemented, and by operational measures, which are more effective. The reduction of speed is seen as the single most effective measure (Henningsen, 2000). The IMO has commissioned an update of this study to be submitted in 2010.

The IMO study deals only with maritime navigation and only with measures related to vessels and their operation. Table 5.1 includes measures related to navigation infrastructure and transport management, as they too provide potential for mitigation. Most of the measures can, to varying degree, be applied to both maritime and inland navigation.

Table 5.1: Technical, operational and transport management measures for mitigation of GHG emissions from navigation

Area of intervention		Measures	Issues / examples
Infrastructure	Waterways – Structures – Fairway	Layout for optimal ship size	
		Minimal manoeuvring necessity	
		Avoiding unfavourable currents	Square instead of trapezoid profile
	Waterway information	Providing information on waterway parameters	Cross-sections, current conditions
		Providing information on traffic conditions	Traffic density and disturbances, blockages
	Vessel traffic management	Traffic control	Optimal vessel speed
		Operation of waterway structures	Avoiding waiting times, engine shut off
	Ports and berths	Minimal manoeuvring necessity	
		Shore connection	Electrical power
		Energy efficient transhipments	
Vessels	Design and equipment	Optimal hull design	Weight
			Hydrodynamic properties (optimisation of main dimensions, hull shape, speed, propulsion organs)
		Optimizing conventional propulsion	Energy efficient layout, avoidance of over-dimensioning, full electric propulsion
		Employing alternative propulsion	Fuel cell, solar, wind (Flettner Rotor, Skysail)
		Use of tank testing	
		Energy efficient equipment	Auxiliary systems, appliances
		Recuperation of energy	Heat exchanger
		Onboard information systems for fuel efficient sailing	Econometer
	Fuels	Reducing GHG during production of conventional fuels	Reducing sulphur increases GHG
		Using biogenic fuels 1. Generation	Questionable ecological & social effects, storage on board
		Using biogenic fuels 2. Generation	Not yet available
		Using gaseous fuels	Production, storage on land, distribution, storage on board
	Operations	General reduction of speed	Probably single most efficient measure
		Adaptation to fairway dimensions	
		Avoiding idling of engine	
		Optimal trim	
		Manoeuvring, as little as possible	
		Choice of optimal travel routes	

Area of intervention		Measures	Issues / examples
	Maintenance	Clean underwater hull surfaces	
		Clean, undamaged propulsion organs	
		Optimal tuned and maintained engines	
Transport management		Avoiding empty vessel journeys	
		Using full capacity of vessels	
		Avoiding waiting times	

The mitigation measures of Table 5.1 are limited to fuel consumption and use of alternative fuels. Further GHG reduction potential can be attributed to the use of material and energy during construction and scrapping of vessels as well as construction, maintenance and demolition of the shipping infrastructure.

5.2 Policies and instruments to create incentives for mitigation action

Most of the above mentioned measures are well known, but their application must be substantially broadened to have a real mitigation impact. A variety of policies and instruments are available for national governments and international organisations to create incentives for their application. Table 5.2 lists those policies together with examples of current or future application in navigation and evaluation of their performance.

Table 5.2: Policies and instruments to create incentives for mitigation (after Barker et al., 2007)

Policies/instruments	Examples in navigation	Performance
Regulations and standards	Emission limits for pollutants, speed limit	Good performance, when regulation can be simple
Taxes and charges	Tax on fuel	Less efficient in richer countries
Tradable permits	Under discussion for maritime shipping	Can be efficient, when market and institutions well developed
Voluntary agreements	(Green ship award)	Questionable
Subsidies and other incentives	Subsidies for clean engines, reduced harbour dues for clean vessels	Questionable
Research and development	Improved/alternative hull and propulsion design	Can be very beneficial, when programs well designed and long-term

Most of the above mentioned policies and instruments have already been studied and some are applied to reduce GHG emissions from maritime navigation (den Elzen, 2007; Henningsen, 2000; IMO, 2005;

IMO, 2006; Kahn Ribeiro, 2007). For inland navigation, this seems not to be the case, possibly due to the fact that inland navigation

- is responsible for much less GHG emission than maritime navigation,
- constitutes a small industry sector with very limited financial resources,
- is not governed by a single international organisation.

5.3 Costs and efficiency of mitigation of GHG emissions

Reducing the speed of vessels has been identified as the most effective measure for reducing fuel consumption and thus GHG emissions. This measure, even though it reduces the operational costs for the individual vessel, can be uneconomical when the increased travel or turnaround time for the vessel makes it necessary to employ a second vessel or when the cargo is of a very high value. Choosing measures that make economic sense is not easy and the cost of the individual measure must always be seen in relationship to its GHG emission reduction potential.

Studies show that the marginal costs of different mitigation measures vary considerably. Therefore measures with lower marginal costs should be given priority. There are even some measures with negative mitigation or abatement cost – allowing cutting emissions and reducing cost at the same time. Low energy lighting is often cited as an example for such a measure (Enkvist, 2007). Calculating the marginal costs for different mitigation measures in navigation would enable informed decision making and allow concentration of further work on those measures that are most cost efficient. However, abatement costs and the potential for navigation don't seem to be included in those studies, even when they cover transport in general (Vahlenkamp, 2007).

One of the most important questions for ship owners as well as regulators is the additional costs that navigation will be faced with, either for mitigation measures or for having to buy emission rights in a future emission trading scheme. Studies have tried to answer this question for the world economy by establishing a price (range) for carbon. For stabilising CO_2 concentration in the atmosphere at 550 ppm or less, which is widely seen as a desirable goal, the price ranges from 20 to 80 USD per tonne emitted carbon, depending on different factors (The Economist, 2007). Using diesel, the standard fuel in inland navigation, as reference, a price of 50 USD per tonne carbon equals some 0.15 USD per litre diesel. In other words, under the chosen scenario, ship owners would have to pay some 0.15 USD extra per litre diesel consumed by their vessels.

5.4 Interdependencies between mitigation, safety and environmental protection

Navigation accidents often lead to additional GHG emissions, due to salvage operations, waiting times or detours for other vessels. Increasing safety of navigation contributes to GHG reduction. In any case, GHG reduction measures that may have a negative impact on the safety of navigation should be avoided.

Even though reducing GHG emissions has become more prominent in navigation, the environmental agenda of maritime and inland navigation is still determined by measures to reduce pollutants, such as NOX and particulate matter. As the burning of fuel is the overriding source of GHG emission from navigation, almost any GHG mitigation measure will also contribute to the reduction of these pollutants and thus create additional benefits (Berk et al., 2006). However, reducing pollutants does not necessarily go hand in hand with a reduction of GHG emissions. For example, producing low sulphur fuel leads to higher CO_2 emissions of the oil refineries.

Many GHG mitigation measures have a positive impact on the aquatic environment as generally GHG emission reduction means more (fuel) efficient navigation. This is often achieved by either fewer vessel journeys or journeys of vessels that move with lower engine power and thus less return current, waves or propeller current (PIANC, 2007)

5.5 Climate change mitigation – opportunities for navigation

Navigation, like many other sectors of the economy, will face serious risks from climate change, with unstable and unfavourable weather conditions making navigation difficult or even impossible, being one of them. Other risks derive from changes in transport demand. In certain parts of the world, fossil fuels such as coal and oil, which constitute perhaps the most important cargoes for navigation, will be replaced by other fuels or renewable sources of energies.

However, research suggests that navigation may well be one of the winners of climate change, most likely due to regulatory measures for climate change mitigation. As transport demand for some traditional cargoes of navigation will decrease, demand for other cargoes will increase as the industry producing or consuming these cargoes benefits from climate change and in particular from the regulatory-market economy dimension of climate change. For example, producers of biogenic fuels will create transport demand for their raw materials as well as for their final product. Other industries being identified as winners of climate change and traditionally relying on transport by navigation are, for example, the chemical and the construction industries (Heymann, 2007).

Navigation is characterized by low energy consumption and therefore a small carbon footprint; in addition it has a good potential for reducing it even further (Ilgmann, 1998; Henningsen, 2000). Its climate-friendly image makes it already attractive for shippers of cargo. Carbon pricing or other regulatory measures will make it even more so and will give it a competitive edge over other modes of transport, especially road transport and aviation. Thus, being itself relatively climate-friendly and becoming a tool for mitigation of GHG emissions in tomorrow's world economy, navigation may even be a double winner from climate change. Fuglestvedt et al. (2008) prepared a comprehensive analysis of radiative forcing by subsector of transport. Road transport was found to be the largest contributor to warming while shipping causes net cooling. Figure 5.1 identifies forcing from CO_2 alone.

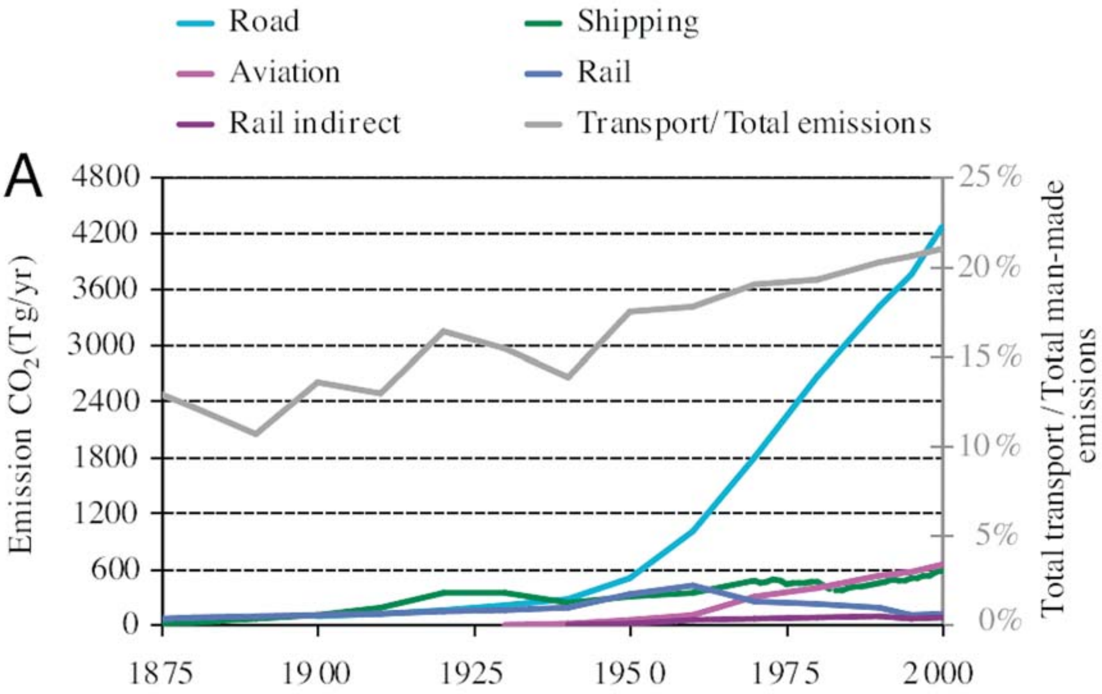


Figure 5.1: Historical development in CO_2 emission from the transport sector (left axis) and development in CO_2 emissions from the various transport subsectors as a fraction (right axis) of total man-made CO_2 emissions (excluding land use changes) (reproduced from Fuglestvedt et al., 2008)

6 Conclusions

Recognition of current climate change impacts and future impacts – both anticipated and unanticipated - provides an opportunity for the navigation community to shape polices, adaptation strategies and mitigation measures for inland and maritime navigation. This report explores climate change impacts and potential responses to infrastructure, vessels, and transport management in an effort to create a continuing dialogue for consideration of adaptation or mitigation strategies to climate change by the navigation community.

We consider adaptation to include strategies that adapt our current systems and infrastructure to account for changing climate. Mitigation, on the other hand, refers to activities that directly decrease the contributions to global warming, which is the major driver of climate change. According to IPCC (Adger et al., 2007), many impacts can be avoided, reduced or delayed by mitigation, and while some adaptation is currently underway to address observed and projected climate change, more adaptation is required to reduce vulnerability and consequences associated with climate change. They point out that sustainable development is required to adapt successfully to climate change, but that costs could be prohibitive for some adaptation alternatives. The European Union recently implemented a Water Framework Directive, including for all new projects the concept of climate-proofing, defined as "Ensuring the sustainability of investments over their entire lifetime, taking explicit account of a changing climate." This may become an important driver in all future planning processes. Portfolio management of adaptation and mitigation options may be useful in prioritizing investment strategies to encourage sustainable development.

Ideally, the navigation community will employ adaptive planning, operational, and infrastructure decision-making that take into account natural and social system features and the impacts of incremental changes over time. A comprehensive systems approach that allows continuous upgrades as new knowledge emerges and new engineering practices are developed will support satisfactory system safety and performance under the dynamic conditions and in the face of nonlinear processes associated with climate change.

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PIANC General Secretariat
Boulevard du Roi Albert II 20, B.3
1000 BRUSSELS
BELGIUM

www.pianc.org
VAT BE 408-287-945