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Waterborne transport, ports and navigation: Climate change drivers, impact and mitigation

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WATERBORNE TRANSPORT, PORTS AND NAVIGATION: CLIMATE CHANGE DRIVERS, IMPACTS AND MITIGATION

by

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ABSTRACT

The paper is based on the recently completed report of a PIANC task group on climate change and navigation. The Intergovernmental Panel on Climate Change updated its reports and recommendations during 2007. Its assumptions, definitions and findings represent a peer-reviewed body of knowledge that identifies changes in climate and projected future changes. It was timely for PIANC to update its position and recommendations regarding climate change.

The main purpose of PIANC EnviCom Task Group 3 was to take a broad look at all aspects of climate change of potential interest to navigation and ports. The Task Group 3 report informs PIANC on how navigation may be affected by climate change and where actions might be taken to develop adaptation strategies, mitigation measures and investments in a pro-active way. This paper reviews the possible effects of climate change on metocean conditions, the consequent impacts on navigation (whether damaging or beneficial), and some of the associated opportunities and vulnerabilities.

1. INTRODUCTION

1.1 PIANC EnviCom Task Group 3: *Climate change and navigation*

PIANC EnviCom Task Group 3, *Climate change and navigation*, met in Brussels (Belgium) in March 2007, in Wallingford (England) in August 2007, and in Hanover (USA, see Figure 1) in February 2008. Its purpose was to take a broad look at ways in which future climate change might affect maritime, inland and arctic navigation, so that PIANC could direct its continuing climate change assessments accordingly.

The Group's report (PIANC, 2008) was issued in May 2008 and is freely available from PIANC. The report informs PIANC on how navigation may be affected by climate change and where actions might be taken to develop adaptation strategies, mitigation measures and investments in a pro-active way. It reviews climate change impacts on maritime and inland navigation, considering climate change drivers, impacts, responses and mitigation. Figure 2 illustrates potential climate change impacts on navigation.

This paper presents some of the main points from the report. The Intergovernmental Panel on Climate Change (IPCC) is taken as the authority on past and future climate change. Where relevant, and not specified otherwise, comments in this paper are based on its 2007 reports (IPCC, 2007a-d). The assumptions, definitions and findings given in the IPCC 2007 reports represent a peer-reviewed body of knowledge that identifies changes in climate and projected future changes. It was timely for PIANC to update its position and recommendations regarding climate change.

Even if future greenhouse gas forcing and future climate were assumed to be known, prediction of impacts, responses, vulnerabilities and opportunities would still be uncertain. Figures 3 and 4 illustrate the propagation of uncertainty from greenhouse gas forcing, through climatological variables, to navigation related variables. Thus, for example, complexity and uncertainty may be inversely related to spatial scale (see Figure 4) but proportional to scientific understanding of processes.

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Figure 1: PIANC EnviCom Task Group 3: Stephan Mai (Federal Institute of Hydrology, Germany), Peter Hawkes (HR Wallingford, England), Kate White (US Army Corps of Engineers), Øivind Arntsen (University of Science and Technology, Norway), Hans Moser, (Federal Institute of Hydrology, Germany, and Group Chairman), Pierre Gaufres (National Centre for Maritime and River Studies, France), at the Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire; Gernot Pauli (Central Commission for Navigation of the Rhine) is missing from this photograph

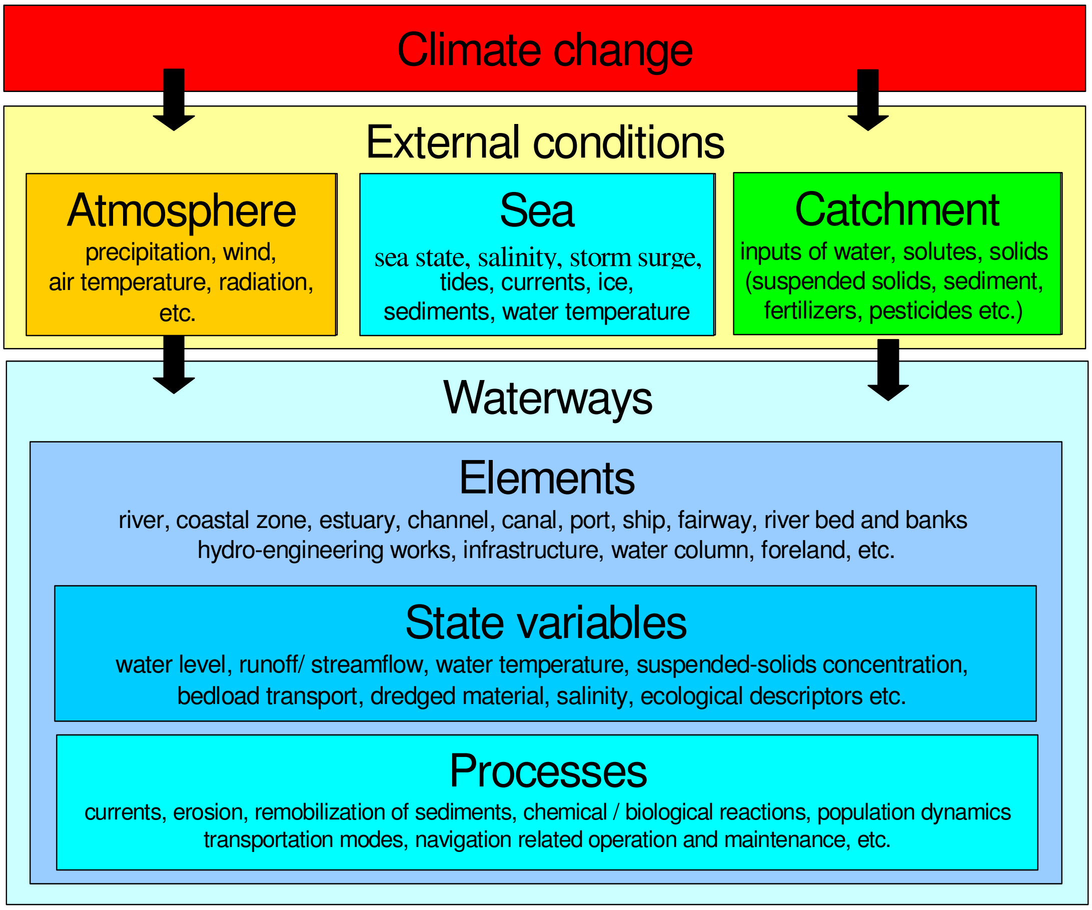

Figure 2: Illustration of climate change influencing the use of waterways (from PIANC, 2008)

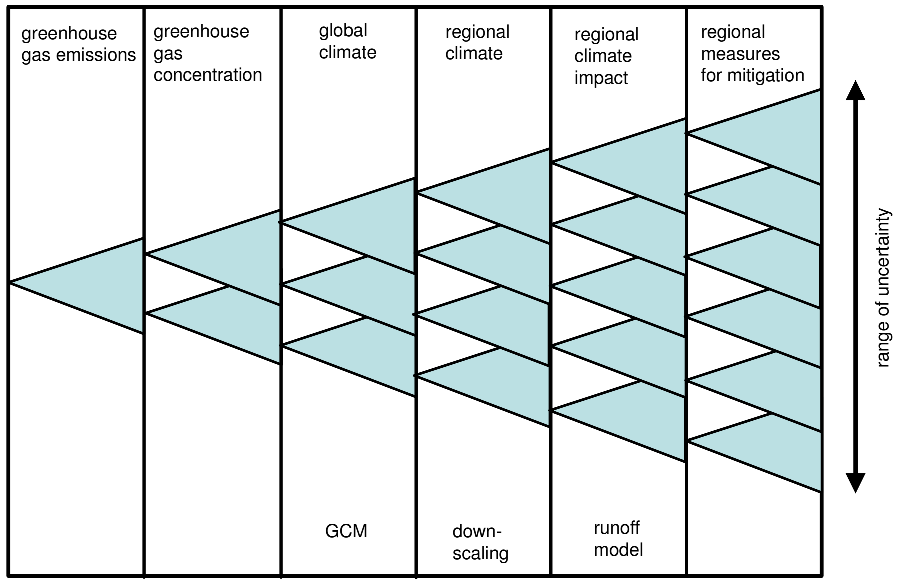

Figure 3: Illustration of the spread of uncertainty from greenhouse gas forcing through to impacts and mitigation (from PIANC, 2008)

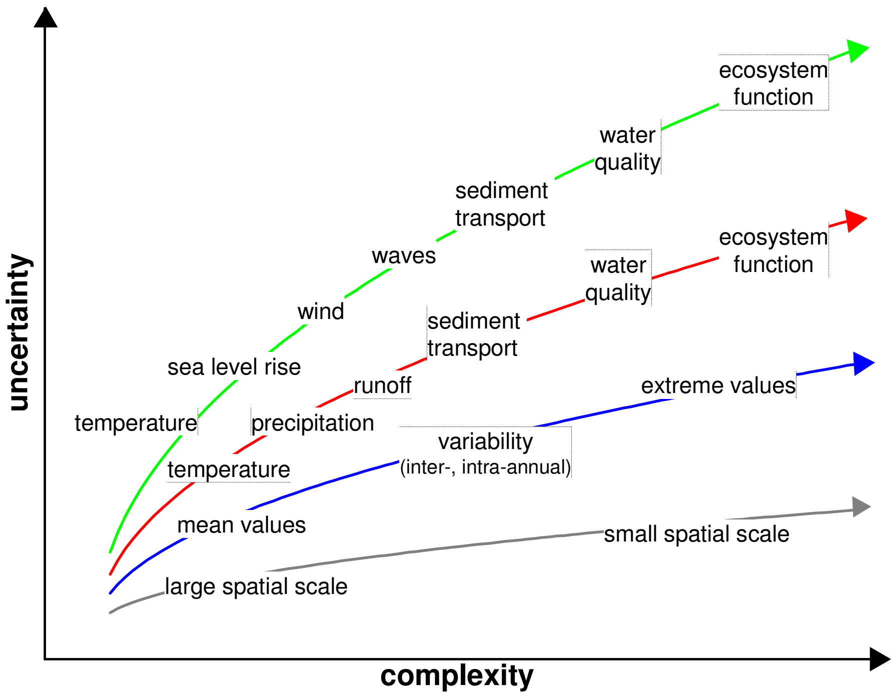

Figure 4: Illustration of the spread of uncertainties from greenhouse gas forcing through to navigation related issues (from PIANC, 2008): red and green curves for inland and maritime navigation, respectively; blue and grey curves for probability and spatial scales, respectively

PIANC (2008) includes:

- Identification of the relevance of climate change for maritime and inland navigation and a summary of the potential effects (e.g. environmental, technical, economic, political).
- Summary of examples where climate change already creates problems for navigation.
- Discussion on how the navigation sector could contribute to reduce climate change effects, e.g. through reduction of CO_2 emissions, and taking cargo off roads and air.
- 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.

PIANC has recently established a *Permanent Task Group on Climate Change*, with chairman Kate White and members representing PIANC's main permanent committees.

1.2 Climate change

Since the industrial age, global average surface temperature has increased by about 0.6° C. Changes are expected to become more pronounced in the future: projections suggest that mean surface temperature will rise by between 0.6 to 4° C between 1990 and 2100 (Figure 5). The range of projections seen in Figure 5 (B1, A2, A1F1 etc) reflects the range of plausible political, industrial and social scenarios (IPCC, 2000) considered when developing the 2007 reports.

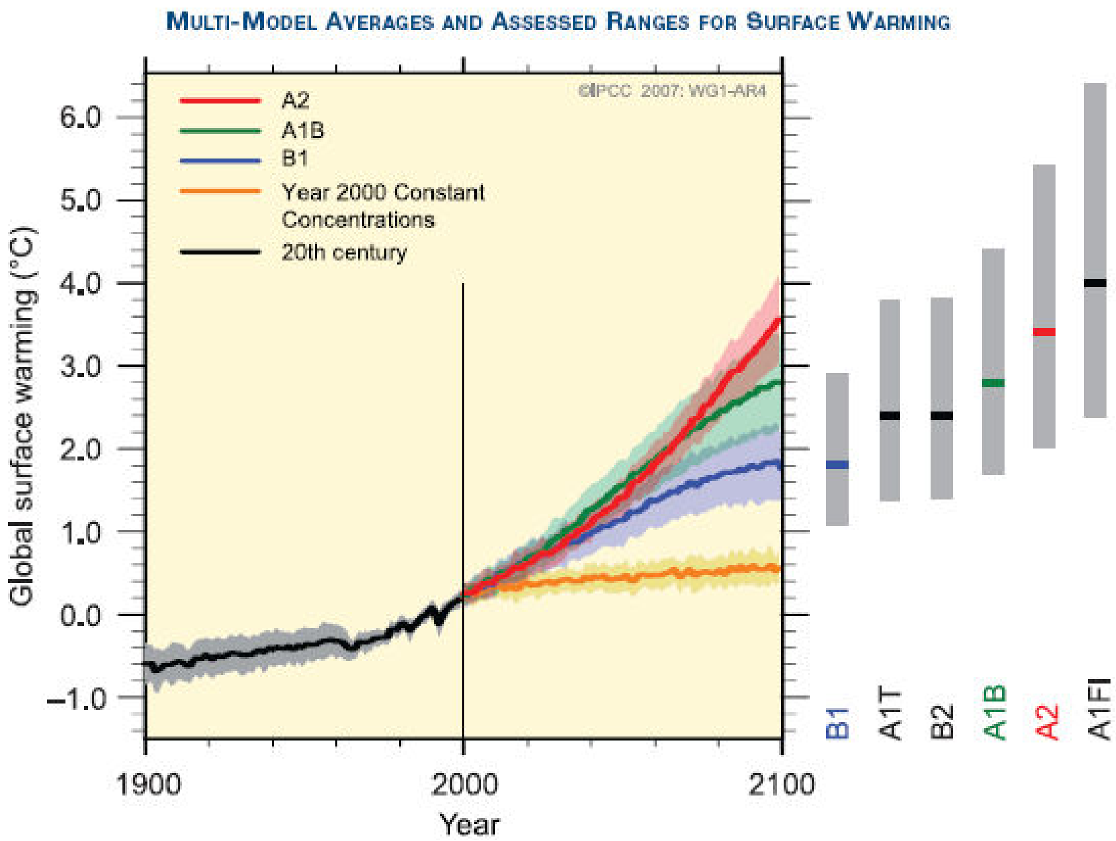

Figure 5: Projected change in surface temperature due to climate change (reproduced from Figure SPM.5 of IPCC, 2007d). Solid lines are multi-model averages of surface warming (relative to 1980-1999). Shading denotes ±1 standard deviation range of individual model averages. The grey bars to the right indicate the best estimate (solid line within each bar) and the likely range.

Due to the continued melting of polar ice and mountain glaciers, and the expansion of the warmer sea water, mean sea level is projected to rise by a few decimetres by 2100 (Figure 6). Figure 6 shows thermal expansion (red) of existing sea water as the largest contribution to sea level rise, and the Antarctic (dark blue) as a negative contribution, meaning that it is projected to increase its ice content.

More frequent and intense extreme weather events are 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.

Climate change could affect ecosystems, biodiversity, human life and many economic activities including navigation. Most 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. Against this background it is appropriate for individual countries, industries and organisations to consider their vulnerability to climate change, and to develop adaptation strategies in preparation to mitigate potential impacts.

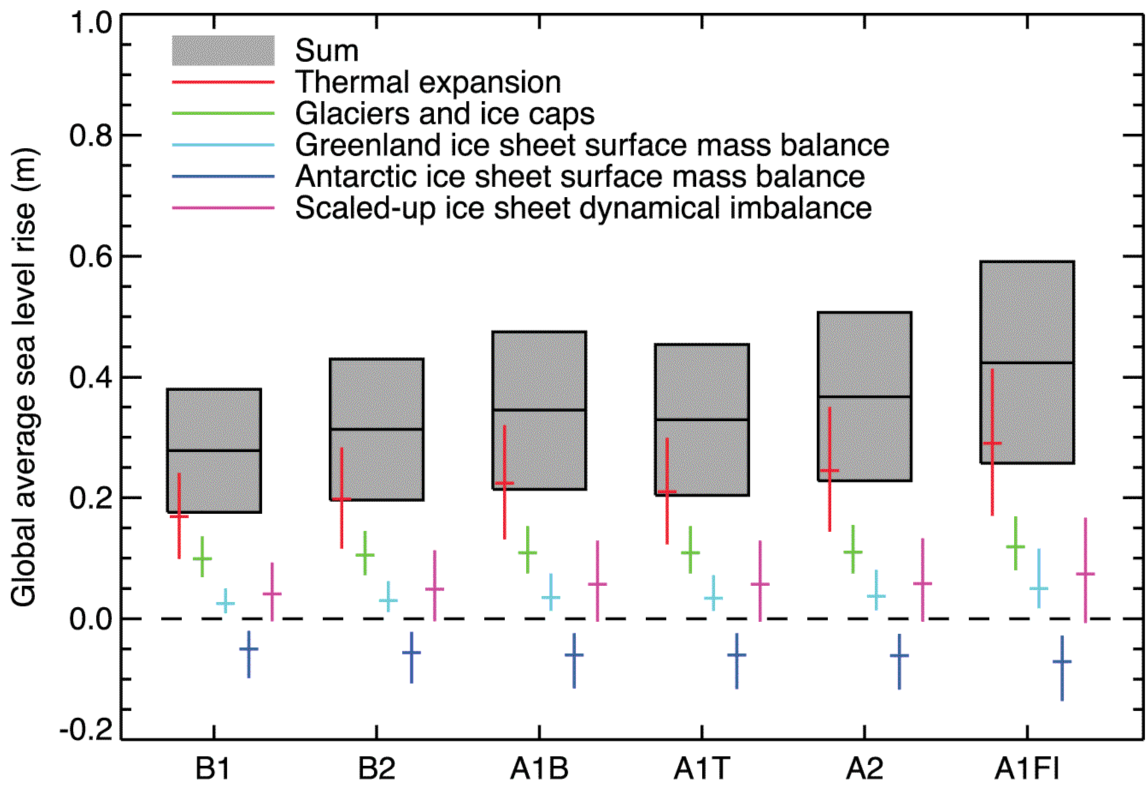

Figure 6: Projections and uncertainties (5 to 95% ranges) of global average sea level rise and its components in 2090 to 2099, relative to 1980 to 1999 (reproduced from Figure 10.33 of IPCC, 2007a). The projected sea level rise assumes that the part of the present-day ice sheet mass imbalance that is due to recent ice flow acceleration will persist unchanged. Each grey box represents the sum of the means and uncertainties of the five associated components.

1.3 Content of this paper

This paper reviews the possible effects of climate change on metocean conditions, the consequent impacts on navigation (whether damaging or beneficial), and some of the associated opportunities and vulnerabilities. Detrimental effects include reduction in water available for inland navigation in some locations during some seasons, and general disruption to infrastructure and activities designed for present-day climate. However, there are some positive effects, including a competitive advantage against land and air freight, based on lower greenhouse gas emissions, new opportunities for arctic exploration, and less ice in navigable rivers.

Chapters 2 and 3 focus on maritime and inland navigation, respectively. In context, 'maritime' refers to waterways having an effectively unlimited supply of water from the oceans, and 'inland' to waterways dependent mainly on rainfall for their water supply. On this basis, the Suez Canal (entirely at sea level) would be 'maritime', the elevated Panama Canal would be 'inland', and the Great Lakes would be mostly 'inland' although travelled by maritime vessels. River sections affected by both tide and fresh water flow may fall into both categories. Chapters 4 and 5 describe example advantages and disadvantages to navigation interests that may be associated with future climate change.

2. THE RANGE OF POTENTIAL IMPACTS ON MARITIME 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 1, where the letter 'x' indicates which changes might affect which navigation-related sectors.

Drivers	Potential impacts	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 overtopping sea walls	Low land flooding	x	x		
Wave attack at a higher water level, reducing the energy loss due to breaking, potentially allowing higher waves to reach structures	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 availability of ports	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), Great Lakes, Magellan Strait, Cape Horn				x
	More freshwater in rivers, giving more ice in estuaries				x
	Reduced ice cover will increase bio-production in Polar Regions, with associated relocation of fish				x
	Change in sea spray affecting icing				x

Table 1: Climate change drivers and associated impacts on maritime navigation

2.1 Increase in 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 effect 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 rise in groundwater level would affect water pressures behind retaining structures, bearing capacity of paving and foundations, and buried utility services and drainage outfalls.

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. Other potential impacts include changed operating envelopes of cargo handling and dry-docking equipment (e.g. cranes, marine arms, ro-ro ramps, shiplifts), reduced stability and increased flotation of gravity structures and embankments, reduced freeboard for lock and dock gates, increased pumping to maintain dry-docks dewatered, increased travel of pontoon moorings, and immersion of enclosed fenders.

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.

2.2 Change in wind conditions

The proportion of winds with speeds above 15 m/s is projected to increase in northern latitudes. 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. Many modern vessels are more sensitive to wind than older ones, and may suffer more downtime. Related effects include reduced calm weather windows 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 also necessitate larger areas for anchoring of waiting vessels.

2.3 Evolution of wave action

Offshore loading and unloading operations are wave height dependent, for example buoy loading ships may require significant wave height H_s to be below 4.5 m for connection, and may have to disconnect if H_s is above 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 and stability of breakwaters and sea walls, 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.

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.

2.5 Changes in ocean circulations and coastal hydrodynamics

Although a change in ocean circulation could affect navigation in the long-term, any direct effect would be small and hard to predict at present, and so is 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 place to another. These might include narrowing or widening (or even closing or opening) of channels, changed dredging requirements, erosion or accretion of beaches protecting port structures and/or changed current velocities.

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. 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 effects of hypothetical changes in morphology as a guide to whether more detailed studies may be needed. In arctic regions, port structures, sea defences and fixed navigation equipment may be destabilized as permafrost melts (ACIA, 2004).

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 reduced accessibility of ports, increased downtime and the requirement for more storage capacity at cargo 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 effects 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.

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 populations and distribution may adapt to changes in salinity and temperature, and to changes in phosphates and nitrates, possibly through changed migration patterns. This may require corresponding adaptation by fishing vessels, for example in the form of different design or equipment to suit different species, and/or operation in different locations.

2.9 Relocation of designated environmentally protected areas

Predicting species or ecosystem response in the face of climate is complex, and detailed studies may be required to assess changes to environmentally protected areas. Changed conditions may dictate relocation of environmentally protected areas, with potential opportunities for the navigation industry in some places and potential problems in others.

2.10 Changes in ice conditions

Reduced ice cover would permit longer and more reliable periods of access to waterways seasonally, or even presently permanently, blocked by ice. More fresh water in rivers in Winter could cause more ice to form in estuaries, which could alter their seasonal salinity and chemistry, 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. Increased sea level may cause ice sheets to overtop sea walls.

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

2.11 Icing

Icing increases the weight and raises the centre of gravity of ships, lowering freeboard and reducing stability, a potentially catastrophic combination, particularly for smaller vessels such as fishing trawlers. Icing also affects personnel, operation of equipment, 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 receive more sea spray during winter. The effectiveness of navigation lights could be reduced by additional sea spray icing.

3. THE RANGE OF POTENTIAL IMPACTS ON INLAND NAVIGATION

Changes in temperature, precipitation, and sea level affect 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 2, where the letter ‘x’ indicates which changes might affect which navigation-related sectors.

Drivers	Potential impacts	Rivers, channels, canals and 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 accretion and erosion)	x	x	x	
	Manoeuvrability		x		x
	Increased loads on structures		x		
	Decreased development land area available		x		
	Reduced availability of ports		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 availability of ports		x	x	
	Changes in sedimentation processes (locations of accretion and erosion)	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 accretion and erosion)	x	x	x	x
Water temperature increases	Ecosystem changes affecting habitat	x		x	
	Oxygen depletion	x		x	
	Reduced capacity of natural systems to recover	x			
River morphology	Changes in sedimentation processes (locations of accretion and erosion)	x	x	x	x
	Ecosystem changes 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	

Table 2: Climate change drivers and associated impacts on inland navigation

3.1 Water supply in the navigable river sections/waterways

Climate drivers in the form of increases and decreases in precipitation and changes in the form and quantity of seasonal precipitation would have a range of impacts on inland navigation. These include increased and decreased water level and velocity, and resultant changes in sedimentation processes such as bank failure, local scour, and locations of accretion and erosion. Changes in water levels that affect the movement of sediment, and hence channel maintenance activities, would require increased or decreased dredging, depending on the locations and specific impacts on commercial activities.

Changes in water level and velocity can also affect 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.

3.2 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 affect these ecosystems. Since oxygen deficits are often compensated by discharging water over spillweirs, the water depth in navigable rivers could be reduced.

3.3 Extreme hydrological conditions

Changes in rainfall would affect the occurrence of floods and droughts. Increased flood levels may result in the need for re-engineering infrastructure design. Droughts may reduce the depth of water available for navigation and the water available for human activities associated with ports. In addition to change in water availability caused by rainfall or run-off, flows and levels could be affected by abstraction for irrigation and domestic consumption, and by regulation for hydro-power, both of which would be influenced by climate and demand for water and electricity. Reduced water availability also affects filling of navigation locks, giving scope to design more efficient systems such as the water-reducing chambers being built for the third set of Panama Canal locks.

3.4 River morphology

Changes in sediment load would 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 would also affect ecosystem structure and functioning.

3.5 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 unpredictable ice influences on inland navigation. 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. 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 currently expected. In the waterways in northern latitudes, e.g. the Great Lakes, decreased duration of ice cover may be beneficial, resulting in extended navigation seasons.

4. EXAMPLE OPPORTUNITIES OF CLIMATE CHANGE

4.1 Access to Polar Regions and Arctic navigation routes

Reduced ice cover would permit better access to Polar Regions and longer navigation seasons on the Great Lakes and reduced need for ice-breaking services in other northern latitudes. These would have multiple benefits, including for vessel transits, 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.

The reduced ice cover indicated in Figure 7 would permit better access to Arctic Regions. If the Northwest Passage, crossing northern Canada, 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, crossing northern Russia, were open during summer, there would be the possibility of a shorter sailing route between northern Europe and the Far East. Similarly, in the southern hemisphere, navigation through the Magellan Strait, or around Cape Horn, where access is presently limited by ice, may become a practical alternative to use of the Panama Canal.

There could be associated negative effects, not only on these regions but also more widely, since increased use of the passages could accelerate the loss of Arctic ice. The overall global effect would then presumably be some redistribution of environmental impacts, resulting from the shift in some vessel traffic from existing routes to the Arctic and increased exploration activities there.

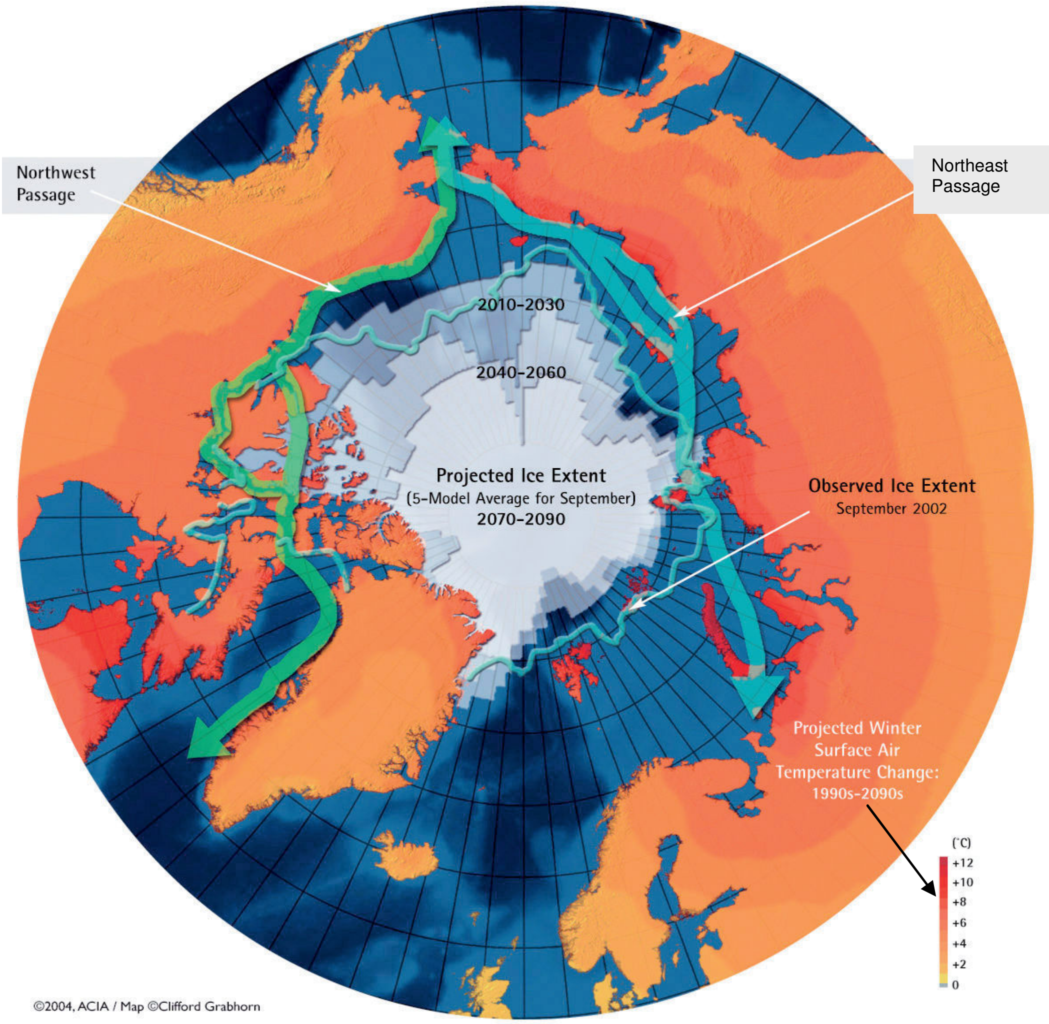

Figure 7: Observed and projected Arctic sea ice extent (from PIANC, 2008; reproduced, with minor changes to the annotation, from ACIA, 2004)

4.2 Low energy transportation

Assessing the greenhouse gas (GHG) emissions from transport activities, and especially their radiative forcing, is difficult. PIANC (2008) states that, in 2004, transport caused some 23 % of the world's energy-related GHG emissions (International Energy Agency, 2006) with navigation accounting for less than 10 % of transport GHG emissions (Kahn Ribeiro *et al*., 2007). A more recent study commissioned by the International Maritime Organisation (Buhaug *et al*., 2008) shows that transport's share of overall CO_2 emissions stood at some 27 % in 2005 and that navigation accounted for about 12 % of transport CO_2 emissions (see Figure 8).

Whereas CO_2 emissions have a positive forcing effect, meaning they contribute to global warming, other emissions from navigation, namely NO_X and SO_2, cause chemical reactions with negative radiative forcing and thus have a cooling effect. As NO_X and SO_2 are dominant emissions from maritime shipping, overall emissions from shipping may actually have a net cooling effect (Hoor *et al*., 2009).

A continuing increase in transport GHG emissions would undermine overall GHG emission targets, as shown for the European Union in Figure 9. Therefore, regulatory measures for emission reductions may be expected, forcing the transport sector to pay for its GHG emissions, in line with overall climate change mitigation strategies. This would lead to structural changes within the transport sector, benefiting modes with lower GHG emissions.

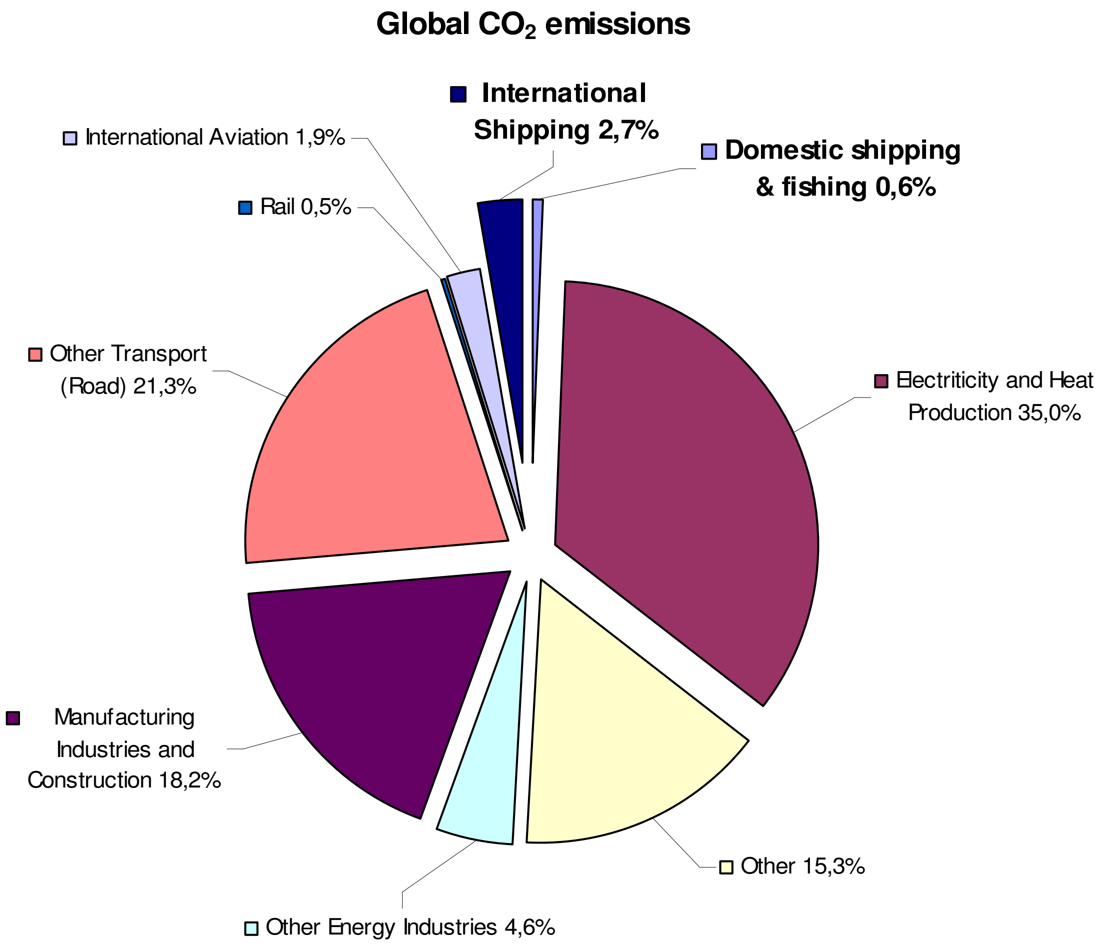

Figure 8: CO_2 emissions from shipping compared with global total emissions (reproduced from Buhaug *et al*., 2008)

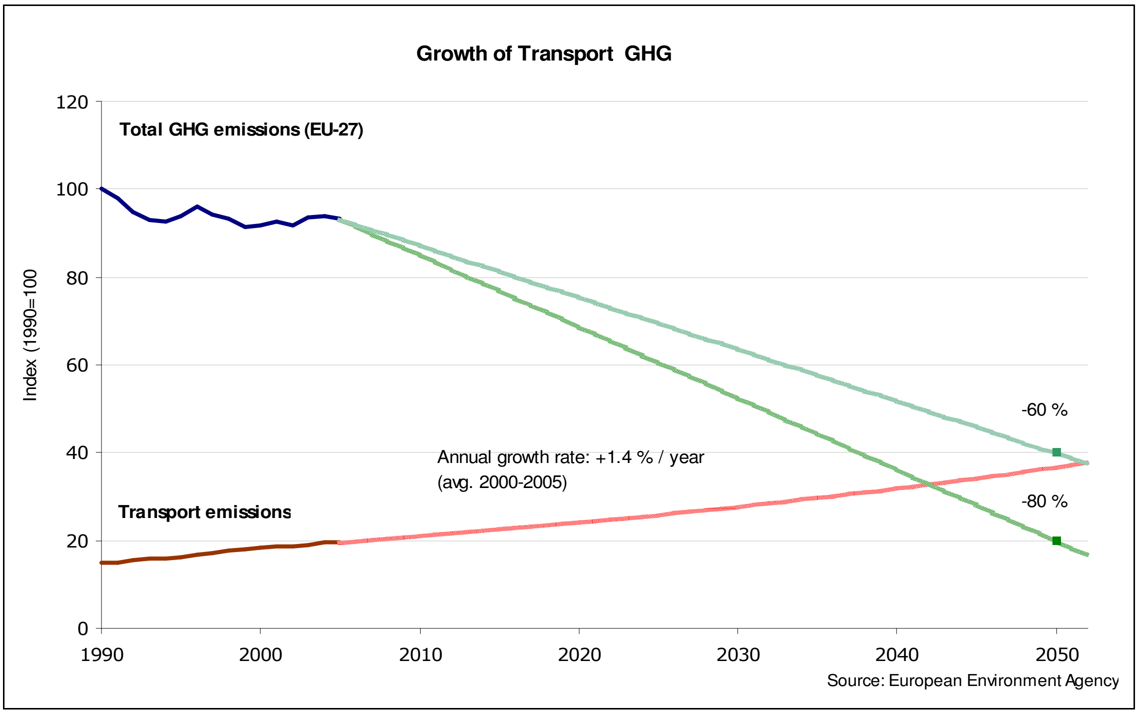

Figure 9: European Union overall emissions trajectories compared with extrapolated transport emissions

The CO_2 emission intensity or emission efficiency of transport describes the total emission from the activity in relation to the total transport network, expressed in tons of CO_2 per ton*kilometre. Figure 10 shows that the CO_2 intensities of freight transport modes differ substantially. These differences matter, where a transport task can be performed by different modes. In these cases, a modal shift may lead to a reduction in CO_2 emissions and thus contribute to climate change mitigation. A shift from rail and especially road to inland navigation seems to be an obvious choice. With coastal navigation the picture is less clear, as for some categories of vessels the specific CO_2 emissions are roughly equal to those of rail or even road. A modal shift in these cases may be warranted, where the transport route by sea would be shorter. In any case, shifting to other modes only makes sense as long as changes in transport routes and necessary additional transhipment operations do not wipe out possible emission gains.

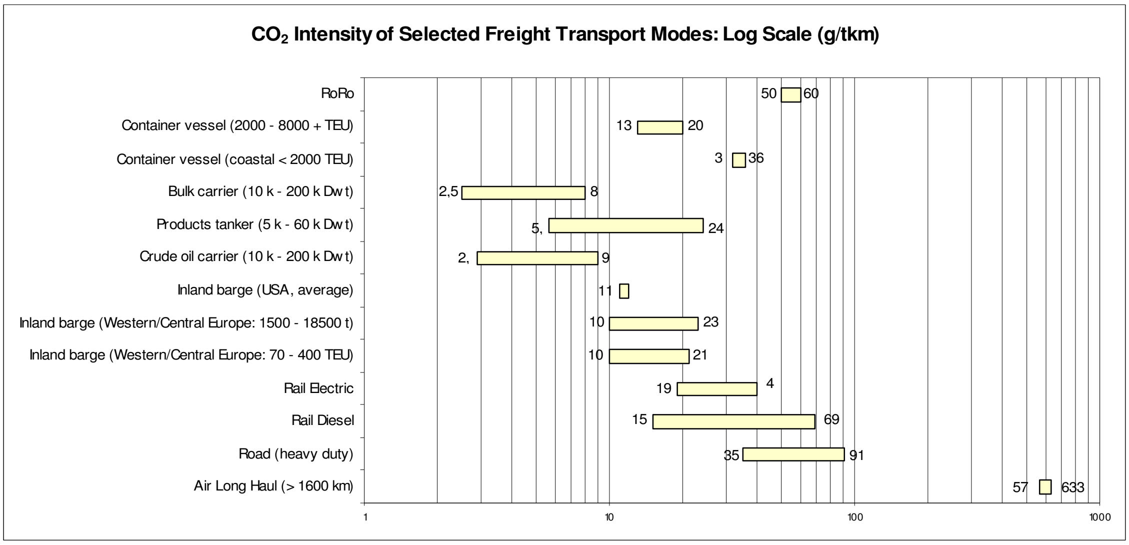

Figure 10: CO_2 intensity of selected freight transport modes (g/tkm) (Sources Buhaug *et al.*, 2008; Christ, 2009; PLANCO, 2007; Kruse *et al.*, 2009)

PIANC (2008) concludes, that "Navigation may well be one of the winners of climate change, most likely due to regulatory measures for climate change mitigation. Navigation is characterised by low energy consumption and therefore a small carbon footprint; in addition it has a good potential for reducing it even further. Its climate-friendly image makes it 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."

5. EXAMPLE VULNERABILITIES TO CLIMATE CHANGE

5.1 The Panama and Suez Canals

The Panama Canal is being expanded, to include new wider and deeper locks, so as to accommodate larger ships. Although the canal joins two oceans, its route rises to 25m above sea level. Its water supply is not from the oceans but from rainfall stored in a series of connected lakes. For context, the Panama Canal uses more fresh water than a large city. This reliance on rainfall means the canal is potentially vulnerable to climate change.

When the new larger locks come into operation, it might be expected that even more fresh water would be needed, but to mitigate this requirement the new locks have been designed to be able to re-cycle a significant proportion of the water used, so that the demand should be no more than at present.

In contrast, the Suez Canal does not suffer from this potential vulnerability, as it has no locks, and is filled directly from the two oceans which it joins. However, the Suez Canal, and to a lesser extent the Panama Canal, could suffer from a loss of revenue, for a reason previously discussed under the 'opportunities' heading. If Arctic routes were to become available on a sufficiently reliable basis, ship operators may choose an Arctic route rather than a canal route. Shipping Gazette (2008) gives the example of a ship travelling from Norway to Japan, for which the approximately 12,000 nautical mile route through the Suez Canal could be roughly halved by switching to an Arctic route.

5.2 Inland navigation in central Europe

Moser *et al* (2008) discuss the potential impacts of climate change on inland navigation in central Europe, focussing on the River Rhine in Germany, the busiest inland waterway in Europe. In addition to increased temperatures, the expectation is for higher winter discharges, as a consequence of an increase in winter rainfall, and a slight decrease in summer runoff, due to an increase of evaporation.

The most crucial aspect of climate change, causing a wide range of effects on inland navigation, is the change in water supply in the navigable river sections. This could cause increased or decreased water level and velocity and resultant changes in sedimentation processes such as bank failure, local scour, and locations of accretion and erosion. Water level changes may also affect availability of water for filling locks. Figure 11 shows navigation in the Rhine at an unusually low water level. Changes in water levels that affect the movement of sediment and hence channel maintenance activities will require increased or decreased dredging, depending on the locations and specific impacts. In addition, the 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 resilience. Higher water levels could require modifications to existing ports and mooring areas or reduce their potential for expansion.

In Germany, decreased duration of ice cover may be beneficial, resulting in extended navigation seasons, especially in the River Elbe and the Main-Donau Canal.

Figure 11: Navigation during extremely low discharge in the River Rhine on 27 July 2006 (from PIANC, 2008; photograph by Helmut Jakobs, Federal Institute of Hydrology)

5.3 Inland navigation in USA

Changes in the timing of seasonal high water and seasonal low water may affect 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 reduce ship clearance in channels and harbours and increase demand for dredging (Kling *et al*., 2003).

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 affected navigation along the Mississippi River (Figure 12).

Figure 12: 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 (from PIANC, 2008; photograph by Russell Elliott, US Army Corps of Engineers)

5.4 Inland waterways in England and Wales

Inland Waterways Advisory Council (IWAC, 2009) reviews climate change, mitigation and adaptation, for inland waterways in England and Wales.

An increase in the frequency of high flow, high water level and flooding during winter may disrupt navigation through increased downtime and risk of damage to vessels. More frequent low water level conditions during summer, particularly in natural rivers, may also disrupt navigation, through increased downtime and the possibility of water shortages affecting the supply for canals.

IWAC (2009) recommends monitoring and preparedness to respond as changes occur. It also notes the potential opportunity for inland navigation to benefit from climate change policy, as a low-emissions alternative to road and rail freight.

6. CONCLUSIONS

Inland navigation, relying primarily on fresh water flow, appears to be more vulnerable to possible future climate change than does maritime navigation. Changes in annual precipitation, or in its form or seasonal distribution, would affect river flow, river level and therefore depth, and supply of water for operation of locks. Changes in water level and velocity could also affect manoeuvrability of vessels and operational efficiency of navigation structures. Although climate trends indicate shorter periods of ice cover, a high degree of variability in local climatic conditions is still expected to cause unpredictable ice influences on inland navigation. The main aspects of future climate change affecting maritime navigation are sea level rise, which will have little direct impact, and reduced ice cover in Polar Regions, which will offer new opportunities for transport and exploration.

Navigation does not immediately need to be concerned about climate change but, as with any industrial sector, should consider it in its future planning. Recognition of the likelihood of climate change and associated impacts – both anticipated and unanticipated - provides an opportunity for the navigation community to shape polices, adaptation strategies and mitigation measures. Adaptation includes strategies to change current systems and infrastructure to account for changing climate, and preparation to respond to new opportunities. Mitigation, on the other hand, refers to activities that directly decrease the contributions to global warming, which is the major driver of climate change. 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 aspect of all future planning processes.

To end on an optimistic note, PIANC (2008) concludes that navigation may be a beneficiary of climate change, through regulatory measures for climate change mitigation and the need to move to lower energy forms of transportation.

REFERENCES

Arctic Climate Impact Assessment (ACIA, 2004). Impacts of a warming Arctic: Arctic climate impact assessment. Cambridge University Press, Cambridge, United Kingdom, http://www.acia.uaf.edu

Buhaug, Ø., Corbett, J. J., Endresen, Ø., Eyring, V. Faber, J. Hanayama, S., Lee, D. S., Lee, D., Lindstad, H., Mjelde, A., Pålsson, C., Wanquing, W., Winebrake, J.J. & Yoshida, K. (2008). Updated study on greenhouse gas emissions from ships: Phase I Report. International Maritime Organisation, London, United Kingdom, 1 September 2008.

Christ, P. (2009). Discussion Paper No. 2009-11: Greenhouse gas emissions reduction potential from international shipping. Joint Transport Research Centre of the OECD and the International Transport Forum, Paris, France, May 2009.

Hoor, P., Borken-Kleefeld, J., Caro, D. *et al.* (2009). The impact of traffic emissions on atmospheric ozone and OH: results from QUANTIFY. *Atmospheric Chemistry and Physics*, 9: 3113-3136.

Inland Waterways Advisory Council (IWAC, 2009). Climate change mitigation and adaptation: Implications for inland waterways in England and Wales. Inland Waterways Advisory Council, London, England.

Intergovernmental Panel on Climate Change (IPCC, 2000). Special report on emissions scenarios. [Nakicenovoc N. and Swart R. (Eds.)]. IPCC report produced for COP 6, The Hague.

Intergovernmental Panel on Climate Change (IPCC, 2007a). Climate change 2007: The physical science basis: Contribution of Working Group I to the Fourth Assessment Report of the IPCC. [Solomon S., Qin D., Manning M., Marquis M., Averyt K., Tignor M. M. B., Miller H. L. & Chen Z. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, 996 pp.

Intergovernmental Panel on Climate Change (IPCC, 2007b). Climate change 2007: Impacts, adaptation and vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the IPCC. [Parry M., Canziani O., Palutikof J., van der Linden P. & Hanson C. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York.

Intergovernmental Panel on Climate Change (IPCC, 2007c). Climate change 2007: Mitigation of climate change: Contribution of Working Group III to the Fourth Assessment Report of the IPCC. [Metz B., Davidson O., Bosch P., Dave R. & Meyer L. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York.

Intergovernmental Panel on Climate Change (IPCC, 2007d). Summary for policymakers. In: *Climate change 2007: The physical science basis: Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. [Solomon S., Qin D., Manning M., Marquis M., Averyt K., Tignor M. M. B., Miller H. L. & Chen Z. (Eds)]. Cambridge University Press, Cambridge, United Kingdom and New York.

International Energy Agency (2006). CO2 emissions from fuel combustion 1971-2004. International Energy Agency, Paris, 548pp.

Kahn Ribeiro S., Kobayashi S., Beuthe M., Gasca J., Greene D., Lee D. S., Muromachi Y., Newton P. J., Plotkin S., Sperling D., Wit R. & Zhou P. J. (2007). Transport and its infrastructure. In: *Climate change 2007: Mitigation: Contribution of Working group III to the Fourth Assessment Report of* *the Intergovernmental Panel on Climate Change*. [Metz B., Davidson O. R., Bosch P. R., Dave R. & Meyer L. A. (Eds.)] Cambridge University Press, Cambridge, United Kingdom and New York.

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

Kruse, C., Protopapas, A., Olson, L. E. & Bierling, D. H. (2009). A modal comparison of domestic freight transportation – Effects on the General Public: Final report. Prepared for the U.S. Maritime Administration and the National Waterways Foundation; Texas Transportation Institute, Center for Ports & Waterways, the Texas A&M University System, College Station, Texas, USA.

Moser H., Hawkes P. J., Arntsen O., Gaufres P., Mai S. & White K. (2008). Impacts of climate change on navigation. PIANC AGA 2008 & International Navigation Seminar, May 2008, Beijing, China.

PIANC (2008). Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation. Report of PIANC EnviCom Task Group 3, Climate change and navigation, PIANC, Brussels, Belgium.

PLANCO (2007). Verkehrswirtschaftlicher und ökologischer Vergleich der Verkehrsträger Straße, Bahn und Wasserstraße: Schlussbericht. Prepared for the Wasser- und Schifffahrtsverwaltung des Bundes; PLANCO Consulting GmbH, Essen, Germany, in cooperation with Bundesanstalt für Gewässerkunde, Koblenz, Germany, November 2007.

Shipping Gazette (2008). New Arctic routes in the tracks of climate change. Shipping Gazette, Issue No. 16, 29 August 2008.

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