Informal document No. 2

4 November 2011

English only

Economic Commission for Europe

Inland Transport Committee

Working Party on Transport Trends and Economics

Group of Experts on Climate Change impacts and adaptation for international transport networks

Second session
Geneva, 8 November 2011
Item 4 of the provisional agenda
Review of scientific background, existing literature and identification of the issues pertinent to climate change impacts on transport infrastructure in the ECE region

DRAFT Report

for consideration and discussion by the Expert Group on Climate Change Impacts and Adaptation for International Transport Networks at its second session (8 November 2011)

Climate Change: an overview of the scientific background and potential impacts affecting transport infrastructure and networks

Prepared by

Adonis F Velegrakis MsC PhD LLM FGS
Professor in Marine Geology
School of Environment
University of the Aegean, Greece

CONTENTS

Figure and Table Lists

1 Introduction

The present report has been prepared to assist the work of the UNECE Group of Experts on Climate Change Impacts and Adaptation for International Transport Networks, in accordance with its agreed work programme and its main objectives, as agreed at the first session of the Group of Experts, held on 5 September 2011 (ECE/TRANS/WP.5/GE.3/2011/1).

The report consists of three substantive parts. Section 2 provides a short review of the scientific background of climate change and its implications on a global scale and in the UNECE region. Section 3 presents some of the potential impacts of climate change on international transport networks, identifying particularly issues pertinent to transport infrastructure in the UNECE region and taking into account the different modes of transportation. In Section 4, based on a review of literature a brief overview of some of the particularly pertinent studies relating to different modes of transportation is provided. Finally, Annex I provides information about some additional literature of relevance to the further study of climate change impacts on international transport networks.

It should be noted that the report is not comprehensive in its scope, nor should it be seen as a full inventory of issues arising. Rather, it represents a first step to take stock of some of the available information (data and analysis) on climate change impacts on international transportation infrastructure in the ECE region and beyond, including their type, range and distribution across different regions and transport modes.

2 Climate Change: The Physical Basis

2. 1. Climate Changes: Phenomenology

2.1.1 Temperature, precipitation and sea level rise

The climate is controlled by the heat inflows and outflows and its storage dynamics in the various constituents of the Earth System, i.e. the ocean, land and atmosphere (IPCC, 2007a). Most of the stored heat is in the ocean and, thus, changes in the ocean temperature are important indicators of climate change; recent estimates show significant warming of the ocean over the recent years (e.g. Domingues, 2008), withstanding the interannual variability due to e.g. sun spot cycle activities and large climatic modulations (e.g. Richardson et al., 2009). With regard to the atmospheric surface air temperature, a long-term increasing trend is clear (Fig. 1), which is in accordance with previous IPCC projections (IPCC, 2001).

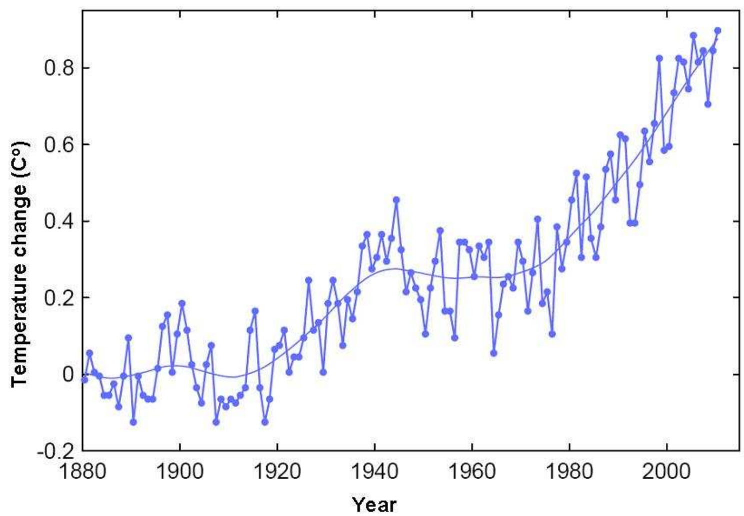

Fig. 1 *Change of mean temperature in the period 1880-2010. Data from NASA (Rahmstorf, 2011).*

Climate does not change uniformly. Temperature is rising faster close to the poles than at the equator, whereas precipitation is changing in a much more complex manner, with some regions becoming wetter and others dryer (Fig. 2). This trend is expected to pick up pace in the future; for example, mean rainfall in the Eastern Mediterranean has been predicted to decrease by up to 25% in the decade 2020-2029 compared to that of the period 1990-1999 (IPCC, 2007a).

The temperature increase is also associated with a substantial rise of the mean sea level, due to the thermal expansion of the seawater and the melting of polar ice sheets. Since 1860, sea level has increased by almost 20 cm, with the rate of increase becoming greater since 1993 (Fig. 3). It is thought that the observed steepening of the curve of the sea level rise during the recent years is mostly due to the increasing contribution of ice loss from the Greenland and Antarctica ice sheets; however, our understanding of the behaviour of these ice sheets appears to be still inadequate to describe the processes; therefore, projections to end of 21st century are uncertain on the basis of process models (Richardson et al., 2009).

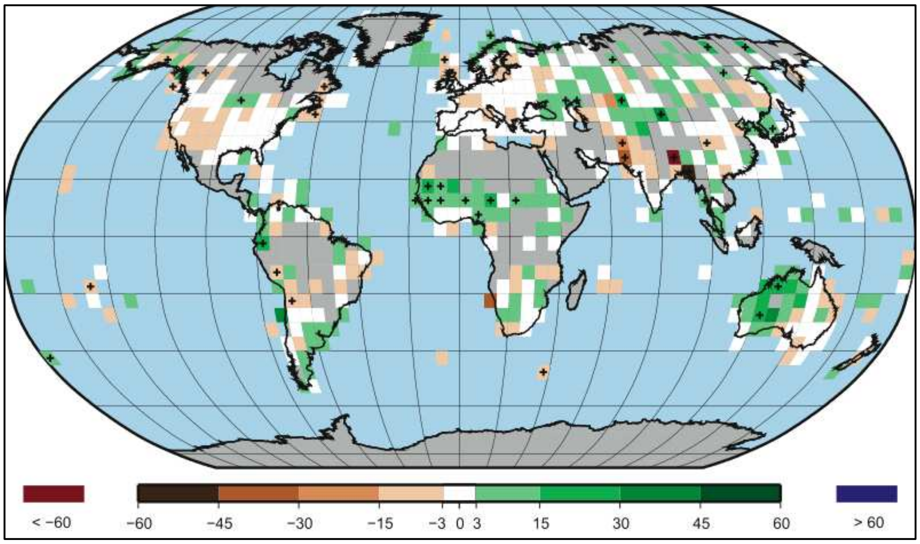

Fig. 2 Changes in annual land precipitation in 1979-2005 (% per decade) relative to the means of the period 1961-1990 (IPCC, 2007a). (Areas in grey denote unreliable trends due to insufficient data). Trends significant at the 5% level are indicated by black areas/marks.

An alternative approach would be to use the observed relationship between the global average temperature rise and the sea-level rise over the past 120 years, assuming that this relationship will hold well into the future; estimates based on this approach suggest a mean sea level rise of 1 m or more by 2100 (e.g. Rahmstorf et al., 2007), which is higher than that forecasted by the IPCC (IPCC, 2007a). Sea-level rise will not cease in 2100, as the changes in ocean heat content could affect thermal expansion for several centuries at least; melting and dynamic ice loss in Antarctica and Greenland will also continue for centuries into the future.

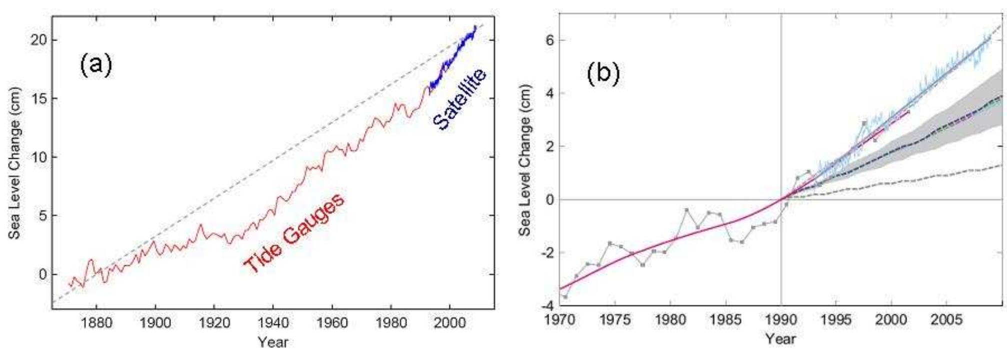

Fig. 3 *(a) Global sea level changes 1860-2010 (Rahmstorf, 2011). (b) Change in sea level in 1970-2008 relative to the 1990 level. Red solid line from tide gauge observations, smoothed to remove the interannual variability, and blue line from satellite observations. The envelope of IPCC projections is also shown (Richardson et al., 2009).*

2.1.2 Extreme events

At smaller spatio-temporal scales, the most important climatic changes are associated with extreme events (e.g. storms, floods and heat waves) (IPCC, 2007a), as well as changes in the behaviour of particular patterns of climate variability e.g. the monsoon systems (Richardson et al., 2009). Changes in frequency/intensity of the extreme events and the patterns of 'natural' variability may have even more severe socio-economic effects upon human societies (Fig. 4) than changes in the mean varaiables, as societies have become dependent on predictable, long-term climatic patterns.

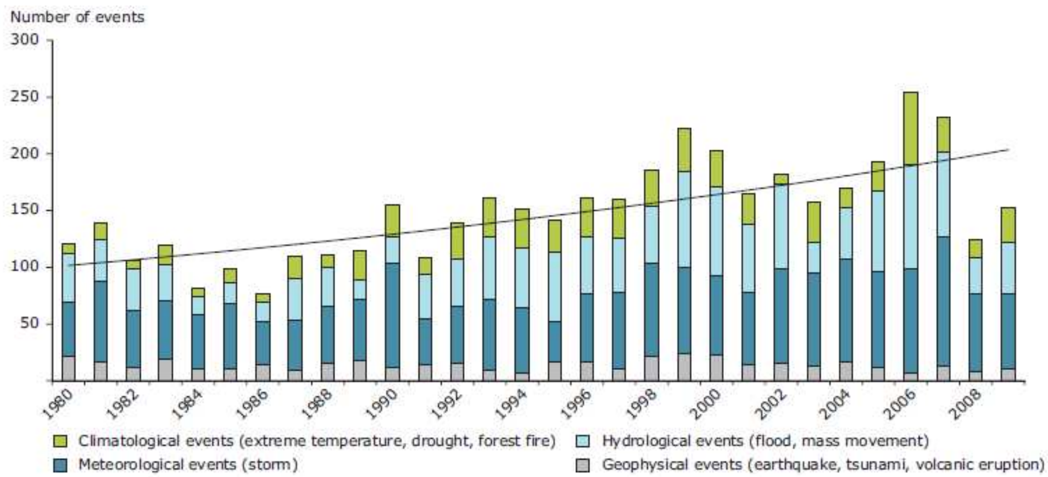

***Fig. 4**. Natural disasters in the EEA member states during the period 1980-2010. The increasing trend appears to be controlled by extreme temperature events, droughts, floods, mass movements/landslides and storms, as the number of geophysical events during this period has remained more or less stable (EEA, 2010).*

Extreme events have consequences that are difficult to predict. The variability of extreme events covers a large spectrum, e.g. sudden and transient temperature changes, rapid retreats of sea and lake ice, bouts of abnormally high precipitation, extended droughts, heat waves and wildfires, sudden water release from melting glaciers and permafrost slumping, which may have very substantial effects (e.g. Post et al., 2009).

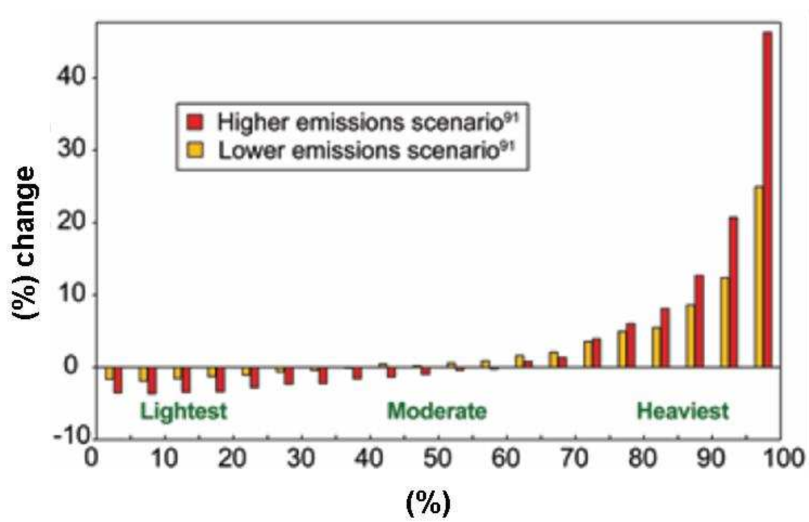

***Fig. 5** Projected changes from the 1990s average to the 2090s average in N. America precipitation, for light, moderate and heavy events (projections according to IPCC, 2007a). It appears that the lightest precipitation is projected to decrease, whereas the heaviest to increase. Note that higher emission scenario yields larger changes (Karl et al., 2009).*

There is evidence that extreme events may respond to a warming climate by becoming even more extreme (Webster et al., 2005; Emanuel, 2005; Allan and Soden, 2008; Ruggiero et al., 2010); for example, even a modest increase (5 m/s) in the surface wind speed of the tropical cyclones-resulting from a 1 ^{0}C rise in the ocean temperature- may result in a substantial increase of the incidence of the most intense/destructive (Category 5) cyclones (e.g. Steffen, 2009). The implications of these extreme events for the coastal communities/infrastructure could be severe, as they increase the likelihood of extreme sea levels-storm surges and consequent coastal floods, especially if combined with the predicted increases in the mean sea level (McKee Smith et al, 2010).

Storm surges pose a particular threat to highly developed deltaic environments (e.g. the Rhine, Danube and the Mississippi river deltas), which are considered as hotspots of vulnerability (IPCC, 2007a) due also to their commonly high relative mean sea level rises; a study involving 40 major deltas, representing all major climatic zones has found relative mean sea level rises ranging between 0.5 to 12.5 mm/yr, with the diminishing fluvial sediment supply being an important determinant (Erickson et al., 2006).

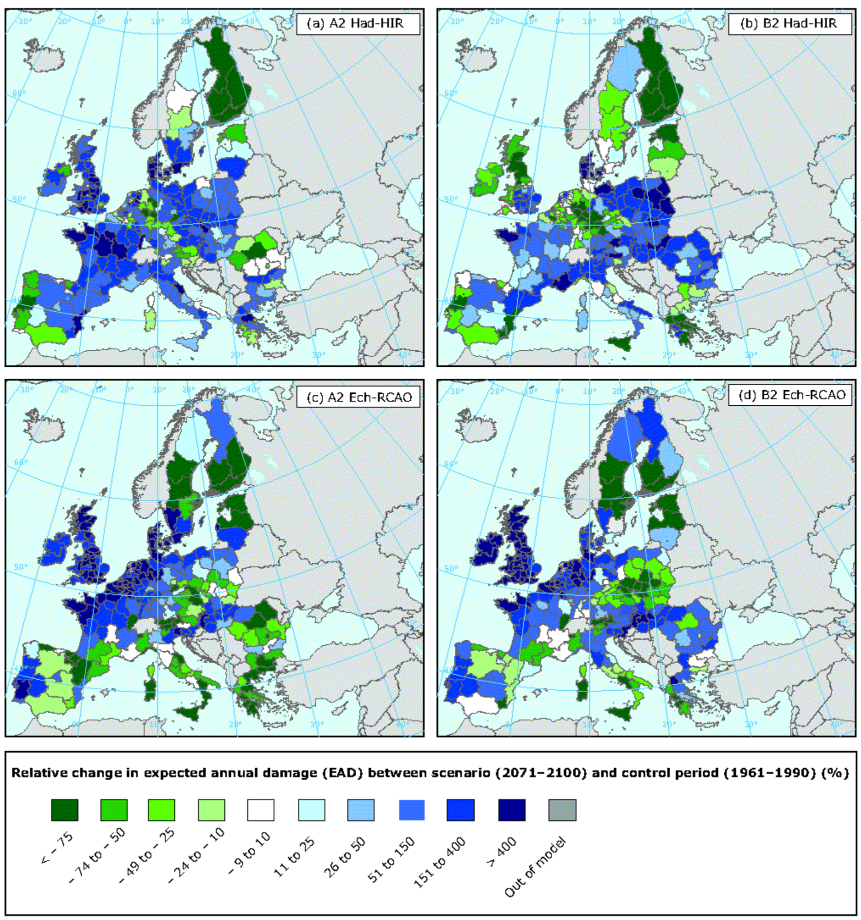

Fig. 6. *Relative change in Expected Annual Damage (EAD) from riverine floods, between scenario (2071–2100) and control period (1961–1990) in Europe (EC JRC, 2010),* http://ies.jrc.ec.europa.eu/).

In recent decades, most of N. America appears to experience more unusually hot days and nights, fewer unusually cold days and nights and fewer frost days. Droughts are also becoming more severe in some regions, whereas the intensity/frequency of Atlantic hurricanes have also substantially changed. One of the clearest trends appears to be the increasing frequency/intensity of heavy downpours; this increase has been responsible for most of the observed increases in overall precipitation during the last 50 years. Climate models project the continuation of this trend during this century (Fig. 5), i.e. increases in the heaviest downpours and decreases in the lightest precipitation (Karl et al., 2009).

Riverine floods are phenomena of extreme riverine discharge that involve both physical and socio-economic factors. The former are strongly connected to the hydrological cycle, which is currently influenced by changes in temperature, precipitation, glacier and snow cover melts (IPCC, 2007a). The latter are controlled by land use changes, river management schemes, and construction in flood plains that reduce their capacity to absorb flood waters. Human development has changed considerably the natural flows of water, making it difficult to detect climate change-induced trends in hydrological variables (EEA, 2010).

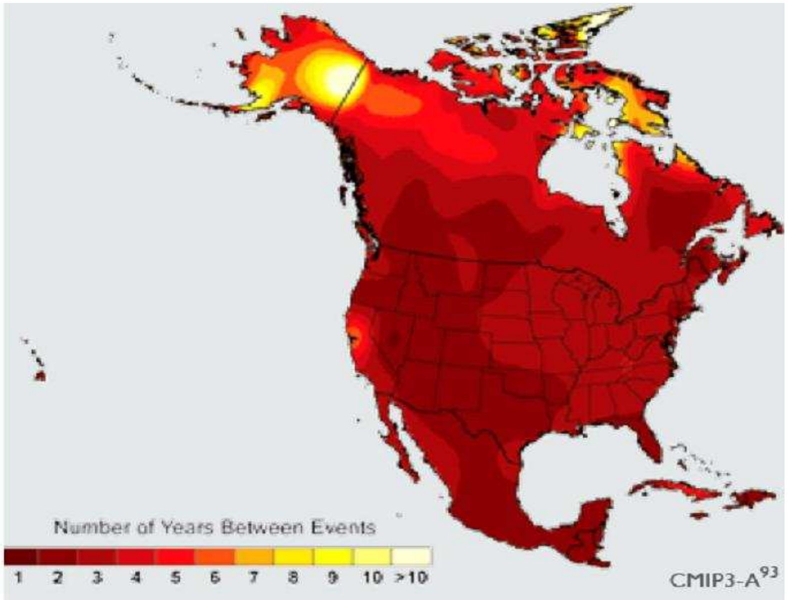

Fig. 7 *Projected frequency of extreme heat waves (2080-2099 average). Simulations for 2080-2099 showing rare extremes (1-in-20-year event) are projected to become more frequent in N. America. An extreme in terms of heat days (20 years return-period) might occur every other year or more frequently by the end of the century (2080-2099) under the higher emissions scenario (Karl et al., 2009)*

In addition, changes in extreme hydrological events (and their results) are better studied at a regional/local scale, with most existing studies focussing on the impacts of floods due e.g. to increases in torrential precipitation. In Europe, annual river flows have generally been observed to increase in the north and decrease in the south, a trend that is predicted to hold in the future (Fig. 6), as is associated with projected changes in precipitation regimes that control the intensity/frequency of rain-fed floods and (possibly) of flash floods *(*Feyen et al., 2006, 2010*)*. Slope failures/landslides (e.g. Kawagoe and Kazama, 2009) are also expected to increase in future at many places, as they are linked to strong rainfalls, the frequency/intensity of which is projected by climate models to increase in the future

There is also some evidence that anthropogenic warming may have also increased the frequency of heat waves, i.e. extended periods (several days to weeks) of abnormally hot weather, often associated with high humidity. For example, the 2003 heat wave (Stott et al., 2004) produced record-breaking temperatures, with absolute maximum temperatures exceeding the record temperatures observed in the 1940s-early 1950s in many European locations and average summer temperatures being up to 5 standard deviations above the long-term summer temperature mean. The 2003 heat wave has been shown to resemble simulations by regional climate models of summer temperatures in the latter part of the 21st century under the A2 IPCC scenario (Beniston and Diaz, 2004).

In N. America, there has also been an increasing trend in high-humidity heat waves over the recent decades, which are characterized by the persistence of extremely high night temperatures (Kunkel et al., 2008). With mean temperatures continuing to rise, the frequency of cold extremes is projected to decrease, whereas the frequency/intensity of high temperature extremes to increase (Fig. 7).

2.2 Mechanism

One of the major causes of the observed increase of the heat content of the planet's surface is considered to be the increasing concentrations of greenhouse gases (GHGs) in the atmosphere (Fig. 8). These gases enhance the "greenhouse effect", which is a well documented and understood physical process of the Earth System, known since the 19th century (e.g. Canadell et al., 2007). GHGs in the atmosphere, such as water vapour, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) absorb heat reflected back from the Earth's surface and, thus, store more heat in the ocean, land and atmosphere. Without the greenhouse effect, average temperatures on Earth would be about -19°C (i.e. ~ 34°C colder than it is at present). All planets with heat absorbing gases in their atmosphere, experience a greenhouse effect; for example, the extreme surface temperature (~440°C) of Venus can only be explained by the high concentration of GHGs in its atmosphere.

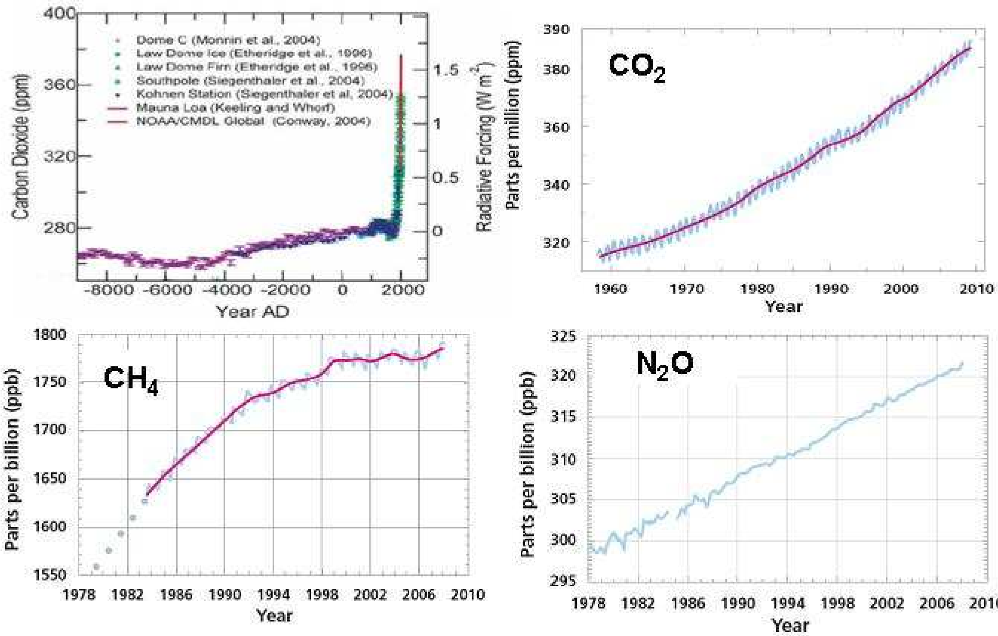

Fig. 8. *CO_2 concentration (in parts per million-ppm) in the atmosphere during the last 11000 years (Rahmstorf, 2011) and the last 50 years. The concentrations of the CH4 and N2O (in ppb-parts ber billion) during since 1978 are also shown (Richardson et al., 2009).*

Changes in the atmospheric GHG concentration affect the magnitude of the greenhouse effect. Water vapour is an abundant GHG and makes the greatest contribution to the 'natural' greenhouse effect. Human activities have not yet shown to have had a significant direct effect on net global flows of water vapour to/from the atmosphere (e.g. Richardson et al., 2009), although locally they may have influenced such flows through e.g. deforestation and irrigation schemes. Nevertheless, as the ability of the atmosphere to retain water vapour is strongly dependent on temperature, atmospheric water vapour is regulated by the Earth's temperature itself, increasing with the global warming; thus, water vapour not only follows, but it also exacerbates changes in global temperature that are induced by other causes, such as the increasing concentrations of the other greenhouse gases (e.g. Richardson et al., 2009). Atmospheric CO_2, CH_4 and N_2O concentrations have increased dramatically over recent decades as a direct effect of human activities (Fig. 8), with Ice core and sediment records showing that the atmospheric concentration of all of these GHGs is now higher than it has been since several million years (Caldeira, 2009).

2.3 Feedbacks and tipping points

The global warming from increased GHG concentrations can be amplified by reinforcing feedbacks, i.e. climate change-driven processes that can induce further warming. In addition to the water vapour feedback described above, an important feedback is associated with the various "carbon sinks", i.e. with processes that can remove CO_2 from the atmosphere. Over half of the CO_2 emitted to the atmosphere through human activities is removed through land and ocean sinks. Without these sinks that remove/store CO_2 from the atmosphere, the total human emissions since 1800 would have caused the concentration of atmospheric CO_2 to increase from its pre-industrial value of 280 ppm to nearly 500 ppm, which is much more than the present value of about 385 ppm (Richardson et al., 2009).

However, the fraction of human CO_2 emissions removed by these sinks appears to have decreased over the last 50 years due to several effects (e.g. ocean acidification, ocean circulation changes and water, temperature and nutrient constraints on land CO_2 uptake), with some evidence suggesting that will be further decreases over the coming decades (e.g. Canadell et al., 2007). If this weakening of the CO_2 sinks continues, a greater fraction of emissions will remain in the atmosphere, requiring a greater reduction in emissions to achieve specific targets for the CO_2 atmospheric concentration. In addition, previously inert carbon reservoirs can be mobilised and release CO_2 and/or CH_4 (a much more potent GHG) to the atmosphere; reservoirs of concern include the tropical peatlands that are vulnerable to land clearing/drainage and the vast stores of organic carbon in Arctic permafrost (e.g. Dobinkski, 2011) that are vulnerable to global warming (e.g. Zimov et al., 2006).

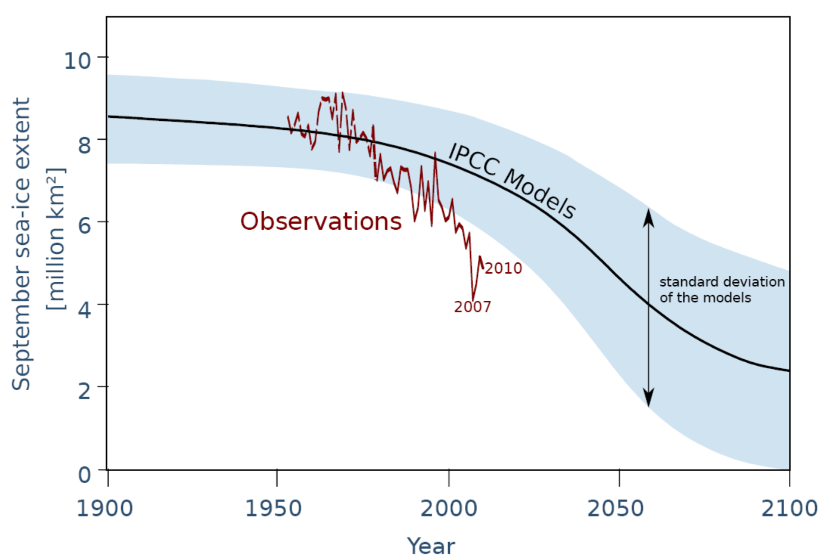

***Fig. 9** Loss of Arctic Ice (Rahmstorf, 2011)*

Table 1. Tipping elements, concerns, triggers and implications for the next 50 years (see also Lawrence and Slater, 2005;, Zimov et al., 2006; Vecchi et al., 2006; Challinor et al., 2006; Scholze et al., 2006; Rahmstorf, 2007; Barnett et al., 2008; Kurz et al., 2008; Lenton et al., 2008, 2009; and Shanahan et al., 2009).

Tipping element(s)	Key concerns	Thresholds -impacts (next 50 years)-
Melting of Arctic sea-ice	Amplified regional/global warming, ice albedo feedbacks; opening of new (shorter) shipping routes	0.5–2℃ above 1980–1999 mean -Yes-
Melting of Greenland, West Antarctica and other ice caps	Global sea level rise of about 0.5 m by 2050 is possible	1–5℃ above 1980–1999 mean -Yes-
Melting of cont. glaciers (e.g. Himalaya and Alpine glaciers)	Initial increased flooding/inundation, followed by river flow reduction (up to 30% over the next 50 years for India) with impacts on (amongst others) inland waterway navigation	1–3 ℃ above the 1980–1999 mean -Yes-
Permafrost and its carbon stores	Amplified global warming; 'runaway' feedback effects maybe exaggerated	9 ℃ for E. Siberia above the 1980–1999 mean -No-
Boreal forest	Forest fires, destruction of relevant transport networks, problems with flights and spread of deceases	3–5 ℃ above the 1980–1999 mean -Some-
Atlantic thermohaline circulation (THC)	Weakening leading to regional dynamic sea level changes (especially in the N. Atlantic) and effects on hydrological elements	3–5 ℃ above the 1980–1999 mean -Yes-
El Nino southern oscillation -ENSO	Impacts on other climate variables/tipping elements–stronger El Niño events will affect many regions	3–6 ℃ above the 1980–1999 mean -Yes-
West African Monsoon (WAM)	Potential greening of the Sahel and parts of the Sahara. In the best-case scenario, the tipping of the WAM might provide a net benefit (IPCC, 2007a)	3–5 ℃ above the 1980–1999 mean -Some, but possible net benefit-
Indian Summer Monsoon (ISM)	Interference with monsoon cycle/ drought frequency, possible monsoon weakening; greenhouse warming could then trigger stronger monsoons with high interannual variability	Related mostly to aerosol forcing -Yes-
Amazon rainforest	Droughts, wildfires, effects on hydroelectric generation, agricultural production and related service industries and river navigation, effects on one of the major carbon sinks	More frequent droughts at ~1 ℃, die-backs at 2 ℃ above the 1980–1999 mean -Yes-
SW N.America (SWNA)	Droughts, more wildfires, impacts on water resources	Underway -Yes-

A significant development is the rapid reduction in the area of Arctic sea ice, particularly during summer (e.g. Richardson et al., 2009). The ice extent has fallen at a rate of 3 to 4 % per decade, with the September ice fallen at an even faster rate (more than 11 % per decade) in that time over the last 3 decades. It appears that the loss of the Arctic ice in recent years is much greater than that predicted by the IPCC models (Fig. 9). Sea ice is a very important part of the climate system. The decreasing Arctic ice coverage is climatically important on a larger scale, as ice and snow reflect most of the impinging radiation from the sun back into the atmosphere, in contrast to the sea water (e.g. ACIA, 2005). Therefore, an ice-free ocean, which absorbs more heat than an ice-covered ocean, creates a climatic “feedback” that increases warming. In addition to direct impacts on coastal arctic areas, such as increasing coastal erosion (e.g. Lantuit and Pollard, 2008), ice reduction affects surface reflectivity, ocean currents, cloudiness, humidity and the heat exchange at the sea surface (IPCC, 2007a).
An important consideration is associated with the levels of climate change at which ‘tipping points’ might be crossed i.e. changes that are no longer linear and reversible, but abrupt and large (and potentially irreversible in human temporal scales), with large impacts to communities/infrastructure (Lenton et al., 2008).

At present, the focus of climate change mitigation policy (UNFCCC) has been mostly on "*preventing dangerous anthropogenic interference with Earth's climate system*". Although there has been no scientific consensus for delineating *dangerous* from *acceptable* climate change, limiting global average temperature rise to 2℃ above pre-industrial levels may be considered as a starting point-focus for policymakers (see also the 2007 Bali Conference and the July 2009 G8 summit) (Lenton et al., 2009). However, if these goals are not achieved, then there could be significant tipping elements-impacts, the most important of which are summarised in Table 1.

3. Climate Change Implications for Transport

The implications of climate change could be very significant to a broad range of human activities/infrastructure. In this section, some of the implications of climate change on a global scale and the UNECE region (e.g. Fig. 10) will be presented, with an emphasis on potential climate change impacts on international transport networks.

Most of the climate change impacts outlined below are relevant to the UNECE region, as the area covers several climatic regions. Sea level rise and storm surges are likely to increase the risks of major coastal impacts, including transient and permanent flooding of airports, roads, rail lines and tunnels. Flooding from intensifying extreme rainfalls will increase the risks of disruptions/delays in air, rail and road transportation and cause damages by landslides (e.g. Kawagoe and Kazama,2009). Heat waves will limit operations and cause pavement/track damages, whereas, increased intensity of hurricanes would lead in more evacuations, infrastructure damage and failure and transportation interruptions. Arctic warming will continue to reduce sea ice, lengthening the northern passage shipping season, but also resulting in greater erosion due to increased wave activity at the northern shorelines. Permafrost thaws in Alaska will also damage infrastructure and ice road seasons in Alaska will become shorter.

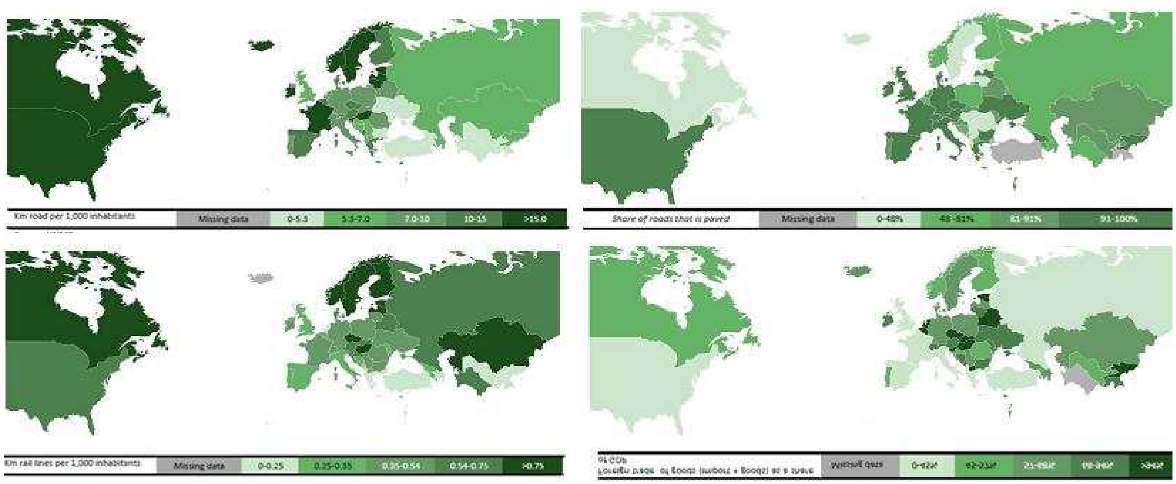

Fig. 10. *Density of road and rail networks, percentage of paved roads to the total and foreign trade of goods (import and goods) as a GDP share in the UNECE region (UNECE, 2011)*

3.1 Impacts in polar areas

The decline in sea ice extent in polar areas may have both negative and positive consequences for transport (see also Table 2). Although longer shipping seasons in the Arctic Routes are projected (including the opening of the northern passages during summer), which may shorten considerably certain shipping routes with substantial economies in e.g. fuel costs, there could be higher costs for new support services, changes in demand/supply of transport services and considerable costs to link Arctic ports to the major national/international networks (e.g. Bennet, 2011). At the same time, lower water levels at the Great Lakes and St. Lawrence Seaway in N. America due to increased evaporation in a warming climate are likely to increase costs, as ships will not be able to carry as much cargo as before; a recent study has shown that, by 2050, there will be a 13-29 % increase in shipping costs for the Canadian commercial navigation due to these lower water levels (National Research Council, 2008). At the same time, degradation of coastal roads and railways is projected due to increased coastal erosion precipitated by (a) wave action at the ice free coasts and (b) (limited?) coastal permafrost thaw (e.g. Lantuit and Pollard, 2008). In addition, there will likely be increased construction/maintenance costs to restore related damages to infrastructure, equipment and cargo. Also, higher energy consumption in ports and other terminals, as well as challenges to service reliability are expected (e.g. Crist, 2011).

The thinning and decrease in the extent of the Arctic sea ice are considered as an opportunity for the transport industry (e.g. Bennet, 2011). In addition to the longer shipping seasons (and the potential opening of the North-West (NW) Passage), it may result in the opening of new ice-free ports, improved access to ports and natural resources in remote areas. Nevertheless, the next few decades might prove to be quite unpredictable for shipping services through these new routes as a result of a number of factors, including the following: (a) there has been a high interannual variability of the sea ice extent in the Canadian Arctic despite the overall decrease in the September sea ice extent; and (b) the loss of sea ice from the shipping channels of the Canadian Archipelago might allow more frequent intrusions of icebergs, which would continue to impede shipping through the Northwest Arctic Passage (ACIA, 2005).

3.2 Impacts on coastal areas

Climate change induces several impacts that are pertinent to transport in coastal areas, including mean sea level rise, warmer water temperatures, higher intensity of cyclones/storm surges and possibly changes in the wave regime; such changes can severely affect ports and other coastal transport hubs and networks. Superimposed upon the intrinsic sea level trends of coastal systems (due to e.g. tectonic movements, see Vott, 2007), are impacts from sea level rise, storm surges and waves and precipitation/run-off extremes of potentially increasing frequency/intensity (e.g. Wang et al., 2008; Allan.and Soden, 2008; Ruggiero et al., 2010). In addition, the increase in coastal development over recent decades tests the ability of coastal systems to respond effectively to climatic changes (Nicholls et al., 2007; Lenton et al., 2009).

However, although predictions of exposure to adverse climatic changes are required at decadal scales (e.g. Viles and Goudie, 2003), most of the available information/models are based on either long-term (century-to millennium) (e.g. Nott et al, 2009) or annual (e.g. Greenwood and Orford, 2008) and even storm event (e.g. Callaghan et al., 2008) scales. There have already been several attempts to develop global coastal hazards data bases (e.g. Vafeidis et al., 2008), as well as methodologies/tools to assess coastal vulnerability to sea level rise and extreme events (e.g. Hinkel and Klein, 2009), but the work is still ongoing (Nicholls et al., 2007).

Although coastal inundation due to long-term sea level rise will certainly be a significant problem for coastal populations, activities and infrastructure/assets in low elevation coastal zones (McGranahan et al., 2007), the most severe implications will be related to extreme sea levels from tropical/extra-tropical storms (e.g. Ebersole et al., 2010), particularly in the case of deltas, small islands and large coastal urban centres (e.g. Dasgupta et al., 2009). The extent/distribution of exposure in each particular area/urban centre will be influenced by both its natural characteristics (e.g. the occurrence of coastal wetlands that may attenuate surges, see Wamsley et al., 2010) and human-induced changes such as water management and land reclamation schemes (Le et al., 2007; Guo et al., 2009). It must also be noted that, as ports and other transport infrastructure links are not associated exclusively with open coasts, but also with estuaries, climate change impacts on these environments are particularly pertinent. In estuaries, sea-level rise generally translates into landward transgression (Pethic, 2001), leading to different (higher) relative water levels and dynamics (e.g. Shennan et al., 2003). Sea level rise can increase the flooding hazard of estuarine ports, particularly in the case of high river flows and storm surges (e.g. Karim and Mimura, 2008). With regard to human-induced changes, it has been shown that their effects on estuarine morphology and dynamics can, in some cases, exceed those of the sea level rise itself (e.g. Chust et al., 2009; Reeve and Karunarathna, 2009).

With regard to the economic impacts of climate change on coastal areas, a recent study by Nicholls et al. (2008) has assessed the population/asset exposure of 136 port cities with more than one million inhabitants (in 2005). They estimated that, by the 2070s, more than 120 million people will be exposed to extreme events in these port cities, if effective coastal protection schemes will not be in place. Lenton et al. (2009), who included tipping point scenarios (see Section 2.3), estimated that, by 2050, the asset exposure in the same 136 port megacities will be close to 28,000 billion US dollars.

Transportation will be affected by extremes in temperature and precipitation, storm surges and rising sea levels. Coastal inundation may damage terminals, intermodal facilities, freight villages and storage areas and cargo and disrupt intermodal supply chains and transport connectivity (e.g. Fig.11). Ports that form key-nodes in international transport networks and link international supply-chains will be particularly impacted, due mostly to (a) the long life-time of their key assets that are sensitive to climatic changes, (b) their exposed location and (c) their dependence on trade, shipping and inland transport which are also climatically-vulnerable (including also indirectly, through changes in demand for transportation) (see also UNCTAD 2011).

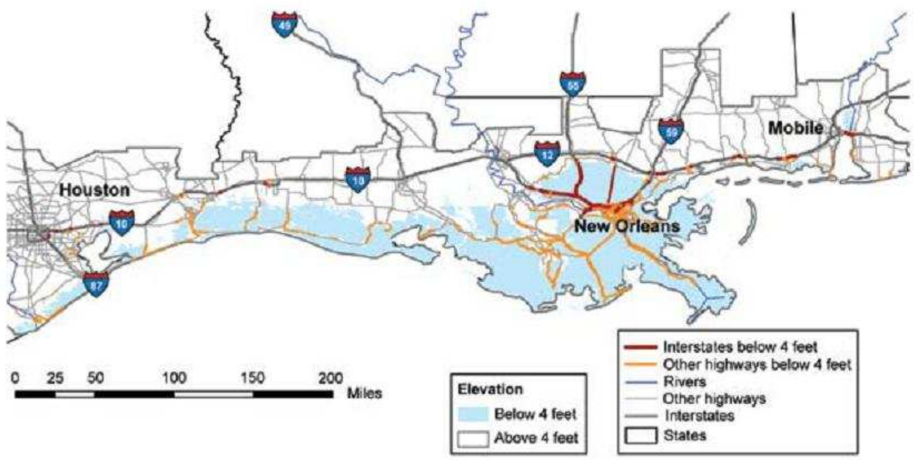

***Fig. 11**. Roads at risk in the event of a sea level rise of about 1.2 m (4 feet) within the range of projections for this Gulf Coast in this century under medium- and high-emissions scenarios. 2,400 miles of major roads are predicted to be inundated. (Karl et al., 2009)*

One of the most detailed studies on the potential impacts of climate change on transportation systems was carried out in the US Gulf Coast (see also Section 4). According to the study, relative sea level rise of ~1.2 m (4 feet) could permanently inundate more than 2400 miles of roads, over 70% of the existing port facilities, 9% of the railway lines and 3 airports; in the case of a ~5.5 m storm surge (less than that of Katrina), more than 50% of interstate and arterial roads, 98% of port facilities, 33% of railways and 22 airports in the US Gulf coast would be affected (CCSP, 2008).

3.3 Riverine floods

Climate-induced changes together with development practices have increased the risk[1] of riverine floods/flash floods (Fig. 12, see also Section 2.1.2) For example, in the period 1998-2002, there have been more than 100 major floods in Europe (including the 2002 catastrophic floods along the Danube and Elbe rivers) that caused several hundred fatalities, the displacement of about 500,000 people and over € 25 billion in insured economic losses (EEA, 2004); more than 10 million people and assets valued at € 165 billion live in areas prone to extreme floods along the Rhine River alone (EEA, 2010). Additional catastrophic floods in the following years prompted the European Union to adopt the Flood Risk Directive (2007/60/EC) (EC, 2007). Figure 6 shows projections of potential flood damage due to climate change, assuming that no adaptation or disaster risk reduction measures are adopted (Feyen et al., 2010; EEA, 2010). Results from the PESETA study (Ciscar et al., 2009) suggest that flood damages are likely to rise across much of Western and Central Europe. At the same time, riverine flows/floods are expected to decrease in the NE Europe (see Fig. 6); Alcamo et al. (2007) assessed the situation in Russia on the basis of interannual climatic variability and suggested that although Russia will experience an overall increase in riverine flows, the SW Russia will be associated with more frequent low runoff events.

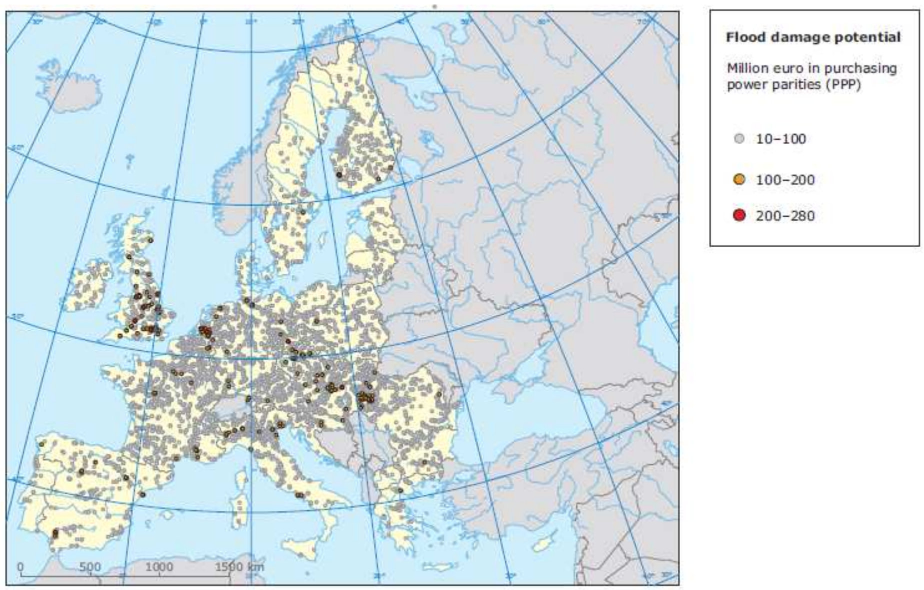

Fig. 12. *Flood damage potential in Europe (EEA, 2010). The estimations have been based on the assumption of a 100-year return period event (i.e. the record flood in 100 years), present climate and no defences. Catchments of less than 500 km^2 are not included.*

With regard to the USA, a recent study (Milly et al, 2008) indicates that, by 2050, runoffs will increase at the NE and decrease at the SW USA (Fig. 13). At the same time, heavy downpours have already increased substantially, with the heaviest 1 % of precipitation events having increased by 20 %, whereas total precipitation increased by only 7 % over the past century (Kunkel et al., 2008). Such intensive precipitation, which is projected to increase in the future (see also Fig. 5), is likely to increase the frequency/intensity of events, that can cause catastrophic flooding along the major river flood plains, affecting all modes of transport. For example, the 2008 Midwest flood resulted in breaching/overtopping of levees

[1] Flood risk is product of flood probability/hazard, exposure of assets/infrastructure and population and vulnerability to flooding based upon land-use information and an assessment of flood inundation

along several States and in flooding huge areas, rendering numerous highway and rail bridges unusable together with long stretches of highways, rail lines and normally navigable waterways (Karl et al., 2009).

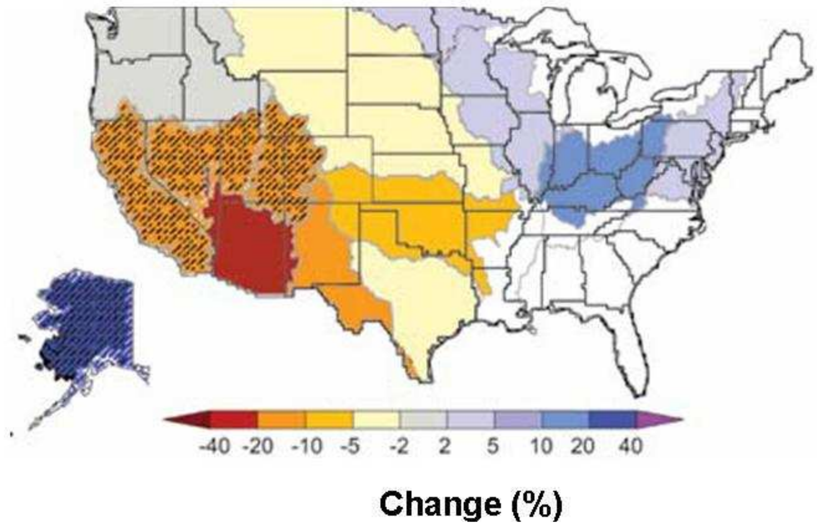

***Fig. 13**. Projected changes in median runoff for 2041-2060 (relative to 1901-1970). Hatched areas show good agreement and white areas poor agreement between model projections. Results are based on emissions in between the lower and higher emissions scenarios. (Milly et al., 2008)*

Increases in heavy precipitation events/floods will cause more weather-related accidents, delays, and traffic disruptions in the already congested networks (Potter et al., 2008). Areas, where flooding is already common, will face more frequent and severe problems. Standing flood waters could impact severely on the roadway system; for example, damages due to long-term road submersion in Louisiana have been estimated as $ 50 million for 200 miles of the state highways. Port facilities will be also vulnerable to short-term rain-induced flooding, whereas extreme precipitation-induced silting could reduce navigation channel depths, increasing considerably the dredging costs (e.g. Karl et al., 2009). Finally, increased delays/cancellations of flight operations due to airport flooding are likely, together with effects on the structural integrity of runways and other airport infrastructure (National Research Council, 2008).

3.4 Heat waves and Droughts

Heat waves, i.e. extended periods (days to weeks scale) of abnormally hot weather may have substantial impacts to transport services and networks. For example, the European 2003 heat wave (which was accompanied by precipitation deficits (of up to 300 mm) in many regions of the western and central Europe (Trenberth et al., 2007) led to a considerable reduction in soil moisture through intensive surface evaporation/evapotranspiration and created strong positive feedbacks (Beniston and Diaz, 2004). The hot and dry conditions led to many large wildfires and crop failures; the (uninsured) economic losses for the agricultural sector alone in the EU have been estimated as €13 billion resulting also in very substantial losses for the transport services. On the other hand, the associated extreme Alpine glacier melt prevented catastrophically low flows in the Danube and Rhine rivers (Fink *et al*., 2004). The 2003 heatwave *cum* drought in Europe affected settlements and economic services in a variety of ways, creating different stresses on water supplies, food storage and energy systems. Many major rivers (e.g. the Po, Rhine and Loire rivers) were at record low levels, resulting in disruption of inland navigation, irrigation and power-plant cooling (Beniston and

Díaz, 2004), whereas the punctuality of the French railways fell to 77% from 87% the previous year. Due to this disaster, France implemented a heat prevention plan, which appeared to work satisfactorily in the following (2006) heat wave (e.g. Pascal, 2008).

Long periods of extreme summer heat (sustained air temperatures over 90 °F (32 °C)) can damage roads through asphalt softening that could lead to rutting from heavy traffic (Field et al., 2007). Extreme heat waves can also deform rail tracks, causing speed restrictions/derailments, whereas temperatures above 100 °F (38 °C) can lead to equipment failure, such as thermal expansion of bridge joints. Vehicle overheating and tire deterioration are additional concerns (National Research Council, 2008). High temperatures are also likely to increase refrigeration requirements (and related costs) for goods in transit, particularly in the warmer areas of the UNECE region (e.g. Kafalenos et al., 2008). Increases in number of very hot days (see e.g. Fig. 7) are expected to limit construction activities due to health and safety concerns (e.g. Karl et al., 2009). Wildfires are also projected to increase, especially in the SW USA and S Europe, threatening transport infrastructure and resulting in road and rail closures. On the other hand, warmer winters could result in reductions in snow and ice removal costs, extend the construction season and improve the mobility/safety of passenger and freight. The projected decrease in the number of very cold days could reduce ice accumulation on vessels, decks, riggings, and docks, ice fog and ice jams in ports; conversely, the greater number of freeze-thaw days projected for the northern regions could result in road and bridge damages (e.g. National Research Council, 2008).

Rising temperatures could also affect airport facilities and runways in particular, although airports in the northern regions could benefit from reductions in the cost of snow and ice removal. More temperature extremes may create operational difficulties, such as greater energy consumption by planes on the ground. They could also affect aircraft lift, as hotter air is less dense and reduces the lift produced by the wing and the engine thrust. Thus, planes would require faster take offs, and in the case of short runways, payload restrictions, flight cancellations and service disruptions could be implemented. A recent study indicates a 17 % reduction in freight carrying capacity for 747s at the Denver airport by 2030 and a 9 % reduction at the Phoenix airport due to increased temperature and water vapour (Karl et al., 2009).

Rising air temperatures increase evaporation, contributing to drier conditions, particularly in regions associated with decreasing (in terms of magnitude and/or frequency). Therefore, droughts are expected to be an increasing problem in several UNECE regions, such as the SW USA and the SE Europe (IPCC, 2007a); this, in turn, may have impacts on transportation. For example, the increased wildfire potential due to droughts could directly threaten roads and other transportation infrastructure and cause road closures. There is also an increased likelihood of mudslides in areas that have been deforested by wildfires. Airports could also suffer due to wildfire-induced low visibility. Finally, inland waterways could be seriously affected by low water levels, resulting in fewer routes, shorter shipping seasons and reduced cargo carrying capacities; in this case, freight movements could be seriously impaired, and extensive (and expensive) dredging could be required to maintain shipping channels (e.g. Karl et al., 2009).

3.5 Permafrost

Climate warming leads to permafrost degradation, I.e. seasonal soil thawing (of 0.4-0.8 m depth), and a northward shift of the isotherm that characterises the southern permafrost boundary (Sherstyukov, 2009). Changes in permafrost distribution can damage building foundations and disrupt the operation of vital infrastructure. Climate change may lead to a shrinkage of the total permafrost area by10-12% in the next 20-25 years, with the southern permafrost borders moving 150-200 km to the north (Anisimov et al., 2004).

The challenges permafrost thawing presents for transportation are considerable (e.g. Field et al., 2007). Permafrost thawing causes settling of the roadbeds and frost heaves at the roadways that affect the integrity of the structures and their load-carrying capacity. In many northern areas of the UNECE region (e.g. Alaska), many highways are already located in areas with discontinuous permafrost, resulting in substantial maintenance costs (e.g. Karl et al., 2009). Bridges are particularly sensitive to movements caused by thawing permafrost and are often much more difficult than roads to repair/modify for changing site conditions. Thus, climate change considerations are even more critical in the design of these facilities than is the case for roads.In addition, temporary ice roads and bridges which are used in many parts of the northern territories to access northern communities and provide support for the mining and oil/gas industries are also under stress; rising temperatures have already shortened the season during which these critical facilities can be used. Moreover, rail lines are located in permafrost terrains; frost heaving and subsidence from thawing can affect parts of the tracks, increasing substantially the maintenance costs (ACIA, 2005).

Finally, airports built on permafrost will require major repairs/relocation, if their foundations are compromised by thawing. A recent study (Larsen et al., 2008) has estimated that the cost of maintaining Alaska's public infrastructure will increase by 10-20 % (by $4-$6 billion) in 2030 due to warming, with roads and airports accounting for about half of this cost. Additional costs will be involved in the maintenance of pipeline systems. As most of these systems were designed in the early 1970s on the basis of the then permafrost/climate, they will need continuous monitoring and maintenance/repairs (Karl et al., 2009).

Table 2. *Potential impacts of climate change driven changes on transportation and adaptation measures.*

Temperature	**Potential implications**	**Adaptation measures**
Higher mean temperatures Melting ice and permafrost Increased temperature spatio-temporal variability	Longer shipping season-NSR, new shorter shipping routes-NWP/less fuel costs, but, possibly, higher costs for new support services; changes in demand and supply of transport services; dilatation of badly designed railways, forest fire impacts on land and air transport; increased landslide risks affecting mountainous road and rail networks; severe damage of roads, railways and pipelines from permafrost melting; damage to infrastructure, equipment and cargo and increased construction and maintenance costs; higher energy consumption in ports and other terminals; challenges to service reliability	Better infrastructure and network designs and resistant construction materials; continuous infrastructure monitoring, repair and maintenance; installation of more efficient refrigeration, insulation, cooling/ventilation systems; improved transit management schemes; increased skilled labour and training requirements; upgrading/harmonisation of infrastructure parameters in international rail, road, inland waterway and combined transport networks
Precipitation	**Potential implications**	**Adaptation measures**
Changes in the intensity/frequency of precipitation extremes (floods and draughts);	Increased flooding/inundation risks for transport networks; impacts on inland waterway navigation; damages and/or destruction of vital transport nodes (e.g. bridges)	Upgrading and/or relocation of transport network infrastructure in less flood-prone areas; design of functioning alternatives routes
Sea level (mean and extreme)	**Potential implications**	**Adaptation measures**
Mean sea level changes Increased intensities of hurricanes/storm surges Changes in the wave energy (level and direction)	Increased coastal flood/inundation risks; erosion of coastal areas and damages to port infrastructure, equipment and cargo; increased port construction and maintenance costs; changes in port/navigation channel sedimentation patterns; effects on key transit points (e.g. The Panama Canal); relocation of people/business and labour shortages; insurance issues	Design/construction, monitoring and maintenance of effective port flood protection schemes (e.g. levees, breakwaters. seawalls, dikes, port elevation); relocation of infrastructure; design of functioning alternatives; integration of emergency evacuation procedures into operations; New designs for sturdier, more versatile vessels; restrictions in development and settlement in low-lying areas coastal areas; Preparedness for service delays/cancellations; new technologies for extreme event detection; upgrading and/or relocation of transport infrastructure on hinterland seaport connections

4 Information on Select Studies on Climate Change Impacts on Transport

As the previous two Sections have illustrated, different climatic change effects/extreme events may have a range of diverse impacts on transport infrastructure and services, but these will vary significantly by mode, climate change factor, and depend on the local or regional circumstances and vulnerabilities, including those associated with the natural environment, (as well as a broad range of socio-economic factors which have not been addressed in this report).

The transport sector is instrumental to many economic and social functions. At the same time, transport infrastructure and services depend on weather conditions and, thus, it is important to improve our understanding on how these would be affected by the present and future climate and its dynamics. Although it is claimed that the transport sector is particularly vulnerable to climate change (e.g. Eddowes et al., 2003; IPCC, 2007b; Karl et al., 2009), there is comparatively little detailed research into specific implications/impacts, adaptation strategies and costs and benefits, compared with other sectors such as energy and agriculture (EEA, 2010).

Enhancing the climate resilience of international transport networks requires a good understanding of the specific impacts that climate change may have on infrastructure, as well as services and operations across the different modes of transport. However, despite the potentially important broad implications of adverse climate change impacts on transport, detailed relevant research available in the public domain appears, at present, to be limited. In addition, although several studies have addressed climate change impacts on transportation infrastructure generally and possible adaptation measures (e.g. in the USA, Canada, the UK and Australia), most are not mode-specific and very few specifically focus on international transport networks.

In respect of adaptation to climate change in the transport sector, a recent review of the available literature by the Potsdam Institute for Climate Impact Research (Eisenack et al., 2011) reveals that the majority of potential adaptation actions address in particular road transport. Means proposed for adaptation are often non-specific with reference being made to technological/physical solutions, planning frameworks, monitoring, information provision, education, research, and some specific investment proposals for new or changed infrastructure. There are few proposals for policy instruments with the exception of spatial planning.

While information about some additional literature of relevance to the further study of climate change impacts on international transport networks is provided in the Annex to this report, some of the particularly pertinent studies are briefly summarized in this Section. These include select studies/case studies with a particular focus on specific modes of transport, i.e. road, rail, inland waterway transport, as well as ports. Also included is the “US Gulf Coast Study on Impacts of Climate Change and Variability on Transportation Systems and Infrastructure”, which is being conducted in several phases and focuses on transportation infrastructure across modes, adopting a comprehensive integrated approach and may be of particular interest as a model for similar studies at a regional level.

4. 1. The US Gulf Coast Study

The US Gulf Coast Study aims to provide a comprehensive assessment of how climate change will affect transportation in the United States Gulf Coast area. The ultimate goal of this research, carried out in 3 distinct phases, is to provide knowledge and tools that could enable transportation planners/managers to better understand the risks, adaptation strategies, and trade-offs involved in planning, investment, design, and operational decisions.

The objective of Phase I (completed in 2008) was to conduct a preliminary assessment of the risks and vulnerabilities of transportation in a segment of the US Gulf Coast, on the basis of the collation/collection and integration of a range of data – its physiography, hydrology and coastal hydrodynamics, land use and cover, past and projected climate, current population and trends, and transportation infrastructure. Phase II (2010-2013) will conduct an in-depth assessment of risks to transportation at selected locations, reporting on implications for long range plans and impacts on safety, operations, and maintenance. This phase will also develop a risk assessment methodology and identify techniques to incorporate climatic and other environmental information in transportation decisions. It aims to enhance regional decision makers' ability to understand potential impacts on specific critical components of infrastructure and to evaluate adaptation options. Phase III will identify and analyze adaptation and response strategies and develop tools to assess these strategies, while identifying/evaluating future research needs.

4.1.1 Gulf Coast Study, Phase I (CCSP, 2008)

The report presents the results of a Phase I of the assessment of climate change and its potential impacts on transportation systems for the region of the US central Gulf Coast between Galveston (Texas) and Mobile (Alabama) which contains multimodal transportation infrastructure that is critical to regional and national transportation services. It considers issues such as climate effects on the design, construction, safety, operations, and maintenance of transportation infrastructure and systems, including critical questions regarding how alterations in temperature, precipitation, storm events, and other aspects of the climate could affect roads, airports, rail, transit systems, pipelines, ports, and waterways.

Historical trends and future climate scenarios were used to establish a context for examining the potential effects of climate change on all major transportation modes within the region. Climate changes anticipated during the next 50 to 100 years for the central Gulf Coast include warming temperatures, changes in precipitation patterns and increased storm intensity. The effects of sea level rise in most central Gulf Coast coastal areas will be exacerbated by high rates of land subsidence at the Mississippi delta, which is accounted for in this assessment.The significance of these climate factors for transportation systems was assessed.

Main findings include the following:

Warming temperatures are likely to increase the costs of transportation construction, maintenance, and operations. More frequent extreme precipitation events may disrupt transportation networks through flooding. Relative sea level rise will make much of the existing infrastructure more prone to frequent or permanent inundation – 27 % of the major roads, 9 % of the rail lines, and 72 % of the ports are built on land at or below ~1.2 m (4 feet) in elevation. Increased storm intensity may lead to increased service disruption and infrastructure damage: more than half of the area's major highways (64 % of Interstates; 57 % of arterials), almost half of the rail miles, 29 airports, and virtually all of the ports are below 7 m (23 feet) in elevation and subject to flooding and possible damage due to hurricane-induced storm surges.

4.1.2 Gulf Coast Study, Phase II

While Phase I took a broad look at the entire Central Gulf Coast region and provided a "big picture" view of the climate-related challenges facing transportation infrastructure, Phase II is focusing on the single Metropolitan Planning Organization (MPO) region of Mobile, Alabama.

The purpose of this Study is to evaluate which transportation infrastructure components are most critical to economic and social functions, and assess the vulnerability of these components to weather events and long-term changes in climate. Phase II will also develop tools and approaches that the South Alabama Regional Planning Commission (which includes the MPO for the Mobile area) and other public and private system operators can use to determine which systems need to be protected, and how best to adapt infrastructure to the potential impacts of climate change. Through this study, US Department of Transportation intends to create a template for an assessment process that can be replicated in other regions of the country. In this study area many transportation modes are well represented, including highways, ports, rail, aviation, and pipelines. It is also a critical port location for the entire United States (importexport of industrial, commercial, and agricultural products, as well as oil and gas).

Primary Phase II Activities include:

- Identify critical transportation assets in Mobile County
- Evaluate projected climate change effects (changes in temperature, precipitation, storm surge, and sea level rise) for Mobile County
- Investigate relationships between changes in climate and impacts to infrastructure
- Combine information on critical assets with information on climate to assess vulnerability
- Conduct detailed engineering/risk assessments for the most vulnerable assets and identify costs/benefits of adaptation strategies
- Use lessons learned through the work in Mobile to develop generic screening tools and approaches that could be employed by other regions to identify which transportation systems need to be protected, and how to protect/adapt those systems

4. 2. PIANC Study, (PIANC, 2006)

This study reviewed climate change impacts on maritime and inland navigation, including sea level rise, wind and wave action, tidal and storm surge propagation/range, storms, ocean circulation, coastal hydrodynamics, ice conditions, riverine water supply/quality, extreme hydrological conditions, and coastal, estuarine and river morphodynamics. Potential adaptation and mitigation responses were identified. Navigation contributions to greenhouse gas (GHG) emissions were discussed, along with opportunities for navigation to contribute to decreases in anthropogenic GHGs, and, through use of alternative fuels, to decreases in other pollutants.

As regards inland navigation, the report noted that this sector has more capability to respond to such drivers than the maritime sector, since in most countries adequate relevant infrastructure exists to control runoff. At the same time, complex political, social, and environmental factors appear to control the balance of inland navigation requirements against competing needs for water supply, flood control, hydro-power, and irrigation.

According to the report, the key drivers of change, directly influencing the navigation on inland waterways, are precipitation and air temperature. These parameters and their effects on inland navigation are discussed in some detail. It is suggested that impacts on rivers, channels and canals may be mitigated through changes in operational control of flow or by cannel modifications. Amongst other things, the report highlighted that operational changes to flow control will require legal and environmental analyses, as inland navigation is connected to and competing with other water users. The relevance of flood control measures, of changes to existing maintenance practices such as channel and bank stabilization and dredging, and of increased automation were discussed.

The report concluded that some of the adaptation responses require additional investment and/or cause higher operational costs, i.e. may be subject to economic limitations, in addition to legal and/or technical limitations; therefore costs and benefits of the individual measures/responses that may be part of a portfolio of measures should be assessed.

4.3. Scottish Road Network Climate Change Study (Galbraith et al., 2005)

Following a number of landslide events in the summer of 2004, the Minister for Transport commissioned 2 studies to consider issues arising from these events. This report presented the findings of the second of these studies, which was to consider the potential trends in climate change in Scotland and how these may affect the road network.

The report outlined the historical information available in relation to extreme weather events and how this has been used in the design and operation of the road network. The report then assessed the implications of current climate change predictions, including work commissioned specifically for this study. Key climate variables (e.g. temperature and rainfall) that may have significant impacts on road networks were modeled, and predictions were provided for 30 year periods centred around the 2020's, 2050's and 2080's.The general conclusion was that the climatic changes expected in Scotland in the near future (i.e. in the 2020's) are relatively small. However, even these small changes may be sufficiently significant to warrant adjustment of current practices. While the report noted that these changes are likely to become more substantial over the longer term, the degree of uncertainty associated with these predictions increases. Consequently the recommendations focussed on responding to climatic changes predicted to occur in the near future. These were presented in terms of design, operation, further research or policy review, as appropriate to the issues identified.

The findings of the report with regard to considered climate change trends are broadly as follows: Temperatures are expected to increase, resulting in higher summer temperatures and fewer (freezing) winter days. Annual rainfall is expected to show little overall change, but winter rainfall is predicted to increase, summer rainfall to decrease and snowfall days to become less. Wind speeds are predicted to increase slightly, but there is significant uncertainty. Fog occurrence is expected to decrease, although this is also a prediction with significant uncertainty. Coastal flooding is expected to increase, particularly when storm surges are included within the assessment.

One area of particular concern that has been identified is the predicted increase in (winter) rainfall; this may result in drainage systems failing to perform in the desired manner. To address this concern, it was recommended that: (i) the design storm parameters used in surface water drainage designs are revised to allow for predicted increases; (ii) the design storm parameters used in culvert and river bridge designs are revised; (iii) locations where road flooding has occurred are identified and potential solutions evaluated on a cost/benefit basis, with priority for those areas where frequent flooding takes place; (iv) pre-emptive clearance of debris from drainage channels/watercourses is undertaken in areas of increased flood risk; and (v) further research is undertaken to improve estimations of catchment runoffs, in order to enable guidance on risk-based design approaches (including evaluation of alternative solutions on a cost/benefit basis).

In addition, recognizing the opportunity afforded by the proposed expansion of the Variable Message Sign (VMS) network, and developing weather prediction technology, it was recommended that: '…*consideration be given to using VMS's to provide a greater level of locally relevant information to road users on predicted severe weather events, expressed in terms of probability of occurrence'*. It was noted that actions are already in place to address some of the issues identified, such as the development of a High Winds Strategy for the trunk road network. Finally, it was suggested that agreement with other UK road authorities is necessary in order to address certain issues, such as changes in design standards.

4. 4 Climate change and the railway industry: a review (Baker et al., 2010).

This article discusses the role that railways could play in reducing overall greenhouse gas (GHG) emissions and focuses on the effect of climate change on the operation of U.K. railways in the next few decades and the adaptation measures that will be required. Some of the key issues highlighted in the paper include the following:

Hot dry summers can be expected to have effects on the UK railway system, such as: (i) increased buckling of tracks; (ii) desiccation of track earthworks; (iii) greater requirements for air conditioning systems; (iv) increased ventilation problems on underground railway systems; and (v) increased leaf fall issues due to longer plant growing seasons. Most of these issues are well understood in technical terms.

The increased frequency of warm wet winters can be expected to have adverse effects on the UK railway system, such as: (i) increased network flooding and strain on drainage systems; (ii) damage to earthworks and failure of saturated embankments; and (iii) track circuit problems. There will also be some beneficial effects, in particular the decrease in snow- and ice-related and low-temperature incidents. Again most of these issues are well understood in technical terms. There will always be pressure for increasing the level of flood protection, and some balance must be struck between the flood protection costs and drainage improvement schemes and the, sometimes, very considerable costs of the events themselves.

The effects of increased frequency of extreme storms and, in particular, of intense rainfall and extreme winds on the rail network are, to an extent, an escalation of the effects of increased winter rainfall. The effects of high winds include: (i) increased likelihood of dewirement; (ii) increased possibility of train overturning/derailment; and (iii) accidents or network disruption due to trees and debris deposited on the tracks. Again these effects have been studied to varying degrees (some quite thoroughly), but usually for the purposes of assessing accident risk during the design process, rather than because of climate change considerations.

The effect of a 0.3–0.4 m sea level rise can potentially have major consequences, both for railway systems in estuarine cities and for coastal lines in general. The need for increased levels of protection (in the case of the London underground) is clear, particularly as the level of protection provided by the Thames Barrier is already predicted to decrease over the next few decades.

It was noted that while the technical issues are fairly well understood, an overall framework for the quantification of the likely effects of these issues on the railway industry is lacking, as is a method for assessing which are the most critical effects to which resources should be given a priority allocation.

The article concluded that, with respect to the effects of climate change on the railways, there is a need for overall system modelling to properly evaluate the major climate change risks to railway operation and to prioritize the use of resources in tackling these issues. Reference was also made to the scope and purpose of some ongoing relevant research.

The article also noted that the potential impact of significant alterations in meteorological hazards must be assessed across all transport modes, and not just rail transport. To this end, it was stated: "*Such an assessment should be driven by the economic benefits of an efficient national transport network, the costs associated with disruption, and the concurrency of the lifespan of many near-term infrastructural developments with the timeframe for climate change. Consideration must also be given to the technological development of the transport network itself. Climate change impacts are not simply a function of weather events, but also of the network's vulnerability. Further, 'studies to assess climate change impacts suffer from serious weakness if by default they merely assume that the projected future climates will take place in a world with a society and economy similar to today'. However, the drivers for transport demand are not well understood, let alone their vulnerability to climate change*".

4.5 Future Resilient Transport Networks (FUTURENET): Assessing Transport Network Security in the Face of Climate Change (Bouch et al., 2012**)**

***Abstract**:* Transport network security is increasingly under threat from climate change. Identification and protection of all vulnerable infrastructure assets is not a realistic response. A different approach is required: one that assesses security in terms of a network's resilience. To facilitate this, a network resilience assessment methodology is required; FUTURENET is a multi-partner, multi-disciplinary research project, investigating the development of such a methodology. It considers changes in climate and weather anticipated for 2050, and assesses the impact of these on the principal modes of transport (road, rail and air). FUTURENET seeks to create a generic methodology that might be applied to any transport network. It involves a number of research strands including investigations of: the influence that climate change will have on travel demand and travel behavior; modelling of transport failure modes and associated triggers and thresholds; generation and application of climate and weather events to networks; development of the network resilience assessment methodology, and; the application of systems engineering techniques to methodology development. The project is due to finish in April 2013.

4.6. Rail safety implications of weather, climate and climate change (RSSB, 2003)

This document presents a report commissioned by RSSB as part of the Rail Safety Research Programme and prepared by AEA Technology plc. It sets out the RSSB's response, summarizing the proposed future actions to be taken by RSSB.

The overall aim of the research was to help Railway Group members understand better the implications that climate change may have on their activities. The research was designed to:

- identify the current status of knowledge concerning climate change impacts on railway safety, and gaps in that knowledge.
- define what work is required to fill those gaps.
- specify what work is needed to determine how the railway industry should respond to the threats associated with climate change.

The report covered the following:

- a robust summary of current information and research, highlighting the development of global, regional and local climate research.
- current documentation and databases within Network Rail and RSSB
- a qualitative assessment of the effect of predicted climate change scenarios on railway infrastructure.

The report also lists individuals, organisations, websites, reports and databases concerned with climate change and weather as a set of references.

Particularly relevant parts of the RSSB response is set out here in full, for ease of reference:

"4.1 While there is uncertainty about climate change, RSSB considers that the United Kingdom Climate Impacts Programme (UKCIP) provides an acceptable set of assumptions for present purposes. These are for the decade of 2080 ie within the design life expectancy of much of the present infrastructure. The main predictions are:

- Average temperature to rise by at least 1-2ºC.
- Precipitation to reduce 5-15% overall but with higher winter rainfall and lower summer rainfall and possibly more extreme hourly rainfall.
- Average wind speed to rise between 4% and 10%, but with possible increase in the number of severe events.
- Sea level to rise between 20-60cm depending upon emission scenario and northwest southeast tilt.

4.2 The report contains valuable qualitative information on the likely effects. It is considered that the main types of infrastructure vulnerable to the changes are:

- track (extreme temperature)
- earthworks (extreme precipitation)
- drainage (extreme precipitation)
- overhead line equipment (extreme wind)
- coastal and estuarial infrastructure (protection/defence) (sea level rise).

The report findings will enable future work to be more focused.

4.3 It is noted that an enormous amount of work is being undertaken by many organisations into weather, climate and climate change so that it is difficult to identify specific gaps in knowledge with respect to railway infrastructure. The following, however, are the main 'gaps' identified:

- Uncertainty in future predictions (the uncertainty varies between weather elements).
- The likely increase in the frequency and intensity of extreme weather events.
- Work directly related to the railway sector.
- The likely effects of the rise in sea level, which are predicted to be substantial and exacerbated in some areas by the effects of the continuing northwest/ southeast UK land tilt and storm surges (but alleviated in other areas).

It should be noted that individual railway localities may be disproportionately affected by climate change. These will need systematic identification."

[…]

“5. Recommendations for future action

5.1 Railway infrastructure and vehicles are generally robust, but the safety performance of train operations can be affected by extreme weather. Although the risk is low generally, it is considered not low enough to be negligible, especially if the number and intensity of extreme weather events increases. It is considered that further research would be justified as set out below.

5.2 Organisationally there should be more formal links between RSSB and the relevant government/research organisations (for example the Environment Agency, and the Department for the Environment, Fisheries and Rural Affairs,) to maintain an up-to-date review of current work and thinking at a national level. There is the potential advantage that RSSB could exert greater influence on such work and thinking. Links should also be strengthened with those concerned with reducing green house gas emissions related to the railway, and other sustainability matters. RSSB could provide a focus for information on climate change matters for Railway Group members (RGMs).

5.3 It is considered that the most valuable way forward is to begin quantifying the changes to safety risk and traffic delay that are likely to result from extreme weather events. This should take into account:

- Different types of infrastructure and how widespread they are (for example, track, drainage, overhead electrification equipment).
- Historical numerical data on delays caused by weather related incidents.
- Current values used in the RSSB risk model for weather related precursors to hazardous events and the predicted consequential harm to people.
- Best available quantitative estimates of likely changes to extreme events based on current industry intervention levels (air temperature, flood level, wind gust speed).

The combining of delays and direct safety risk (safety performance) could be based on the methods and model being developed for assessing the effect of vandalism on railway safety performance. The vandalism research programme is being managed by RSSB on behalf of the railway industry.

5.4 Specific research projects related to climate change should be initiated to:

- Understand better the effects of climate change on trackside vegetation.
- Identify more clearly how railway locations are most likely to be affected
- by the rise in sea level.

Consideration could also be given to addressing how the railway industry could best help in mitigating the predicted climate change, possibly in conjunction with other transport undertakings.

5.5 It is considered that the proposals contained in 5.2 and 5.3 would be the most effective way to forward the research, by providing a more quantitative assessment of the likely effects of climate change on safety performance and by gaining more detailed knowledge in specific areas. In the longer term there may be ways in which the railway industry might help in mitigating the predicted climate changes through addressing sustainability issues. The results of this further work could, for example, help RGMs in determining how existing assets would be most effectively managed, whether revised design standards for new assets would be beneficial, and how operational measures might best be adapted.

4.7 Climate Adaptation of Railways: Lessons from Sweden (Lindgren et al., 2009)

Abstract: The current variability in weather and climate is posing a challenge for transport infrastructure. However, during the past decade the need to adapt to a changing climate has attracted increasing attention. This paper summarises a case study on the future vulnerability to climate change of the Swedish railway transport system and its adaptive capacity. The combination of a long time horizon in planning and an expected increasing demand for rail traffic raises many questions regarding how adaptation to climate change can be accounted for in future planning, design and management of railways. The case study was essentially based on interviews with key personnel within the Swedish Rail Administration. Views on vulnerability and adaptation to climate change were documented, and the need for improved methods to assess the vulnerability and adaptive capacity related to climate change for the Swedish railways was addressed. The conclusions of the paper are addressed to the European railway context at large. Firstly, systematic mapping of current climate vulnerabilities and their consequences is important in order to guide the implementation of adaptation measures. Secondly, climate change should be considered in the early stages of planning and included in risk and vulnerability assessments. In assessing future conditions with the aim of prioritising adaptation measures, current methodologies should be complemented with more future-orientated tools. When designing adaptation measures, the effects of potential goal conflicts should also be assessed, in order to avoid the implementation of counter-productive measures. The possibility of creating synergies with climate mitigation goals and other environmental goals should also be investigated.

4.8 Railway construction techniques adapting to climate warming in permafrost regions (Wu Qingbai et al., 2008)

Abstract*:* The climate warming, which has an evident effect on the warm/ice-rich permafrost, should be considered in the engineering design of the Qinghai-Tibet Railway in permafrost areas. Based on the rule mentioned above, many design ideas and measures such as cooling embankment and controlling of heat conduction, radiation and convection were proposed during the construction of the Qinghai-Tibet Railway to reduce the permafrost temperature and to reduce the impact of climate warming on the railway. These measures ensure the stability of the railway embankment in permafrost regions.

4.9 Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east UK (Dobney et al., 2009)

Abstract*:* Extreme high temperatures are associated with increased incidences of rail buckles. Climate change is predicted to alter the temperature profile in the United Kingdom with extreme high temperatures becoming an increasingly frequent occurrence. The result is that the number of buckles, and therefore delays, expected per year will increase if the track is maintained to the current standard. The paper uses a combination of analogue techniques and a weather generator to quantify the increase in the number of buckles and rail related delays in the south-east of the United Kingdom. The paper concludes by assigning a cost to the resultant rise in delays and damage before making recommendations on how these effects can be mitigated.

4. 10 ARISCC Adaptation of Railway Infrastructure to Climate Change (Nolte et al., 2011)

The IZT performed and implemented a climate change adaptation strategy for the International Union of Railways (UIC) together with some of the major European railway infrastructure companies (see www.ariscc.org) under the framework of the ARISCC.

The aim of the UIC ARISCC project was to prepare rail infrastructure for weather and climate related natural hazards. The background for the ARISCC project is that railways have an extremely long life time and are constructed to withstand natural hazards, such as the 1-in-100-year flood. However, as the frequency/intensity of incidents caused by extreme events Is likely to increase in the future, the pressure on the capacity of the rail system will also rise together with the costs for the sector. If the right measures are taken at the right time, the risk will be bearable.

The outcomes of the project include: (i) an update and extension of an existing survey on the current status of adaptation of European railways to climate change; (ii) a guidance document on integrated natural hazard management; (iii) an extensive collection of good practices; and (iv) two case studies using regional climate models for the identification of future regional climate loads and existing vulnerabilities of railway infrastructures.

The ARISCC guidance document for Railway Infrastructure Managers for an integrated natural hazard management comprises the following elements: (1) Weather Information and Weather Warning; (2) Documentation & Assessment of Past Weather Events; (3) Natural Hazard Mapping; (4) Monitoring and Documentation of the Status of Infrastructure; (5) Vulnerability Mapping; (6) Risk Assessment and Risk Management; (7) Regional Climate Models and Future Climate Loads, and (8) Adaptation Recommendations.

A range of general and specific recommendations are made in the report, including the following:

- Without an adaptation strategy and adaptive action, the present resilience of railways could prove to be insufficient in the near and medium future. Therefore, it is recommended to develop a proactive adaptation strategy to systematically build up adaptive capacity. The strategy should include short term and long term objectives and measures and has to take into account affordability. The guiding principles of the integrated strategy should be: Readiness, Resilience and Recovery.

- As a short to mid term option, engineering specifications should be reviewed to improve the resilience of the railways systems, including in the dimensioning of drainage system, flood protection and for the protection against heat waves. The objective should not be the single assets of railways lines but the improvement of system resilience.

- A core part of an efficient natural hazard management system is a well structured and integrated database for asset management, maintenance planning, disruptions, digitized network data and incidents. For current operation, adaptation to climate change aspects should be integrated into current maintenance planning. For future projects, adaptation should be integrated into the design of assets. This can be achieved by integrating adaptation into the early stages of current planning processes. There is a wide range of practical adaptation measures ranging from warning systems and monitoring to improving maintenance standards, reinforcing protective structures, and changing standards. Prioritisation of measures and finding the optimum combination for a project or a railway line depends on many factors such as the types of assets, time horizon, importance of route, financial constraints, cost benefit ratios, etc. Soft measures such as real time monitoring of vulnerable sections and rapid alert systems can have much better cost benefit ratios than hard engineering solutions.

- The implementation of an integrated natural hazard management starts s a process of capacity building for the adaptation of the company to climate change. This process can be improved by way of better knowledge exchange.

4.11 Climate Risk and Business: Ports – Terminal Marítimo Muselles el Bosque Cartagena, Colombia (Stenek et al., 2011)

The study was commissioned by the International Finance Corporation (IFC) to help develop knowledge, tools and methods for analyzing climate-related risks and opportunities and evaluating adaptation responses, focused on the case of the Terminal Maritimo Muelles El Bosque (MEB), in Cartagena, Colombia. It analyzed climate related risks and opportunities facing IFC's client, Muelles el Bosque, and provided a quantitative assessment of climate impacts and related adaptation responses. While the study focused on the impacts on this specific port and its surroundings, it also briefly explored how other ports in Colombia and elsewhere in the world can expect to be affected by climate change.

The report noted that infrastructure and transport are among the sectors most exposed to climate change, and in turn are critical to national economic performance, growth and development. Ports, in particular, play a vital role in the world economy. More than 80% of goods traded worldwide are transported by sea. Ports in developing countries handle more than 40% of the total containerized traffic, of which a significant portion relates to materials and export of goods produced in the country. Hence, the impacts of climate change on ports will have much wider socio-economic ramifications.

Select key findings of the study include the following:

(a) In general, the physical infrastructure at ports, and port activities, may be highly vulnerable to changes in climate. For instance, the risks could manifest through changes in the level or patterns of shipping, increased flooding affecting movements within ports and causing damage to goods stored, reduced navigability of access channels and business interruption. Some ports will also see opportunities as a result of climate change. A port's reputation for reliability is key to its success, so ports that are more resilient to disruption from climate events should fare better. Higher temperatures may benefit ports in cold regions where navigation is currently restricted by ice, through increasing the length of the shipping season. Changes in trade flows driven by climate change will also see winners and losers. To understand the significance of these risks for a given port, it is necessary to analyze the factors affecting the success of that port and evaluate climate-related impacts, taking account of existing vulnerabilities, critical climate related thresholds and climate change projections.

(b) The analysis undertaken for the study found that the materiality of climate change impacts will vary greatly from one port to another, though there are some key risk areas that all ports should consider. There will be considerable differences in the nature and level of climate change risks and opportunities between ports depending on the characteristics of their locations – be they in regions prone to tropical or extra-tropical cyclones, in areas where permafrost is thawing, or on lakes or rivers whose levels are changing. Further, ports vary considerably in the functions they perform. Climate change will have different implications for ports with cargo handling and warehousing functions compared to those providing exclusively pilotage, navigation and dredging services, or for cruise/passenger ports.

(c) The analyses undertaken for the particular port covered by the study have shown that climate change can have material business implications for ports. Though some of the risks analyzed in this study are likely to be specific to the port under investigation, and may not apply to other ports, a number of them will be of broad relevance to the industry around the world.

Based on the findings of the study on Muelles el Bosque terminal and a comprehensive literature review, a checklist has been prepared to help port operators and their stakeholders to identify climate-related risks and possible adaptation options.

The Checklist:

- Categorizes climate impacts (risks and opportunities) according to the key operations undertaken at cargo ports (navigation, berthing, goods handling, etc.), along with other factors related to port performance, such as demand, insurance availability and environmental and social performance.

- Gives an overview of the climate-related sensitivities and thresholds of cargo ports in general, and also outlines some impacts which are specific to ports in particular environments (e.g. tropical and polar regions).

- Provides a list of adaptation measures which can be considered by port operators in response to climate change risks and opportunities. These include actions which help to build adaptive capacity (such as improved monitoring of climate impacts) as well as the implementation of physical adaptation measures, such as modifications to port infrastructure.

References

ACIA, 2005. Arctic Climate Impact Assessment. Cambridge University Press, Cambridge, UK. 1042 pp. http://www.acia.uaf.edu/pages/scientific.html

Alcamo J, N Dronin, M Endejan, G Golubev and A Kirilenko, **2007**. A new assessment of climate change impacts on food production shortfalls and water availability in Russia. Global Environment Change, 17, 429-444.

Allan RP and BJ Soden, **2008**, Atmospheric warming and the amplification of precipitation extremes. Science 321, 1481-1484.

Anisimov OA, AA Velichko, PF Demchenko, AV Yeliseyev, II Mokhov and VP Nechaev, **2004**. Impact of climate change on permafrost in the past, present and future. Physics of Atmosphere and Oceans, 38(1), 25-39.

Arnell NW, 2010. Adapting to climate change: an evolving research programme. Climatic Change, 100, 107–111.

Baker CJ, L Chapman, A Quinn and K Dobney, **2010.** Climate change and the railway industry: a review. Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science, 224, 519-528.

Barnett TP et al., **2008**. Human-Induced Changes in the Hydrology of the Western United States. Science 319, 1080-1085.

Beniston M, 2003. Climatic change in mountain regions: a review of possible impacts. Climatic Change, **59**, 5-31.

Beniston M and HF Diaz, 2004. The 2003 heat wave as an example of summers in a greenhouse climate? Observations and climate model simulations for Basel, Switzerland. Global and Planetary Change, 44, 73-81.

Bennet S, 2011. Preparing for the Worst – the Shipowners' Perspective**.** Presentation in UNCTAD AdHoc Meeting 'Climate change impacts and adaptation: A challenge for global ports' Geneva 29-30 September 2011

Bouch C, Baker C, Chapman L, Hooper L, Jaroszweski D, Quinn A, Avery K, Paulley N, Reeves S, Dijkstra T, Dixon N, Fleming P, Frost M, Ryley T, Wilks J, Zanni A, Dingwall R, Goulden M, Gunn D, Lawley R, Sivell P, and Wade S, **2012**. Future Resilient Transport Networks (FUTURENET): Assessing Transport Network Security in the Face of Climate Change. Submitted for presentation and publication to the 91st Annual Meeting of the Transportation ResearchBoard, January 22–26, 2012, Washington DC.

Caldeira K, 2009. Ocean acidification: Humanity and the environment in geologic time, IOP Conference Series: Earth and Environmental Sciences 6 (3): 462004. http://www.iop.org/EJ/toc/1755-1315/6/46

Callaghan DP, P Nielsen, A Short and R Ranasinghe**, 2008**. Statistical simulation of wave climate and extreme beach erosion. Coastal Engineering, 55, 375–390.

Canadell JG, Le Quırı C, Raupach MR, Field CR, Buitenhuis E, Ciais P, Conway TJ,Gillett, NP, Houghton RA and G Marland, **2007**. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences 104, 18866-18870.

CCSP, **2008**. Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Savonis MJ, VR Burkett, and JR Potter (eds.)]. Department of Transportation, Washington, DC, USA, 445 pp.

Challinor A, J Slingo, A Turner and T Wheeler, **2006**. Indian Monsoon: Contribution to the Stern Review http://www.hm-treasury.gov.uk/d/Challinor_et_al.pdf.

Chust G, Á Borja, P Liria, I Galparsoro, M Marcos, A Caballero and R Castro, **2009**. Human impacts overwhelm the effects of sea-level rise on Basque coastal habitats (N Spain) between 1954 and 2004. Estuarine, Coastal and Shelf Science, 84, 453-462.

Ciscar JC et al., 2009. Climate change impacts in Europe. Final report of the PESETA research project. JRC Scientific and Technical Reports. European Commission – Joint Research Centre Institute for Prospective Technological Studies, Institute for Environment and Sustainability. http://ftp.jrc. es/EURdoc/JRC55391.pdf

Crist, P., 2011. Transport infrastructure and network adaption to climate change: Issues and strategies for ports**.** Presentation in UNCTAD AdHoc Meeting 'Climate change impacts and adaptation: A challenge for global ports' Geneva 29-30 September 2011.

Dasgupta S, B Laplante, S Murray and D Wheeler, **2009.** Sea-Level Rise and Storm Surges: A Comparative Analysis of Impacts in Developing Countries. Policy Research Working Paper 4901, the World Bank Development Research Group, Environment and Energy Team. 41pp.

Dobinski W, 2011. Permafrost, Earth Science Reviews doi:10.1016/j.earscirev.2011.06.007

Dobney K, CJ Baker, AD Quinn and L Chapman, **2009.** Quantifying the effects of high summer temperatures due to climate change on buckling and rail related delays in south-east United Kingdom. Meteorological Applications, 6(2), 245–251 (Doi: 10.1002/met.114)

Domingues CM, Church JA, White NJ, Gleckler PJ, Wijffels SE, Barker PM and JR Dunn, **2008**. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature 453:1090-1094.

Ebersole BA, JJ Westerink, S Bunya, JC Dietrich and MA Cialone, 2010. Development of storm surge which led to flooding in St. Bernard Polder during Hurricane Katrina. Ocean Engineering**, 37**, 91-103.

EC, 2007. EU Floods Directive (2007/60/EC) on the assessment and management of flood risks. European Commission http://ec.europa.eu/environment/ water/flood_risk/index.htm.

Eddowes MJ, Waller D, Taylor P, Briggs B, Meade T, Ferguson I, **2003**. Railway safety implications of weather, climate and climate change. Rail Safety and Standards Board UK.

EEA, 2004. Mapping the impacts of recent natural disasters and technological accidents in Europe. Environmental issue report No 35 European Envronmental Agency, Copenhagen,

EEA, 2010. The European environment: State and outlook 2010, Adapting to climate change. European Envronmental Agency**,** Copenhagen, 2010. ISBN 978-92-9213-159-3

Eisenack K, Stecker R, Reckien D, Hoffmann E, 2011. Adaptation to climate changein the transport sector:a review. Potsdam Institute for Climate Research, Report 122. ISSN 1436-0179

Emanuel, K., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. Nature, **436**, 686-688.

Ericson JP, CJ Vörösmarty, SL Dingman, LG Ward, and M Meybeck, **2006**. Effective sea-level rise and deltas. Causes of change and human dimension implications. Global and Planetary Change, 50, 63-82.

Feyen L, Dankers R, Barredo JI, Kalas M, Bódis K, de Roo A and Lavalle C, **2006**. PESETA Flood risk in Europe in a changing climate. Institute of Environment and Sustainability, Joint Research Center, EUR 22313 EN.

Feyen L, Dankers R and Bodis K, **2010**. Climate warming and future flood risk in Europe. Climatic Change.

Field CB et al., 2007. North America. In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (ML Parry, OF Canziani, JP Palutikof PJ van der Linden and CE Hanson (eds.). Cambridge University Press, Cambridge, UK, and New York, pp. 617-652.

Fink A, T Brücher, A Krüger, G Leckebusch, J Pinto, and U Ulbrich, **2004**. The 2003 European summer heatwaves and drought – synoptic diagnosis and impacts. Weather, **59**.

Galbraith RM, J Price and L Shackman, 2005. Scottish Road Network Climate Change Study, Jacobs Scottish Executive, Scotland, 2005 64 pp and 43 pp.

Greenwood RO and JD Orford, **2008**. Temporal patterns and processes of retreat of drumlin coastal cliffs — Strangford Lough, Northern Ireland Geomorphology, 94, 153-169.

Hinkel J. and RJT Klein**, 2009**. Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. Global Environmental Change, 19, 384-395.

IPCC, 2007a. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Solomon S, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller (eds)). Cambridge University Press, Cambridge, UK and New York, NY, USA, 996 pp.

IPCC, 2007b. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK, for Intergovernmental Panel on Climate Change

IPCC, 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, UK.

Jetzkowitz J, 2007. The relationship between tourism and climate from a sustainability science perspective - towards a conceptual framework for research on the future of tourism. In:

Matzarakis A, de Freitas CR, Scott D (eds) Developments in Tourism Climatology, 3rd International Workshop on Climate, Tourism and Recreation, 282–289.

Kafalenos RS et al., 2008. What are the implications of climate change and variability for Gulf coast transportation? In: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I. (Savonis MJ, VR Burkett and JR Potter (eds.). Synthesis and Assessment Product 4.7. U.S. Department of Transportation, Washington, DC, pp. 4-1 to 4F-27 (104 pp)

Karim FM and N Mimura, 2008. Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. Global Environmental Change, 18, 490-500.

Kawagoe S and S Kazama, **2009**. Slope failure risk evaluation due to global warming. Global Environmental Research, 14(2) 143-152.

Kurz WA et al., **2008**. Mountain pine beetle and forest carbon feedback to climate change. Nature 452, 987-990.

Karl TR, Melillo JM and Peterson TC (eds.), **2009**. Global Climate Change Impacts in the United States. Cambridge University Press. www.globalchange.gov/usimpacts

Kunkel KE et al., 2008. Observed changes in weather and climate extremes. In: Weather and Climate Extremes in a Changing Climate: Regions of Focus: North America, Hawaii, Caribbean, and U.S.Pacific Islands. In TR Karl et al (eds): Synthesis and Assessment Product 3.3. U.S. Climate Change Science Program, Washington, DC, pp. 35-80.

Lantuit H and WH Pollard, **2008**. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. Geomorphology, 95, 84–102.

Larsen PH, S Goldsmith, O Smith, ML Wilson, K Strzepek, P Chinowsky and B Saylor, **2008**. Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environmental Change, 18(3), 442-457.

Lawrence DM and AG Slater, **2005.** A projection of severe near-surface permafrost degradation during the 21st century. Geophysical Research Letters, 32, L24401

Le TVH, HN Nguyen, E Wolanski, T C Tran, and S Haruyama, **2007**. The combined impact on the flooding in Vietnam's Mekong River delta of local man-made structures, sea level rise, and dams upstream in the river catchment. Estuarine, Coastal and Shelf Science, 71, 110-116.

Lenton TM, Held H, Kriegler E, Hall JW, Lucht W, Rahmstorf S, and Schellnhuber HJ, **2008**. Tipping elements in the Earth's climate system. Proceedings of the National Academy of Sciences 105 (6): 1786-1793.

Lenton T, A Footitt and A Dlugolecki, **2009.** Major Tipping Points in the Earth's Climate System and Consequences for the Insurance Sector. WWF, Gland, Switzerland and Allianz SE, Munich, Germany.

Lindgren J, DK Jonsson and A Carlsson-Kanyama, **2009**. Climate Adaptation of Railways: Lessons from Sweden. European Journal of Transport and Infrastructure Research (EJTIR), 9 (2), 164-181.

McGranahan G, D Balk and B Anderson, **2007**. The Rising Tide: Assessing the Risks of Climate Change and Human settlements in Low Elevation Coastal Zones. Environment & Urbanization, International Institute for Environment and Development (IIED).Vol 19(1): 17–37. doi: 10.1177/0956247807076960.

McKee Smith J, MA Cialone, TV Wamsley and TO McAlpin, **2010**. Potential impact of sea level rise on coastal surges in southeast Louisiana. Ocean Engineering, 37, 37–47.

Milly PCD, J Betancourt, M Falkenmark, RM Hirsch, ZW Kundzewicz, DP Lettenmaier and RJ Stouffer, **2008.** Stationarity is dead: Whither water management? Science, 319, 573-574.

National Research Council, 2008. Potential Impacts of Climate Change on U.S. Transportation. Transportation Research Board special report 290. Transportation Research Board, Washington, DC, 280 pp.
http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf

Nicholls RJ, PP Wong, VR Burkett, JO Codignotto, JE Hay, RF McLean, S Ragoonaden, and CD Woodroffe, **2007**. Coastal systems and low-lying areas. In: Climate change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change. [Parry M, OF Canziani, JP Palutikof, PJ Van der Linden,and CE Hanson (eds.)]. Cambridge University Press, Cambridge, UK, 315-356.

Nicholls RJ, S Hanson, C Herweijer, N Patmore, S Hallegatte, J Corfee-Morlot, J Château, and R Muir-Wood**, 2008.** Ranking Port Cities With High Exposure And Vulnerability to Climate Extremes: Exposure Estimates. OECD ENV/WKP 2007-1, 62 pp

Nolte R, C Kamburow and J Rupp, **2011**. ARISCC Adaptation of Railway Infrastructure to Climate Change, Final Report, 6th Draft, UIC Project, Berlin, July 2011. 60 pp.

Nott JS, J Smithers, K Walsh and E. Rhodes, **2009**. Sand beach ridges record 6000 year history of extreme tropical cyclone activity in northeastern Australia. Quarternary Science Reviews, 28, 1511–1520.

Pascal M, 2008. Commentary: Our next challenge in heatwave prevention. International Journal of Epidemiology, 37,1365–1366.

Pethick J, **2001.** Coastal management and sea-level rise. Catena, 42, 307-322.

PIANC, 2006. Climate Change and Navigation: Waterborne transport, ports and waterways: A review of climate change drivers, impacts, responses and mitigation, PIANC- EnviCom - Task Group 3, 58 pp.

Post E, MC Forchhammer, MS Bret-Harte, TV Callaghan, TR Christensen, B Elberling, AD Fox, O Gilg, DS Hik, and TT Hoye, **2009.** Ecological Dynamics Across the Arctic Associated with Recent Climate Change, Science, 325, 1355-1358.

Potter JR, VR Burkett, and MJ Savonis, **2008**. Executive summary. In: Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I (Savonis M J, VR Burkett, and JR Potter (eds.)). Synthesis and Assessment Product, U.S. Department of Transportation, Washington, DC, pp ES-1 to ES-10.

Rahmstorf S, **2007**. A semi-empirical approach to projecting future sea-level rise. Science 315, 368-370.

Rahmstorf S, Cazenave A, Church JA, Hansen JE, Keeling RF, Parker DE, and RCJ Somerville, **2007**. Recent climate observations compared to projections. Science 316, 709-709.

Rahmstorf S, 2011. Climate Change-The State of Science. Presentation in UNCTAD Ad Hoc Meeting 'Climate change impacts and adaptation: A challenge for global ports' Geneva 29-30 September 2011.

Reeve DE and H Karunarathna, 2009. On the prediction of long-term morphodynamic response of estuarine systems to sea level rise and human interference. Continental Shelf Research, 29, 938-950.

Richardson K, W Steffen, HJ Schellnhuber, J Alcamo, T Barker, D M Kammen, R Leemans, D Liverman, M Munasinghe, B Osman-Elasha, N Stern and O Ole Wæver., 2009. Synthesis Report. Climate change: Global Risks, Challenges and Decisions. University of Copenhagen, 39 pp. www.climatecongress.ku.dk

RSSB, 2003. Safety implications of weather, climate and climate change. Rail Safety and Standards Board's (RSSB's) Research Programme Engineering. AEAT/RAIR/76148/R03/005 Issue 2 141 pp.

Ruggiero P, PD Komar and JC Allan, **2010**. Increasing wave heights and extreme value projections: The wave climate of the U.S. Pacific Northwest. Coastal Engineering, 57, 539–552

Savonis MJ, Burkett VR, Potter JR, **2008**. Gulf coast study: Phase I - Impacts of climate change and variability on transportation systems and infrastructure, United States Climate Change Science Program.

Shanahan TM et al., **2009**. Atlantic Forcing of Persistent Drought in West Africa. Science 324, 377-382.

Shennan I, T Coulthard, R Flather, B Horton, M Macklin, J Rees, and M Wright, **2003**. Integration of shelf evolution and river basin models to simulate Holocene sediment dynamics of the Humber Estuary during periods of sea-level change and variations in catchment sediment supply. The Science of The Total Environment, 314-316, 737-754.

Sherstyukov AB**, 2009**. Climate Change and Its Impact in the Russian Permafrost Zone. RIHMI-WDC, Obninsk, 127 pp.

Solomon S, Plattner G-K, Knutti R. and P Friedlingstein, 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences 106: 1704-1709.

Scholze M, W Knorr, NW Arnell and IC Prentice, **2006.** A climate-change risk analysis for world ecosystems. Proceedings of the National Academy of Science 103, 13116.

Steffen W, 2009. Climate Change 2009: Faster Change and More Serious Risks. Report to the Department of Climate Change, Australian Government,

Stecker R, Pechan A, Steinhäuser JM, Rotter M, Scholl G, Eisenack K, **2011**. Why are utilities reluctant to adapt to climate change? Report. Oldenburg, Berlin.

Stenek V et al., **2011**. Climate Risk and Business: Ports – Terminal Marítimo Muselles el Bosque Cartagena, Colombia. International Finance Corporation (IFC). Word Bank Group, April 2011. 190 pp.

Stott PA, DA Stone and MR Allen, **2004**. Human contribution to the European heatwave of 2003. Nature, 432, 610–614.

Trenberth KE et al., 2007. Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. (Solomon S, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller (eds.)). Cambridge University Press, Cambridge, UK.

UNCTAD, 2011, Climate change impacts and adaptation: a achallenge for global ports, Information Note by the UNCTSD secretariat, UNCTAD/DTL/TLB/2011/2, Geneva 2011.

UNECE, 2011. Trnasort fr Sustainable Development in the ECE region. UNECE Transport Division, Geneva 2011.

Vafeidis AT, Nicholls RJ, McFadden L, Tol RSJ, Hinkel J, Spencer T, Grashoff PS, Boot G and Klein RJT, 2008. A new global coastal database for impact and vulnerability analysis to sea-level rise. Journal of Coastal Research, 24, 917–924.

Vecchi GA et al., **2006**. Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. Nature 441, 73-76.

Viles HA and AS Goudie, 2003. Interannual, decadal and multidecadal scale climatic variability and geomorphology. Earth-Science Reviews, 61, 105–131.

Vött A**, 2007**. Relative sea level changes and regional tectonic evolution of seven coastal areas in NW Greece since the mid-Holocene. Quaternary Science Reviews, 26, 894-919.

Wang S, R McGrath, J Hanafin, P Lynch, T Semmler and P Nolan, 2008. The impact of climate change on storm surges over Irish waters. Ocean Modelling, 25, 83–94.

Wamsley TV, MA Cialone, JM Smith, JH Atkinson and JD Rosati, **2010**. The potential of wetlands in reducing storm surge. Ocean Engineering, 37, 59-68.

Webster PJ, GJ Holland, JA Curry and H-R Chang, **2005.** Changes in tropical cyclone number, duration, and intensity in a warming environment. Science, 309, 1844-1849.

Wu Qingbai, Cheng Guodong, Ma Wei, Liu Yongzhi, **2008**. Railway Construction Techniques Adapting to Climate Warming in Permafrost Regions, State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, China.

Zimov SA, EAG Schuur and FS Chapin, **2006**. Permafrost and the Global Carbon Budget. Science, 312, 1612-1618.

ANNEX

Select additional literature of relevance to the further study of climate change impacts on international transport networks

Andrey, J. and B.N. Mills, 2003: *Chapter 9: Climate Change and the Canadian Transportation System: Vulnerabilities and Adaptations*. In: *Weather and Transportation in Canada* [Andrey, J. and C. Knapper (Eds.)], Department of Geography, University of Waterloo, Ontario, Canada.

Arkell, B. P., and G. J. C. Darch, 2006: *Impact of climate change on London's transport network.* In: Proceedings of the Institution of Civil Engineers, Municipal Engineer 159, December 2006 Issue ME4, Pages 231–237, 2006.

Asian Development Bank (ADB), (Ed.), 2010: *SOL: Transport Sector Development Project.* Climate Change Adaptation Measures, Project Number: 41171-02, November 2010.

Becker, A., M. Fischer, M. Caldwell, and B. Schwegler, 2009: *Impacts of climate change on seaports: A survey of knowledge, perceptions, and planning efforts among port administrators*. In: Proceedings of Coastal Zone 09, Boston, Massachusetts, July 19 to 23, 2009.

Cambridge Systematics, Inc., 2009: *Transportation Adaptation to Global Climate Change (White Paper).* Published by Bipartisan Policy Center, Washington D.C. and Cambridge Systematics Inc., Cambridge Massachusetts, 2009.

Cochran, I., 2009: *Climate Change Vulnerabilities and Adaptation Possibilities for Transport Infrastructures in France*. Climate Report, Issue No. 18, September 2009.

Dewar, J. A., and M. Wachs, 2008: *Transportation planning, climate change and decision making under uncertainty*, TRB, Washington D.C, 2008 TRB Special Report 290.

Frans A.J. Van Den Bosch, F.A.J., R. Hollen, H.W. Volberda, M.G. Baaij, 2011.*The strategic value of the Port of Rotterdam for the international competitiveness of the Netherlands: A first Exploration.* Research Report for the Port of Rotterdam Authority, Rotterdam.

ICF International, 2008: *Planning for Climate Change Impacts at U.S. Ports*. White Paper. Prepared for the U.S. Environmental Protection Agency. July 2008.

ICF International, 2007: *The Potential Impacts of Global Sea Level Rise on Transportation Infrastructure. Phase 1 - Final Report: The district of Columbia, Maryland, North Carolina and Virginia*. Phase 2 - New York, New Jersey, Pennsylvania, Delaware, South Carolina, Georgia, Atlantic Coast of Florida.

Lindquist, E., 2010: *Climate Change/Variability Science and Adaptive Strategies for State and Regional Transportation Decision Making*. Report No. SWUTC/10/167165-1, April 2010.

Lindquist, E., 2007: *Climate Change and Adaptive Strategies in Sub-national Transportation Planning Agencies in the United States*. Presented at the 2007 Amsterdam Conference on the Human Dimensions of Global Environmental Change “Earth System Governance: Theories and Strategies for Sustainability”, Vrije Universiteit, Amsterdam, 2007.

Liu, M., Ashok K. Pandey and Jacob Kronbak, 2009: *New Era in Arctic Shipping?* International Association of Maritime Economists Annual Conference. Copenhagen, 24-26 June, 2009.

Love, G., Alice Soares, and Herbert Püempel, 2010: *Climate Change, Climate Variability and Transportation (Draft White Paper)*.World Climate Conference-3, World Meteorological Organization (WMO), Geneva, Switzerland. In: Procedia Environmental Sciences, Volume 1, 2010, Pages 130-145.

Meyer, M. D., 2008: *Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change*.Transportation Research Board, Washington, D.C.

Moe, A., and Øystein Jensen, 2010: *Opening of New Arctic Shipping Routes: Standard Briefing*. Briefing prepared for the European Parliament, Directorate-General for External Policies, Directorate B, Policy Department, 31 August 2010. EXPO/B/AFET/FWC/2009-01/Lot 2/03. PE 433.792.

Millerd, F., 2005: *The Economic Impact of Climate Change on Canadian Commercial Navigation on the Great Lakes.* Canadian Water Resources Journal, Vol. 30, No.4, Pages 269–80.

National Research Council of the National Academics, 2008: *Potential Impacts of Climate Change on U.S. Transportation*. Committee on Climate and U.S. Transportation, Transportation Research Board Special Report 290, March 2008.

National Research Council of the National Academics, 2008: *Potential Impacts of Climate Change on U.S. Transportation, Report Summary*. Committee on Climate and U.S. Transportation, Transportation Research Board Special Report 290, March 2008.

Parkman, M., 2008: *Assessing the impact of climate change on transport infrastructure, Rail Safety and Standards Board*. Produced for Rail Safety and Standards Board, 2008.

Peterson, T. C., M. McGuirk, T. Houston, A. Horvitz and M. Wehner, 2008: *Climate Variability and Change with Implications for Transportation*. American Meteorological Society Seminar on Adaptation to Climate Change, April 2008.

PIANC – EnviCom, 2009: *Sustainable Waterways Within The Context of Navigation and Flood Management.*

Regmi, M.B.; Hanaoka, S., 2009: *Impacts of Climate Change on Transport and Adaptation in Asia*. Proceedings of the Eastern Asia Society for Transportation Studies, Vol. 7, 2009.

Schmidt, N., 2008: *Climate Change and Transportation: Challenges and Opportunities*. MS.C. Thesis, School of Civil Engineering, Georgia Institute of Technology, August 2008.

Schmidt, N. and M. Meyer, 2008: *Incorporating Climate Change into Transportation Planning.* Journal of the Transportation Research Board 2119, Washington D.C: National Academy Press, 2009.

Seaports and Climate Change - An Analysis of Adaptation Measures, 2010. Study commissioned by the International Association of Ports and Harbors (IAPH) - Port Planning and Development Committee. Unpublished Draft, November 2010.

State of California, Dept. of Transportation, 2008: *Climate Change Adaptation and Transportation System.*
In: Climate Change Adaptation Strategy (CAS) Infrastructure Sector – Public Meeting 12/05/08.

Sustainable Development Research Network (SDRN), 2008: *Developing a Transport Strategy for Climate Change Adaptation: Workshop Report.* SDRN/DfT Event Report, 7th December 2007, Church House Conference Centre. Published 21 January 2008.

Taylor, M. A. P., and M. Philp, 2010: *Adapting to climate change – implications for transport infrastructure, transport systems and travel behaviour.* Presented at the 33rd Australasian Transport Research Forum held in Canberra, October 2010. Published in: Road & Transport Research Journal, Vol.19, No.4, December 2010.

Total Environment Centre Inc., *Freight Transport and Climate Change, Exposure and Opportunities*. Industry Partnership Program, July 2008.

United Kingdom (U.K.), Dept. for Transport, 2010: *Building Resilience to Climate Change: An Adaptation Plan for Transport 2010-2012.*
DfT Publications, March 2010

URS Corporation Ltd. (URS), 2010: *Adapting Energy, Transport and Water Infrastructure to the Long-term Impacts of Climate Change (Full Report).* Ref. No RMP/5456, January 2010.

URS Corporation Ltd. (URS), 2010: *Adapting Energy, Transport and Water Infrastructure to the Long-term Impacts of Climate Change (Summary Report).*Ref. No RMP/5456, January 2010.

United States (U.S.), Dept. of Transport, Federal Highway Administration (FHWA), 2008: *Adaptation of Transportation Infrastructure to Global Climate Change (GCC) Effects: Implications for Design and Implementation, Adaptation* (White Paper). Appendix to Summary Report: Peer Workshop on Adaptation to Climate Change Impacts, December 2008, Washington D.C.

United States (U.S.), Dept. of Transportation, Center for Climate Change and Environmental Forecasting: Potter, J. R., 2002: *The Potential Impacts of Climate Change on Transportation: Workshop Summary*.In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Select Discussion Papers:

Burkett, V.R., 2002: *Potential Impacts Of Climate Change And Variability On Transportation in the Gulf Coast/Mississippi Delta Region*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Caldwell, H., K.H. Quinn, J. Meunier, J. Suhrbier, and L. Grenzeback, 2002: *Potential Impacts Of Climate Change On Freight Transport.* In: The Potential Impacts of Climate Change on

Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

duVair, P., D. Wickizer, and M. J. Burer, 2002: *Climate Change and the Potential Implications for California's Transportation System*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Easterling, D.R., 2002: *Observed Climate Change And Transportation*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Kulesa, G., 2002: *Weather and Aviation: How Does Weather Affect the Safety and Operations of Airports and Aviation, and How Does FAA Work to Manage Weather-related Effects?* In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

MacCracken, M.C., 2002: *National Assessment of the Consequences of Climate Variability and Change for the United States*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Mills, B., and J. Andrey, 2002: *Climate Change and Transportation: Potential Interactions and Impacts*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Pisano, P., L. Goodwin, and A. Stern, 2002: *Surface Transportation Safety and Operations: The Impacts of Weather within the Context of Climate Change*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Quinn, F. H., 2002: *The Potential Impacts of Climate Change on Great Lakes Transportation*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Rossetti, M.A., 2002: *Potential Impacts of Climate Change On Railroads.* In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Smith, O. P., and G. Levasseur, 2002: *Impacts of Climate Change on Transportation Infrastructure in Alaska*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Titus, J., 2002: *Does Sea Level Rise Matter To Transportation Along The Atlantic Coast?* In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Trilling, D. R., 2002: *Notes on Transportation into the Year 2025*. In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.

Vidal, J. H., 2010: *Environmental sustainability and climate change effects: an investigation into ports' response and readiness*. A dissertation submitted in partial fulfilment of the Degree of MSc. in Maritime Operations and Management, School of Engineering and Mathematical Science, City University, London, June 2010.

Wilson, K.J., Falkingham, J., Melling, H., De Abreau, R., 2004: *Shipping in the Canadian Arctic, Other Possible Climate Change Scenarios.* Proc. International Geoscience and Remote Sensing Symposium (IGARSS), Anchorage, Alaska, USA.

Zimmerman, R., 2002: *Global Climate Change and Transportation Infrastructure: Lessons from the New York Area.* In: The Potential Impacts of Climate Change on Transportation, Federal Research Partnership Workshop, October 1-2, 2002. Center for Climate Change and Environmental Forecasting, U.S. Department of Transportation, Washington, D.C.