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Climate Change, Climate Variability and Transportation

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Abstract

The contribution of the transport systems, including road, air and sea, are making to climate change through the emission of greenhouse (GHG) gases, and new technologies and programmes of action to mitigate their impact on climate is reviewed. The actitivites of the transport systems in most countries are sensitive to a range of weather extremes, including those related to precipitation, thunderstorms, temperature, winds, visibility and sea level. The impact of climate, climate variability and climate change, in particular the impact of these extremes on transport systems and adaptation measures are discussed. This paper also discusses the foundation of climate services to assist informed decision-making for climate change adaptation, planning and designing, which require close collaboration among a wide range of disciplines and the engagement of the users such as the transport systems' communities.

Keywords: Transport, climate change, impact, adaptation, services

1. Introduction

This paper reviews the interaction between transport and climate. While designing, implementing and operating any transport system requires that it be sustainable in the face of the known climate, the reality of human-induced climate change requires that equal consideration be given to the impact of the transport system on the climate as well as the policy environment that the system will be operated in, throughout its lifetime. Hence, this paper considers the interaction between climate and transport with a particular focus on future trends and how meteorological services, that is, weather and climate services, can best be developed and used to support efficient and effective transportation systems.

In Section 2 of the paper the focus is on the relative and absolute contribution transport systems are making to climate change. Included in this discussion is a very brief review of options for mitigating the impact of transportation systems on climate, but as the focus of this paper is not climate change per se, this material is only included to give a sense of the options and to point to those areas where meteorological services can assist in emissions mitigation.

In Section 3 there is a more detailed discussion on the impact of climate, climate variability and climate change on transportation systems and the adaptation measures than can and should be taken to best accommodate the climate change currently expected as a result of human-related greenhouse gas (GHG) emissions.

2. Transportation: contribution to climate change

The transport sector was estimated to contribute approximately 14 per cent of the total greenhouse gas emissions in 2004 (Table 1). Such emissions include not only CO_2 but also CH_4, N_2O and fugitive gases from refrigerated systems used in transportation such as CFC-12 and CFC-134a. The Intergovernmental Panel on Climate Change (IPCC), in Chapter 7 of its Working Group III Report [1], notes that in 2004 transport energy use amounted to about 26 per cent of world energy use, a figure that possibly overstates the contribution of the transport sector to the human-induced release of greenhouse gases; nevertheless, as a sector, transport is the third largest contributor to greenhouse gas releases.

The projection of energy usage by mode of transport [1] shows that light duty vehicles (essentially the private use of motor cars) is the sector with the highest energy usage, followed by freight trucks and air transport (Figure 1). The forecasts underlying these curves assume that world oil supplies will be sufficient to meet the increasing demand for petroleum-based fuels for transport and that the global economy will continue to grow.

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Table 1. Greenhouse gas emission contribution by sector in 2004

SECTOR	*CO_2 EQ Mt*	*% of Total*
Buildings	13 215	27.0
Industry	13 893	28.3
Transport	6 829	14.0
Agriculture	6 100	12.4
Deforestation	5 800	11.8
Waste	1 300	2.7
Other forest	1 862	3.8
TOTAL	49 000	100.0

Source: Rynn, 2009 – extracted from the IPCC Fourth Assessment Report.

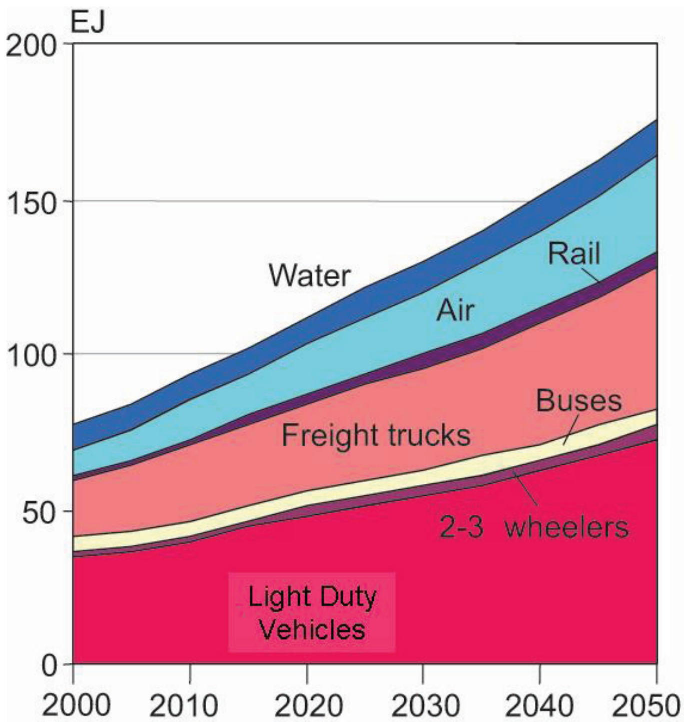

Figure 1. Projected energy usage, by transport sector, in ExaJoules (10**18 Joule) (Source: IPCC, [1]; derived from data provided by the World Business Council for Sustainable Development)

In 2004 the transport sector produced 6 200 Mt of CO_2 [1] or 6 800 Mt CO_2 Equivalent (Table 1). At that time the share of the non-Organization for Economic Co-operation and Development (OECD) countries was estimated to be 36 per cent; this share is expected to grow to 46 per cent by 2030. While the technologies used in motor vehicles continue to improve in greenhouse gas emission efficiency, the increasing weight and power of vehicles that comprise the global fleet counter-balances these increases in efficiency, and, at the same time, the world auto fleet continues to grow in number, particularly in the developing world.

There are a range of measures and technologies available to reduce the emissions from the road transport sector. Lighter vehicles, lower average speeds, the use of more efficient engines and the use of less greenhouse-intensive fuels (for example, natural gas in place of oil-based fuels) could all play a role. None of these requires a meteorological input, however, and so they are not discussed in this paper.

2.1 The aviation sector

Aircraft contribute to climate change in two principal ways – through the emission of greenhouse gases such as CO_2, NO_x and radiatively significant particles such as soot, and through the generation of contrails which in turn may have an impact on the global heat balance. The International Civil Aviation Organization (ICAO) has created a Group on International Aviation and Climate Change, mandated by the Assembly of ICAO in 2007 to pursue a globally harmonized framework for tackling greenhouse gas emissions from international aviation through an ICAO Programme of Action on International Aviation and Climate Change.

2.1.1 Emission of greenhouse gases and soot

The rate of emission of greenhouse gases and soot is directly proportional to the rate of fuel burn. The aviation industry is an extremely competitive one, and with fuel costs amounting for approximately 20 per cent of total costs, every effort is made to minimize the fuel burn per passenger mile flown. From the airline operator perspective, in the long run more efficient engines are a part of the solution and innovation is constantly occurring in this area. In the shorter term improved weather forecasts, provided in conjunction with improved air traffic management, also offer opportunities to reduce fuel burn. The benefits can flow from a number of areas. Improved destination terminal forecasts lead to lower amounts of fuel being carried and, all things being equal a lighter aircraft burns less fuel than a heavy one. Improved en route wind forecasts provide an opportunity for airline to maximize their tailwind components through the choice of track and flight level. Improved air traffic management can reduce aircraft taxiing and in-flight holding times.

Publicly available studies of the economic benefits of improved en route wind and destination terminal forecasts are not plentiful because such information is usually held as commercial-in-confidence and possibly also because airlines fear that highlighting the benefits of improved forecasts, which are invariably developed at taxpayers' expense, would lead to higher government charges. Nevertheless, some information exists as to the benefits of improved en route forecasts. Emirates Airline, in the five years it has been operating services to Australia (2003–2008) estimates that it has saved 9.6 million litres of fuel and cut flight times by 772 hours. Emirates further estimates that it has reduced CO_2 emissions by 26 644 tonnes and NO_x emissions by 163 tonnes through the implementation of its "Flex Track" system of accessing updated forecasts en route and modifying its flight plans to minimize headwind components and/or maximize tailwind components. There have also been estimates of the economic impact of improved terminal forecasts. Keith and Leighton [2] show that moving from the traditional categorical terminal forecast to one based on probabilities using the latest observations, resulted in average savings of around US$ 23 000 (2003) per flight at a typical United States airport as a result of reductions in the amount of fuel that the flights were required to carry.

2.1.2 Generation of contrails

Contrails form when water vapour in the exhaust from jet engines freezes high in the troposphere where airliners cruise (Figure 2). Because contrail ice crystals are efficient absorbers of long-wave radiation for the time that they persist, they have a greater greenhouse effect than the carbon dioxide gas also produced by jet engines; the CO_2, however, may persist for 75 to 100 years.

Measuring contrails' impact is not an exact science. Depending on an aeroplane's altitude, and the temperature and humidity of the atmosphere, contrails can vary enormously in their thickness and duration, and therefore in their reflecting or insulating power. Most contrails last minutes or hours. During the day, persistent contrails trap slightly more heat than they reflect back into space, and at night they continue to trap heat. In areas with dense air traffic, such as Europe and North America, contrails could be warming the atmosphere by up to 0.1°C [3].

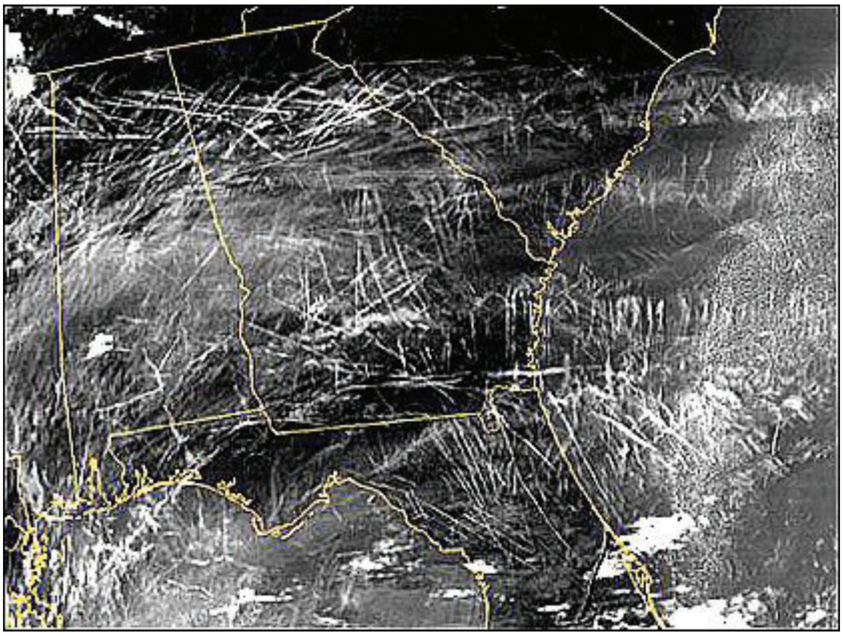

Figure 2. Contrails over the United States (Source: Federation of American Scientists) http://www.fas.org/irp/imint/docs/rst/Sect14/contrails_southeast.jpg)

Although warming by contrails is minor – about one seventy-fifth that of man-made CO_2 – the forecast for passenger air traffic is an increase of about 5 per cent to the year 2020 and for air freight traffic of about 6 per cent per year. Figure 3 shows the projected increase in air traffic over Europe over the 23-year period 1997–2010.

Myhre and Stordal [4] have combined satellite images with data on journey length and fuel consumption of air traffic. Comparing this with models of how contrails scatter light, they estimated how much heat contrails trap or reflect. Like others before them, they found a net warming effect; however, taking into account previous measurements of the reflecting properties of ice crystals in icy cirrus clouds, they also found that when light hits contrails at low angles, as occurs at dawn and dusk, the contrails reflect light, causing a cooling effect. Although cleaner burning, next-generation jet engines may lead to lower greenhouse gas emissions per passenger mile, the aircraft using these engines are expected cruise at higher altitudes and to make more contrails than current generation aircraft.

Contrails present a scientific challenge in that their contribution to climate change has not been quantified. Flying at lower levels, with an increase in fuel burn, could reduce their incidence – as could avoiding those relatively shallow layers of the atmosphere that were reasonably expected to contain supersaturated ice. At the present, research should possibly have a two-pronged approach; more work needs to be done on modelling the impact of contrails on climate while in parallel more work needs to be done on detecting and forecasting those layers where aircraft activity is highly likely to lead to contrail formation.

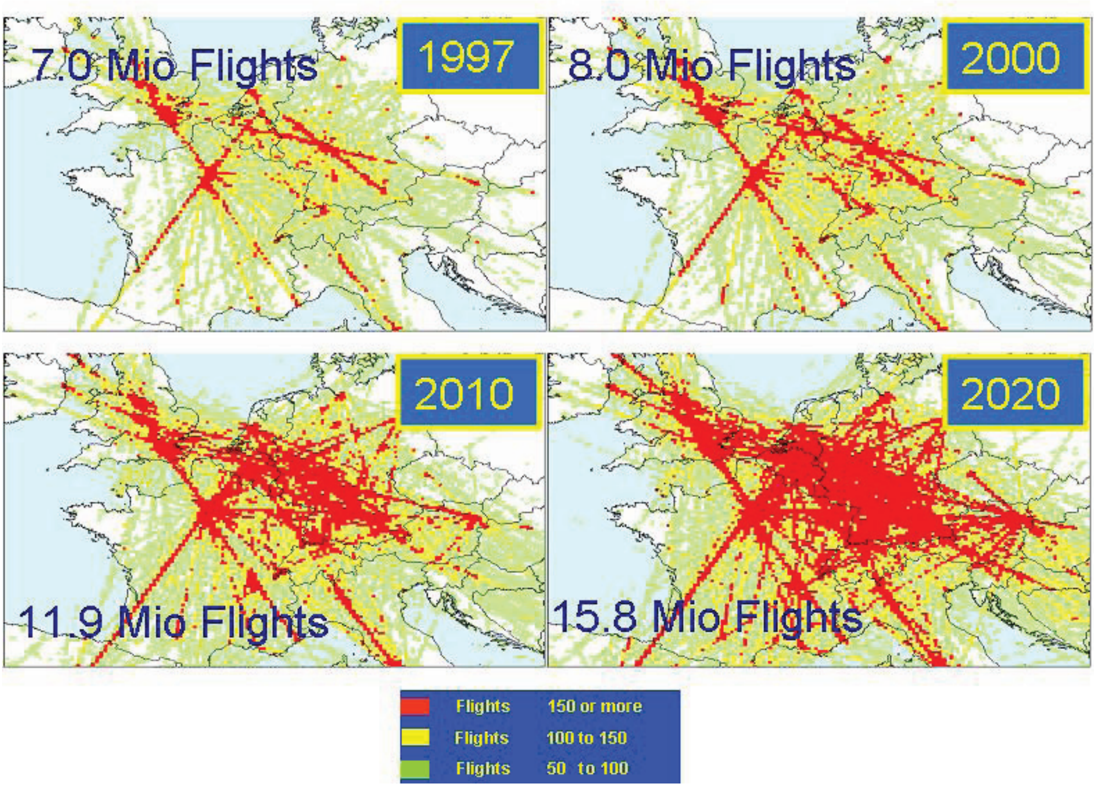

Figure 3. Projected changes in flight density over Europe between 1997 and 2010 (Source: EUROCONTROL Division DED4 , Based on STATFOR 97)

2.2 Shipping

International shipping in 2007 accounted for about 2.7 per cent (870 million tonnes) of the global manmade CO_2 emissions, and mid-range emission scenarios suggest that by 2050, in the absence of reduction policies, ship emissions may grow 150–250 per cent (compared to 2007 emissions) as a result of growth in world trade [5]. Using the parameter of tonnes of CO_2 emitted per ship-tonne nautical mile indicates that shipping is the most efficient way to move goods if that form of transport is an option. Nevertheless, the industry, through the activities of the International Maritime Organization (IMO), is exploring ways to reduce greenhouse gas emissions. The International Maritime Organization has established an action plan to address GHG emissions from international shipping and is now working towards a robust regime that will regulate shipping at the global level to ensure that GHG emissions from international shipping are reduced or limited.

The IMO GHG Study [5] concludes that there is a significant potential for reduction of GHG through technical and operational measures. The mitigation measures available are essentially two-fold: reducing the speed at which ships travel (slow steaming) and implementing new technologies into ship and engine design that make their overall operations more greenhouse gas efficient. Together, if all measures are implemented, they could, by 2050, increase efficiency and reduce the emissions rate very considerably below the current levels on a tonne per mile basis. In this context, the IMO Marine Environment Protection Committee adopted in July 2009 a package of technical and operational measures providing for an Energy Efficient Design Index for new ships, a Ship Energy Management Plan for new and existing ships and an Energy Efficient Operational Indicator for existing ships.

2.2.1 Slow steaming

A business case for slow steaming for a vessel taking either 24 days or 25.5 days between Curaçao and Hamburg shows that for a 5 per cent speed reduction there is about a 9 per cent increase in fuel efficiency [6]. The example notes that in 2006 the charter rate for the Aframax-class vessel was about US$ 30 000 per day (or US$ 45 000 per day-and-a-half) and the 80 000 tonnes of cargo valued at US$ 400 per tonne would need to be financed at a rate of 8 per cent, leading to an additional cost of about US$ 10 000 for the additional day-and-a-half travel time. So, for a 9 per cent reduction in greenhouse gas emissions the ship charterer would face additional costs of about US$ 55 000 less 9 per cent of the overall fuel bill. Many of the costs in the shipping industry are highly volatile. Freight rates can increase and decrease by 400 per cent within a year. For example, the August 2009 rate for an Aframax tanker has plummeted to about US$ 10 000 per day. Fuel prices are highly volatile, interest rates are variable, as are insurance fees. Under different assumptions, slow steaming may be cost-effective and under yet other assumptions, the same tanker would require a much larger financial incentive to make up for the opportunity costs of fast steaming.

2.2.2 New technologies

Approximately 86 per cent of shipping is driven by diesel engines that have a 30- to 40-year lifetime and so the rate at which greater engine efficiency could be deployed is relatively slow. Options include the greater use of liquefied natural gas, which would have the co-benefit of reduced emissions of NO_x and SO_x that occur from current marine fuels. The longer-term options include a mixture of large sails in combination with existing diesel engines, in which case the industry would have an increased reliance on meteorological information for planning and carrying out routine voyages.

3. Transportation: impacts of extremes

In the previous section we briefly considered the contributions road, air and sea transport make to climate change by way of release of greenhouse gases and to a lesser extent by changing the Earth's reflectivity to incoming sunlight. In this section the focus is on the long-run impact of a warming world on the same transport systems: road, air and sea. It is clear that there are significant differences in these systems across the globe and that climate change impacts will also differ among regions. These regional differences in climate change and transport infrastructure make it impossible to generalize as to the impacts of climate change on road, air and sea systems, and restrict the discussion to a regional focus.

The other aspect of climate change impacts upon transportation and transportation infrastructure is the nature of climate itself. Climate change does not occur through the steady change of temperature which is then reflected into a steady change in other atmospheric and ecosystem variables. Rather, measured at any one location, or averaged daily over the whole globe, temperature moves up and down in response to all sorts of weather system changes (Figure 4). If we anticipate that transport systems are adversely affected by temperature or wind or rain above some threshold X_c, then as the long-term average value of that parameter rises over time the deviation from the average necessary to reach X_c becomes progressively smaller and the likelihood of the destructive impact being observed increases.

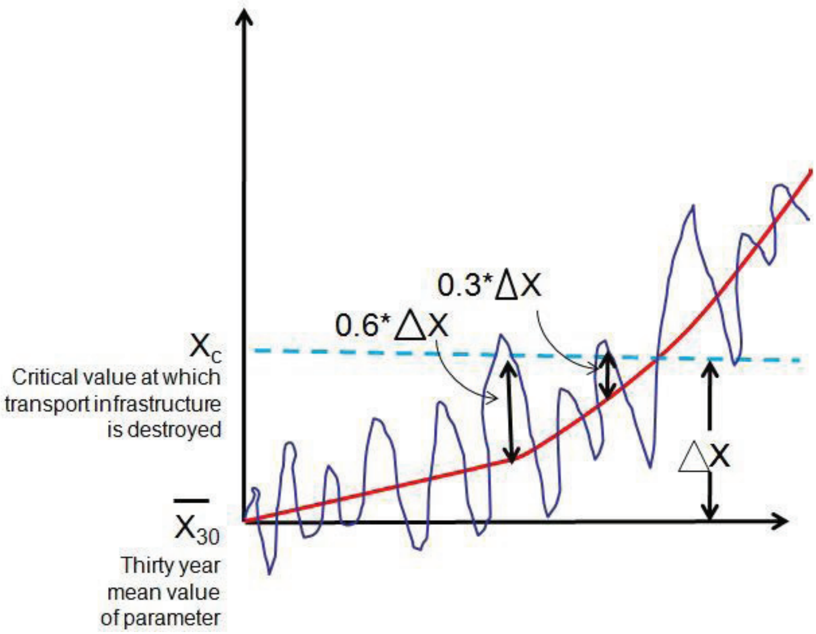

Figure 4. Schematic showing the varying nature of atmospheric parameters over time when superimposed on a slowly increasing mean value

Moving the long-term mean of a variable such as temperature can change substantially the likelihood of extreme temperature events. This is demonstrated schematically in Figure 5. Figure 5 (a) indicates the likelihood (or probability) of an extreme event exceeding some specified temperature (say, 32^{o}C) for a given statistical sample of such events. The likelihood is represented by the shaded area under the curve at the tails of the distribution, shaded red and blue in Figure 5 (a). A shift in the mean of the temperature distribution with an increase brought about by global warming increases significantly the area under the curve for days above 32^{o}C, as shown in Figure 5 (b).

Most measurements of temperature (top of Figure 5 graphs) will tend to fall within a range close to average, so their probability of occurrence is high. A very few measurements will be considered extreme and these occur very infrequently (Figure 5 [a]). A relatively small shift in the mean produces a larger change in the number of extremes for both temperature (Figure 5 [b]) and precipitation (not shown).

For transport and transport infrastructure, the fact that temperature is not slowly varying, but rather moving up and down around a long-term mean, leads to the conclusion that the first impacts of climate change are felt through extreme events. Transport system planners and implementers therefore need to allow for these changes in the extreme event climatologies. For example, if railway tracks are laid such that they can withstand a temperature up to 22^{o}C (40^{o}F) above the long-term average temperature before the tracks buckle, as they are in the United States of America, [8], then the rise in the long-term mean of 1^oC will change significantly the likelihood of exceeding this 22^oC limit.

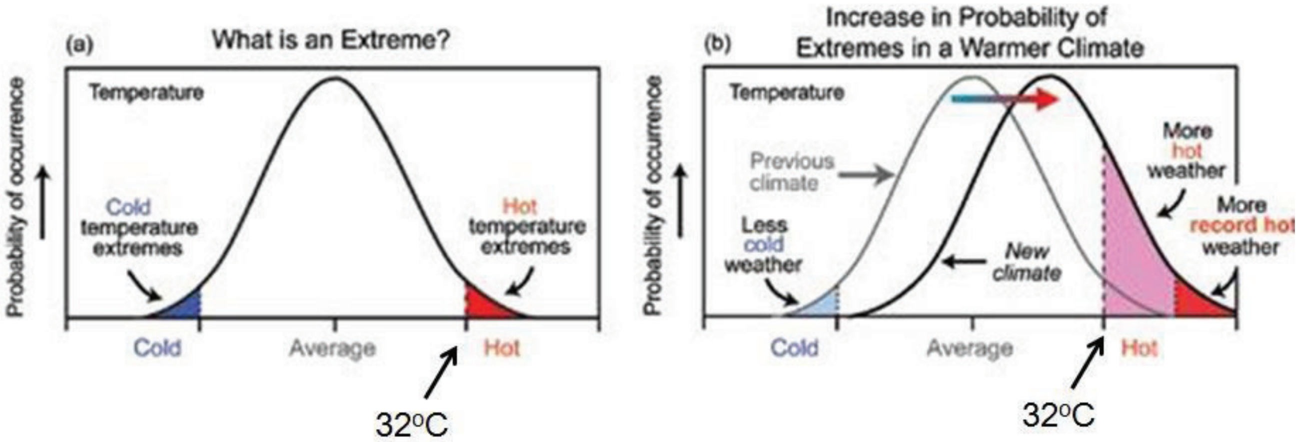

Figure 5. Probabilities of extreme temperatures (Source: CCSP [7])

The day-to-day activities of transportation systems in most countries are sensitive to a range of weather extremes including those related to precipitation, thunderstorms, temperature, winds, visibility and sea level (Table 2).

Table 2. Weather parameters that give rise to disruption to transportation services and infrastructure

Weather parameters	*Category*	*Impacts*
Precipitation Elements	Freezing precipitation, snow accumulation, liquid precipitation, precipitable water vapour, soil moisture, flooding, inland waterways and water body depths, fire weather	Loss of traction and control; delays; reduced speeds; stresses on vehicle components and tires; rules on tire chains; wet pavement; road spray; flooding causing road and airport closures; rerouting; weak and uneven braking; intermodal impacts; softened railroad beds; roadbed scouring Drought causing risk of dust and smoke reducing visibility; highway closures; increased forest fires with smoke and flames causing road closures; intermodal impacts from barge shutdowns due to low river levels
Thunderstorm Related	Severe storm cell tracks, lightning, hail	Acute, rapidly changing conditions with multiple risks of collisions and damage from loss of control; impaired visibility; rock slides causing risk of collisions and delays; damage to infrastructure; blocked railroads
Temperature Related	Air temperature including maximum and minimum, first occurrence of season, heat index, cooling or heating degree days	Stresses on vehicle components and infrastructure, and at high temperature, perishable cargoes, rail buckling (sun kinks), reduced speeds on rails; new surface and air routes in northern regions, including road transportation in non-permafrost regions (possible reductions in the costs of snow and ice control; safer travel conditions); less lift due to high temperatures affecting take-offs and landings at airports
Winds	Wind speed, upper air winds	Instability, loss of control, blowovers; re-routing; damage to vessels and aircraft
Visibility	Restrictions from fog, haze, dust, smog and sun glare, upper atmosphere restrictions from volcanic and desert dust	Delays; re-routing; airport closures; reduced speed; risk of collisions and damage from rapid change
Sea Level Related	Tropical cyclone including tracks and elements affecting evacuation routes, open water sea ice Sea level rise, high surf, storm surge, abnormal high or low tides, freezing spray, hurricane winds, sea state, coastal flooding, coastal erosion and loss of beaches, wind wave height, swell wave height	Supply chain disruptions; road, port and airport (located in coastal and low-lying areas) closures; extensive damage to infrastructure and vehicles; obstructions; blocked rails; sea-level rise causing extreme water levels and coastal flooding during storms; coastal erosion and beach degradation; closure and scouring during storms; risk and damage to infrastructure; changes in coastlines affecting life cycle of road, rail, port, bridge and airport (located in coastal and low-lying areas); changes in agricultural and manufacturing production and shipments; disruption of supply chains; opening of the Northern Sea Route for international shipping

Adapted by the authors from Peterson et al. [8]; McGuirk et al.[9]

3.1 Extremes in precipitation

Unusually heavy rainfall can have a major impact on road transportation. The reduction in traction leads to increases in vehicle collisions and casualties. Andrey et al. [10] show that the relative risk of collisions increases for every type of precipitation event in Canada while Andrey [11] shows that collision rates for those precipitation events not involving snowfall are generally decreasing. McGuirk et al. [9] note that heavy rains also lead to road and railway flooding and mudslides that can further disrupt transportation systems. (See Figure 6.)

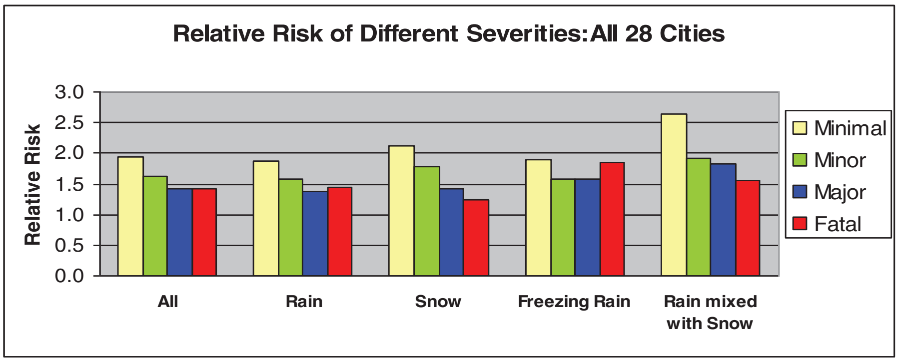

Figure 6. Aggregate risk of motor vehicle collision injury in 28 Canadian cities during various types of precipitation relative to comparable periods without precipitation (1984-2000) (After Andrey et al. [10])

The Climate Change Science Program (2008) notes that over most of North America heavy rainfall has increased in frequency and intensity in recent decades. For example, the heaviest 1 per cent of daily precipitation totals over the continental United States have increased by 20 per cent over the past century while precipitation has increased by 7 per cent. Furthermore, they show that modelling of the IPCC Special Report on Emissions Scenarios (SRES) climate change scenarios indicates that with increasing greenhouse gas concentrations the amount of precipitation that falls in the heaviest 5 per cent of rainfall events can be expected to continue to increase (Figure 7).

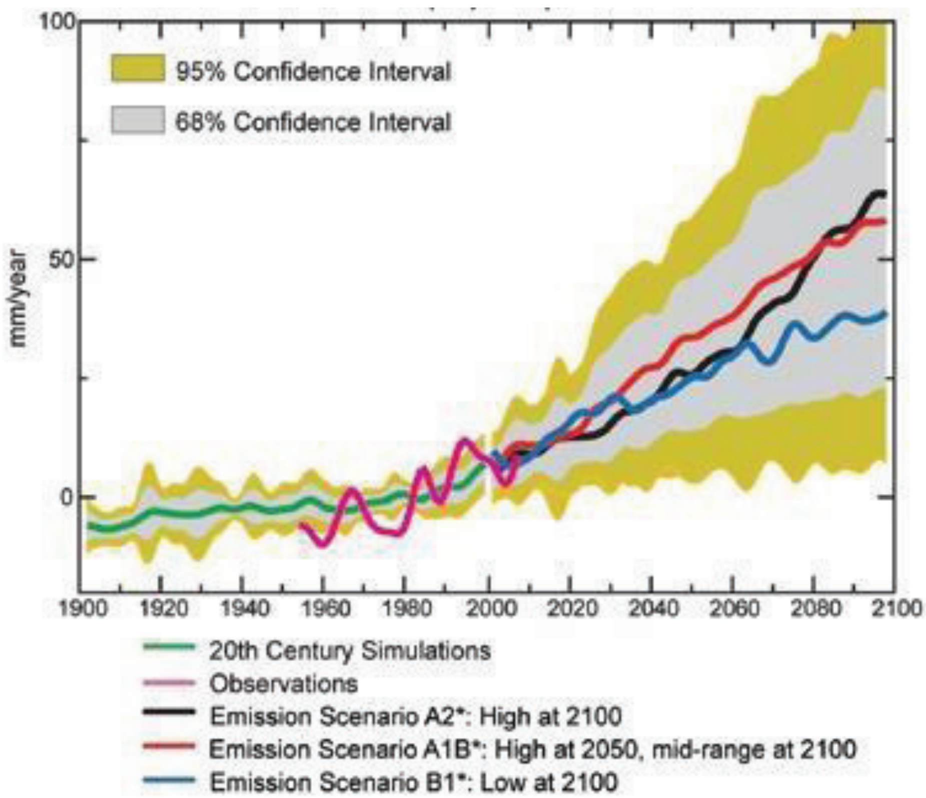

Figure 7. Increase in the amount of daily precipitation over North America that falls in heavy events (the top 5 per cent of all precipitation events in a year) compared to the 1961-1990 average (After CCSP [7])
*Various emission scenarios are used for future projections. Data for this index at the continental scale are available only since 1950.

In China over the past fifty years there has been an increase in the number of days with heavy rain in the Yangtze River Basin, in the North China Plain and in southern north-east China, while no significant change in the extreme precipitation events has been detected for the country as a whole [12]. With the increased heavy rainfall events over the low rainfall North China Plain and southern north-east China, there has been a trend towards decreasing incidence of dust storms (Figure 8).

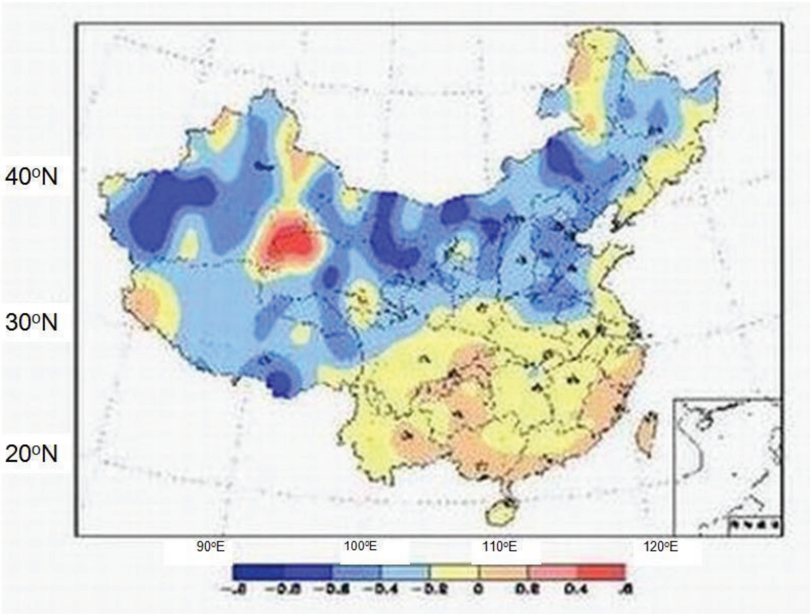

Figure 8. Tendency of days with duststorms in China 1960-2000 (After Ren et al.[12]).
Blue: positive trend; yellow: negative trend.

3.2 Extremes in temperature

Assessing the risk of long periods of hot weather (heatwaves) is an important task of National Meteorological and Hydrological Services (NMHSs) and community leaders in countries subject to sub-tropical and mid-latitude climates. The impact of extreme heat on both above ground and underground rail systems is quite severe. Underground railway systems heat up over time. Initially when the rail tunnels are constructed, the air temperature in the tunnels is equal to that of the surrounding soil – generally about 14°C.

As trains operate, heat from their engines, their braking systems and the people in the trains leads to a slow warming. Over a period of thirty years or so the background temperature within the underground rail system can rise 10°C or 15°C if there is inadequate ventilation. Underground rail systems rely on the "piston effect" to draw fresh air into the tunnels. Essentially ventilation shafts connect the tunnels to the surface, and when a train moves through a tunnel it pushes air ahead of it (much like a piston) and behind the train is a partial vacuum into which air is drawn down the ventilation shaft. If the air coming down the shaft has an ambient temperature of about 32°C to 35°C the underground system can rapidly heat up to extreme levels threatening the health of those that use the system.

The London Underground is known to have inadequate ventilation and, according to the Greater London Authority [13] "On stations such as King's Cross, Waterloo, Victoria and Oxford Circus, the temperature can be 11°C above ambient temperature above ground. In some instances recorded temperatures have reached 40°C."

With the increasing frequency of hot days underground rail systems will require substantial investment in improved ventilation and air conditioning on-board trains. In addition, higher efficiency engine systems (less heat loss, more energy converted to kinetic energy of the train) will be required along with regenerative breaking rather than friction-based breaking. With these investments in upgraded technology the systems will be better placed to cope with a warmer world

The threat to above ground rail systems is no less severe than those underground. During the record breaking European heatwave of 2003 (see Schär et al.,[14]), the heat caused substantial problems on the British above ground rail system. Progressive speed restrictions were applied by Network Rail at air temperatures of 36°C, and at lower temperatures where the rail and track were considered to be in anything less than ideal condition. There were 165 000 delay minutes nationally (compared with just 30 000 in the cooler summer of 2004). The number of buckled rails (approximately 130) was also high and consistent with earlier hot years (1976 and 1995). The economic cost of the delays to British Rail in four of the railway sectors around London in 2003 was at least £750 000 [13].

A similar situation has been reported more recently in Australia, with up to 200 train cancellations per day in the summer of 2009 as extreme heat led to buckling of lines throughout the above ground rail network. Clearly rail infrastructure faces some major challenges globally if these two examples are representative of the issues more generally.

3.3 Extremes in sea level

Although coastal inundation by global sea-level rise will be a problem for unprotected transportation infrastructure in low-lying areas, Gornitz et al. [15] show that the most devastating impacts are likely to be associated with changes in extreme sea levels resulting from the passage of storms in coastal regions, especially as more intense tropical and extra-tropical storms are expected [16].

Changes in the frequency of extreme (high) sea-level events have already been observed, primarily attributable to changes in long-term mean sea level [17][18], rather than to any variation in the height of the extremes relative to the mean (caused, for example, by meteorologically driven surges).

Based on tide gauge records from the Australian ports of Fremantle and Fort Denison (Sydney), Church et al. [19] show that the Average Recurrence Interval (ARI), also called return period, of flooding events that occur on annual to decadal timescales decreased by a factor of about three from the pre-1950 period to the post-1950 period (see Figure 9). This is mainly caused by sea-level rise, with a smaller contribution coming from changes to intra-annual, interannual or decadal variability, which may or may not be related to long-term climate change. The rise in sea level that has occurred during the twentieth century has therefore already caused a significant change in the frequency of extreme sea-level events.

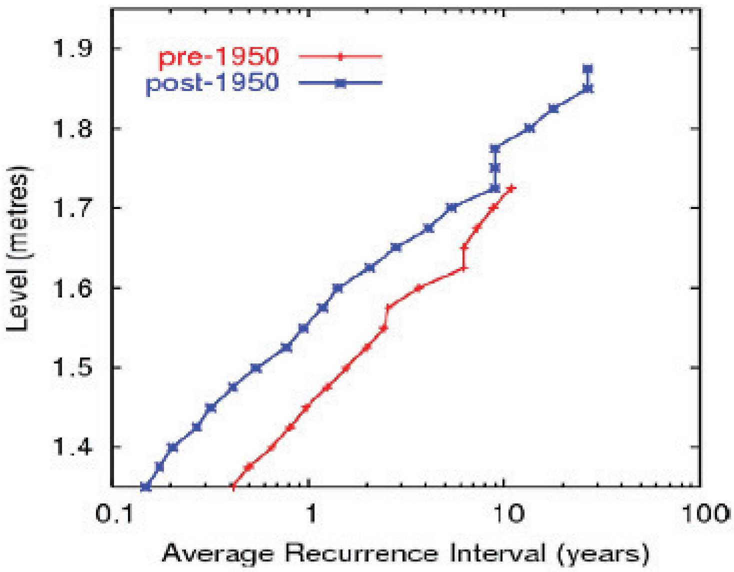

Figure 9. Change of average recurrence interval for extreme high levels from pre-1950 to post-1950 conditions for Fremantle (Source: Church et al., [19]).
Note that return periods are shown on a logarithmic scale on the horizontal axis.

The relationship between the average recurrence interval for a sea level of a particular height is approximately logarithmic (see Figure 9), indicating a Gumbel distribution (for example, Pugh [20]). The slope of this relationship may be used to estimate the increase in frequency for a given amount of sea-level rise. If a sea-level rise of h increases the frequency of occurrence by a factor r, then a sea-level rise of H increases the frequency of occurrence by a factor $r^{H/h}$ (a consequence of the form of the Gumbel distribution). Figure 10 shows the estimated increase in the frequency of occurrence of extreme high levels, caused by a sea-level rise of 0.1 metres, for the 29 Australian sea-level records [19]. This multiplying factor has a range of 1.8 to 5.8 and a mean of 3.1, which is broadly consistent with the twentieth century observations for Fremantle (see Figure 9). For a typical mid-range twenty-first century rise of mean sea level of 0.5 metres (see Figure 12), the mean multiplying factor for Australia would therefore be $3.1^{0.5/0.1}$ or 286, indicating that events which now happen every few years would happen every few days in 2100 [21].

3.4 Sea-level rise and infrastructure planning

Coastal transportation infrastructure is vulnerable to the combined effects of the various components leading to relative sea-level changes. These include global eustatic sea-level rise; any spatial variation from that global average; local land movements (subsidence or uplift), which can result from post-glacial rebound, water extraction or sediment compaction; local meteorological changes; and changes in frequency of extreme water level events. Figure 11 shows that, due to the land movements, different regions can have quite different sea-level rise.

Figure 10. Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events (indicated by the diameter of the discs), caused by a sea-level rise of 0.1 m (Source: Church et al.[19])

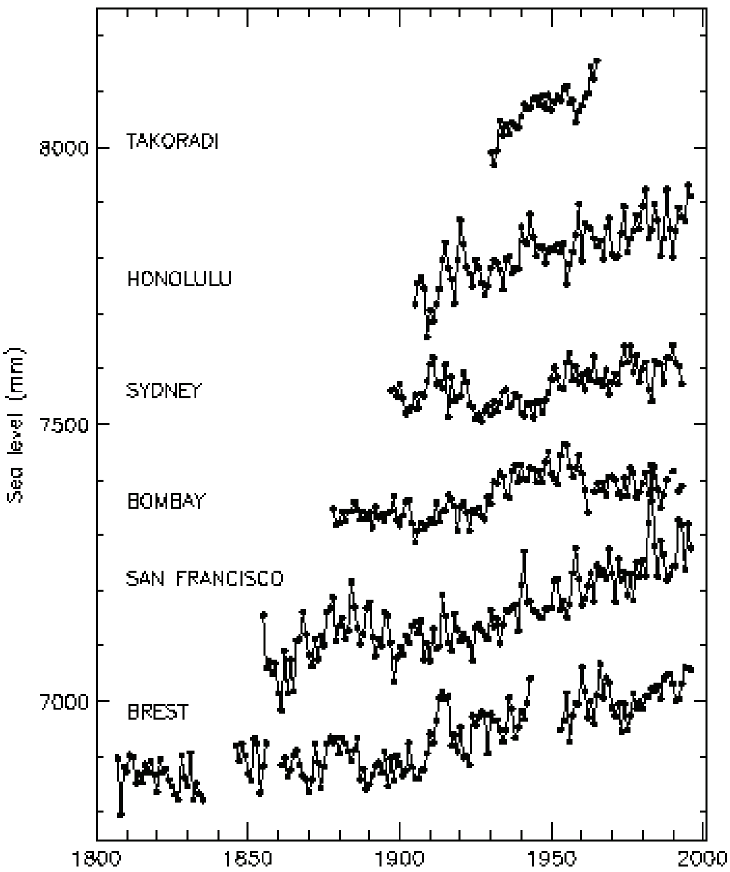

Figure 11. Individual locations having different rates of sea-level rise or even sea-level fall (Source: Woodworth et al. [22])

The projected range of global averaged sea-level rise from the IPCC Third Assessment Report [23] for the period 1990 to 2100 is shown in Figure 12 by the lines and shading, and the updated Fourth Assessment Report IPCC projections of 2007 for the SRES scenarios [16] are shown by the bars plotted at 2095. Hay et al. [24] identify several challenges that confront the transportation sector in coastal and low-lying areas as a result of global sea-level rise. These include closure of roads, airports and bridges due to inundation, flooding and landslides, and damage of port facilities.

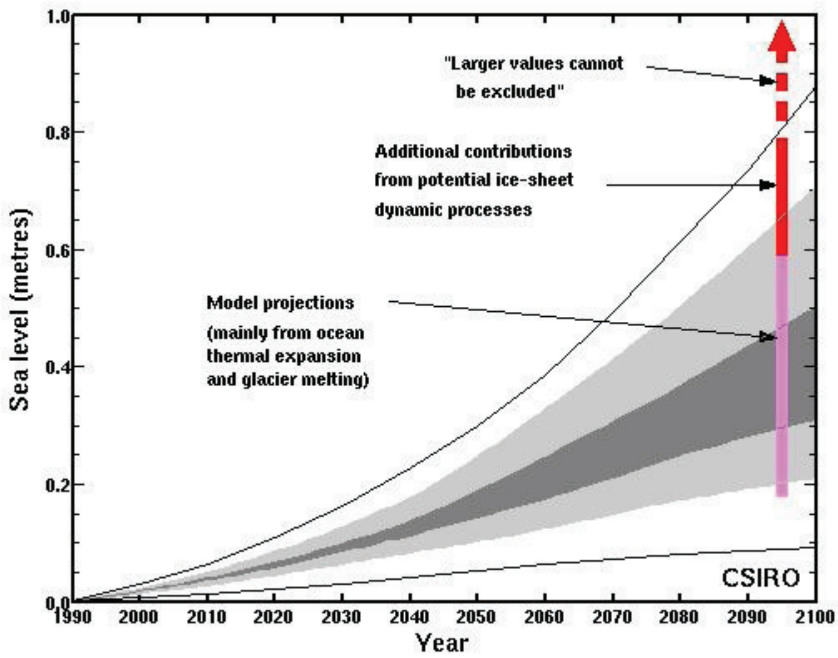

Figure 12. Projected sea-level rise for the twenty-first century (Source: Church et al.[23]; modified by Meehl et al.[16])

The probability of flood risk in coastal areas is generally expressed in terms of extreme sea-level distributions. Such distributions are usually computed from observed annual maximum sea levels from several decades of tide gauge data, or from numerical models. While such distributions are readily available for many locations, a worldwide set has never been computed to common standards for studies of impacts of global sea-level change. Figure 13 shows that the road network will be affected by the change in flooding due to climate change for Cairns (Australia). This study was based on a combination of stochastic sampling and dynamic modelling, assuming a 10 per cent increase in tropical cyclone intensity, which implies more flooding than sea-level rise alone would suggest [25]. Lowe and Gregory [26] note that detailed patterns and magnitudes of changes in extreme water levels remain uncertain; better quantification of this uncertainty and further field validation would support wider application of such scenarios.

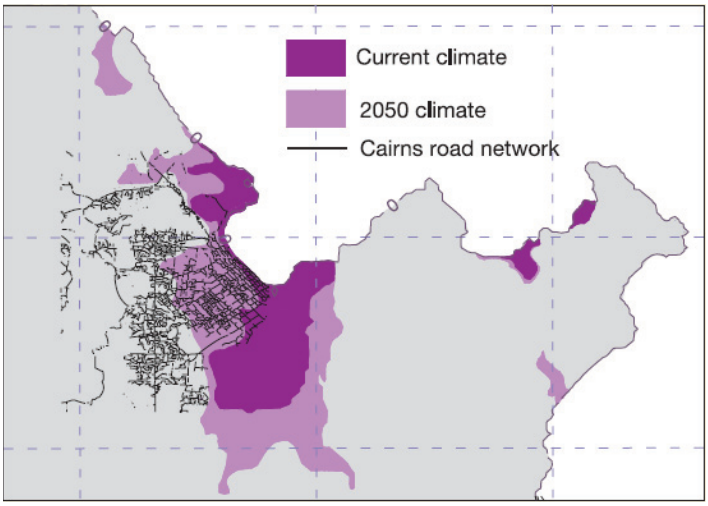

Figure 13. Change in flooding for Cairns (Australia), during the >100 year return period event under current and 2050 climate conditions based on a 2xCO_2 scenario (Based on McInnes et al. [25]). The road network is shown in black.

Several studies (for example, Zhang et al. [27]; Forbes et al. [28]) have shown that sea-level rise over the last century has reduced the return period of extreme water levels, exacerbating the damage to fixed structures from modern storms compared to the same events a century ago. These studies have raised major questions, also relevant to coastal transportation infrastructures, including: (a) the feasibility, implications and acceptability of shoreline retreat; (b) the appropriate type of shoreline protection (for example, beach nourishment, hard protection or other typically expensive responses) in situations where rates of shoreline retreat are increasing; (c) doubts as to the longer-term sustainability of such interventions; and (d) whether insurance encourages to build, and rebuild, in vulnerable areas. Bernier et al. [29] present selected tools that support coastal adaptation assessments and interventions, including evaluating and mapping return periods of extreme events. These tools, together with predicting shoreline retreat and land loss rates, are critical to planning future coastal transportation infrastructure.

The Greater London Council notes that the Thames River tidal defences comprise the Thames Barrier, 185 miles of flood walls, 35 major gates and over 400 minor gates. They have been designed to protect London and most of the Thames Estuary against storm events that might happen on average only once every 1 000 years. A recent study notes that the existing defences originally anticipated 8 mm per year sea-level rise, whereas sea levels are currently rising by only 6 mm per year, thereby providing some margin for error in future sea-level rise estimates [30]. Estimates of when the next upgrading of this infrastructure must occur have been made (for example, Hall et al.[31]). The studies conclude that the timing will be dependent upon the rate of global temperature rise which is in turn related to the greenhouse gas emissions pathway the world follows over the current century (Figure 14), and further note that losses avoided by the upgrading of flood defence infrastructure would be about £13–£14 billion (adjusted to 2005 values using an initial discount rate of 3.5 per cent that falls to 2.5 per cent by the end of this century). The choice of discount rates for valuing the losses avoided for an event likely to occur in the next century is a highly controversial area and one that is beyond the scope of this paper.

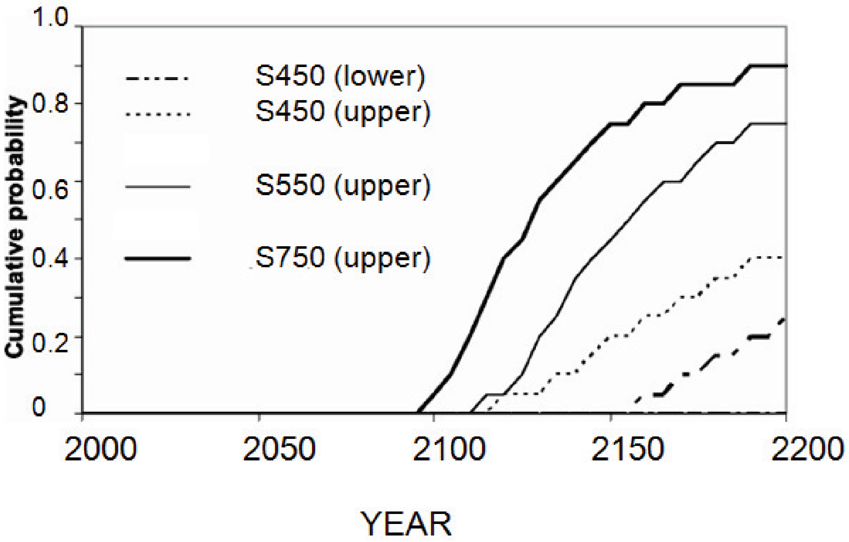

Figure 14. Probable year of next upgrade of the Thames River defences given the difference between the greenhouse gas emission scenario in IS92a and stabilisation at 450 ppm CO_2 Eq, 550 ppm CO_2 Eq and 750 ppm CO_2 Eq. (After Hall et al. [31])
Lower and upper relate to the estimated sea levels under these atmospheric concentrations of greenhouse gases.

In many ways the Australian studies and that of the Thames River Estuary presented above provide a useful example of how to deal with climate change and the threat of sea-level rise on a range of communities. It would appear that there are adequate historical datasets available to understand both the meteorology and the hydrology of the situation. Good use has been made of the available global modelling of climate change scenarios and there has been widespread community discussion about the scientific analyses and engineering options available.

4. Services to assist adaptation

The foundation climate services to assist informed decision-making for climate change adaptation are the basic climatological data for the locations of interest to the user. These are typically long-term (30-year minimum) averages of parameters of interest such as rainfall, temperature, humidity, wind speed and direction and atmospheric pressure. In addition to the long-term averages, data describing extreme hydrometeorological events and the frequency distribution of these events are also required. These data must be readily accessible in electronic form and be supported by metadata and professional support services.

A science-based climate service must provide services well beyond these basic climatological statistics so as to be of maximum value not only to the transport sector but also sectors including tourism, agriculture, water, energy, health, ecosystem support and the general public.

For the transport sector climate-related information will rarely be the key driver of investment decisions, but rather one of many variables to be considered. Long-term infrastructure design questions such as the height for new wharves, the temperature range new railway lines should withstand and whether to construct more and bigger airports should all use climate services as one of many inputs.

There are a range of climate-related decisions to be made on timescales shorter than decades. As discussed above, all elements of the transport infrastructure are affected by severe storms and other extreme events. On the weeks to months timescales transport systems that serve the tourism and agriculture sectors will be sensitive to droughts, floods and other longer lasting meteorological events. It is to be expected that future weather, climate and water services will be seamless between these timescales. The services will be based upon the best science available, and forecasts and scenarios will include assessments of the confidence level that can be attached to the information provided. The user of the service will not need to know or understand the technology being used to produce the service, but sufficient communication between the user and the service provider is necessary to ensure that the users' needs are being properly met and that they understand the information (including its limitations) being provided. The skill of prediction generally decreases with time from the moment hydrometeorological information is provided. Different applications are used for weather forecasts (the first 10 days), seasonal (or long-range) forecasts (2 weeks to 14 months) and climate scenarios (1 to 100 years plus). (See Figure 15.)

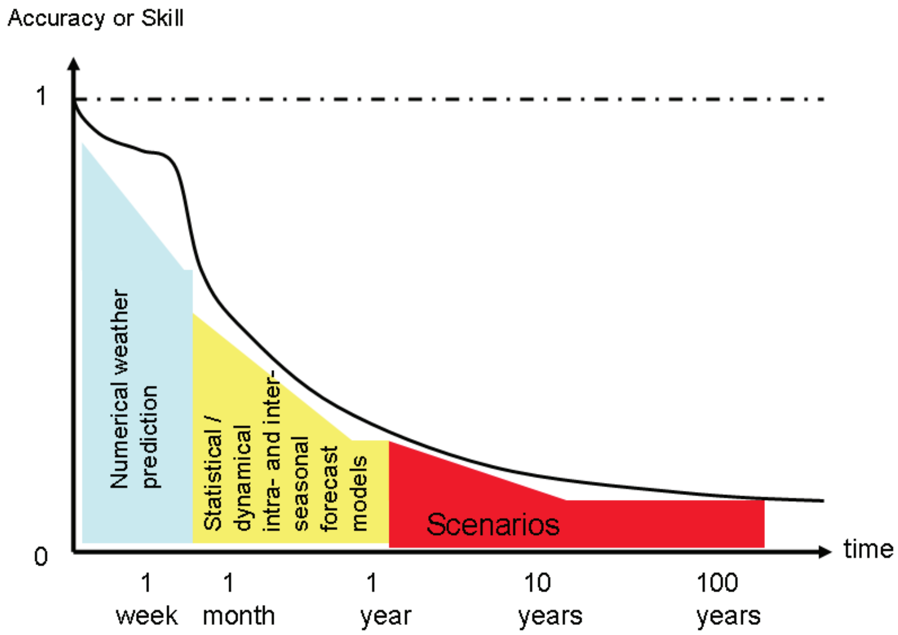

Figure 15. A schematic of timescales and skill over time of climate services

4.1 Applications

The role of the applications component of a climate service is to bring together the data, the science and the user requirements as inputs and then develop, and operationally implement applications (or systems) that enable the delivery of high quality services. Following the simplification introduced earlier, it is useful to look at the applications that would support seamless services across all timescales: two years to two hundred years (using climate models forced by particular scenarios); two weeks to two years (using coupled ocean–atmosphere climate models); and two hours to two weeks (using numerical weather prediction systems). (See Figure 16.)

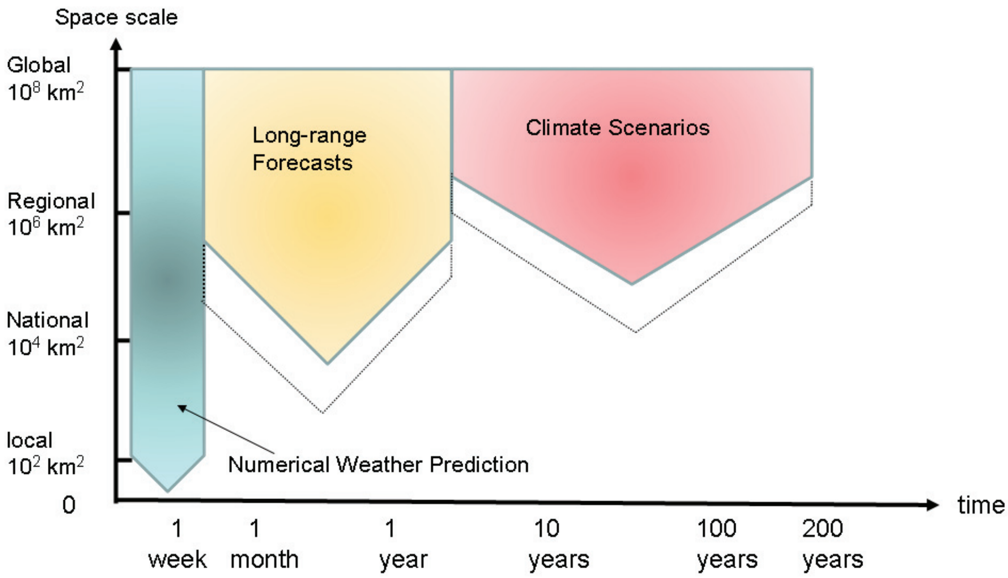

Figure 16. Applications that support the seamless production of services covering timescales from two hours to two hundred years

The systems that provide the basis for many climate services are coupled ocean–atmosphere models. Operated in “climate mode” they are a system of equations that represent the behaviour of two fluids on Earth – the air that comprises the atmosphere and the water that comprises the oceans. Using the most powerful supercomputers available this system of equations is solved at a series of grid points through the ocean, at the ocean and land surface, and through the free atmosphere.

4.2 Two to 200 years

In essence the current climatic conditions of Earth are reproduced as the steady state of the model and then a forcing is applied, such as the increase of greenhouse gases under one of the IPCC SRES scenarios [32] or the newer Representative Concentration Pathways (RCP) scenarios [33]. The RCP scenarios are intended to span the range of potential climate forcing, including policy and no-policy scenarios (Table 3). The next step is for Climate Model and Earth-System Model simulations to use these pathways to generate a suite of model outputs that can be used for impacts, adaptation and vulnerability analyses. Emissions and land use for the RCP scenarios will be extended to 2300 to allow for long-term climate simulations.

Table 3. The four RCP scenarios now under development for use by the climate change impact assessment/adaptation strategy community and expected to be reported on extensively in the IPCC Fifth Assessment Report

RCP 8.5 • >8.5 W/m^2 in 2100 • Rising	RCP 6 • ~6 W/m^2 at stabilization after 2100 • Stabilization without exceeding the target
RCP 4.5 • ~4.5 W/m^2 in 2100 • Stabilization without exceeding target	RCP 3-PD • <3 in W/m^2 2100 • Peak and decline stabilization

Very often the climate model systems are run at coarse resolution compared with weather forecast systems, and to make their output useful at a regional or local scale, downscaling is carried out through the use of fine scale models driven by the scenario system output and/or the use of statistical methods. To successfully employ statistical downscaling it is vital to have background data captured at the locations of interest. Without such data any downscaling will by necessity be model-based and without any real opportunity to validate the results. For these reasons alone it is vital that vulnerable communities have in place networks that capture, store and exchange vital environmental data that can be used by researchers and those who provide operational climate-related services.

4.3 Two weeks to 14 months

Coupled ocean–atmosphere models, starting from realistic initial conditions, are used to model system development. An important component of their skill is the ”memory” of the ocean for temperature anomalies, particularly those associated with large-scale events such as the El Niño–Southern Oscillation, and the role these have in driving atmospheric processes. Again these are relatively coarse resolution systems and rely on knowledge of statistical relationships between particular large-scale patterns and regional and local weather anomalies.

4.4 Zero to ten days

Conventional numerical weather prediction systems, global in scope and heavily reliant on accurate starting analyses, have led to ever more skilful weather forecasts over the past thirty years. Data from these systems are a key decision-making tool for all managers with operational responsibilities for transport systems. They generally give accurate warning of developing extreme weather events and provide time for making those short-term decisions that can minimize the impact of these events.

5. Summary and conclusions

Transportation, as the sector making the third largest contribution to human-made greenhouse gas emissions, will be called upon to find ways of reducing these emissions. As noted there are new technologies emerging that show promise and there are also opportunities to make better use of existing weather and climate information to make better operational decisions in the day-to-day management of transport systems, decisions that would also lead to a reduction in greenhouse gas emissions. This information should be science-based, developed in close interaction with the users and be seamless across the timescales that the users require, with confidence limits attached to all relevant guidance.

From consideration of the impact of extreme events on countries and communities it is clear that the focus of climate change studies must begin to shift from global impact assessments and emission mitigation to finer regional and local-scale studies that take full account of these extreme events, and to provide more focused adaptation measures that consider all aspects of the socio-economic and political dimensions of the issue. Without adequate datasets at the local scale, downscaling of output from global systems to regional and local space scales has increased uncertainties. Long-term monitoring networks serving all vulnerable communities are essential for detecting and quantifying climate change and its impacts. The effectiveness of adaptation strategies and actions then requires continuous feedback and adjustments based on the scientific assessment of the data provided by those networks.

The internationally coordinated, collaborative applied research and development effort that is currently supported by the World Climate Research Programme needs to develop stronger links to the operational community that supplies the emerging climate services to users throughout the world. It is important that the services developed are science-based, and are developed through close interaction with decision makers – and that feedback systems are in place to enable continuous improvements of the services.

As indicated briefly in the discussion of the Thames River study, the assessment of damages avoided in the next century is a difficult issue, with the choice of discount rates currently being the likely determinant as to whether adaptation measures are warranted or not. A new methodology is required for informing decisions relating to new infrastructure investments and projects that includes more appropriate economic decision criteria. The planning and design of new infrastructure also requires tools for dealing with a non-stationary climate, mechanisms for incorporating very uncertain and qualitative climate change scenario information, and a basis for including socio-economic and other considerations that are not easily valued (for example, loss of biodiversity).

In summary then, the impacts of climate change upon the transport sector are slowly evolving, and in many ways uncertain in impact. It is clear that at any moment in time decisions relating to how to manage operational transport systems and invest in future systems will have to be taken in the face of inadequate knowledge. Furthermore, because of humankind's economic activities, and efforts to mitigate climate change, decisions made on the basis of existing information will need to be constantly re-evaluated. In essence what will be required will be an adaptive management approach that includes:

(a) Planning and designing infrastructure to account for climate uncertainties;

(b) Engaging the community broadly and involving professionals from a wide variety of disciplines such as meteorology, hydrology, engineering, statistics, ecology, biology, economics and financial management;

(c) Taking a whole-of-life approach to the management of infrastructure;

(d) Constantly updating risk assessments and the benefit and cost analyses of adaptive strategies;

(e) Stressing the need for ongoing research and development oriented towards climate change and variability;

(f) Developing improved forecasting for climate;

(g) Improving the range and geographical extent of the collection of Earth-system data, and the exchange of these data between agencies undertaking climate change research and infrastructure development;

(h) Strengthening emergency management and preparedness plans for extreme events that current science indicates are likely to increase in frequency under the range of generally accepted climate change scenarios.

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