Chapter 1. The potential effects of climate change on transport infrastructure

Much of the understanding of the linkages between human-caused emissions of greenhouse gases and other anthropogenic climate changes is based on complex climate models that have generally performed well in tracking current global temperatures. Nonetheless, these models are approximations (albeit very sophisticated ones) that cumulate several possible sources of errors. This chapter will discuss in general terms the current scientific state of understanding of the direction and scope of climate change and how these changes may give rise to transport infrastructure or network service-damaging hazards. It also addresses the extent with which confidence can or should be ascribed to projections of future hazards such as temperature change, sea level rise, changes in precipitation, etc.

The United Nations Intergovernmental Panel on Climate Change (IPCC) has identified anthropogenic emissions of greenhouse gases (GHG) as the primary driver behind significant and potentially critical changes in global climate on the basis of wide-ranging empirical evidence, observations and model-based analysis (IPCC, 2013).

Though climate models are imperfect predictors of complex climate system dynamics, there is little systemic evidence or analysis that points to future climatic patterns that are substantially different or counter to the trends depicted by the bulk of models used to underpin the IPCC analysis. Nonetheless, the scientific understanding of climate change continues to evolve. The current state of knowledge is characterised by areas where the science is well understood and accepted, areas where there is a general consensus but continued debate and areas characterised by substantial uncertainty.

In addition, while broad evidence seems to support the view that man-made emissions of greenhouse gases may be responsible for climate change, there remains considerable uncertainty over the exact scale, scope and regional impacts of climate change which complicates policy making. Both levels of uncertainty – on the science and on the impacts – are relevant for transport since addressing climate change should aim for synergy between transport and climate policy goals and ensure that trade-offs between these objectives are undertaken knowingly and transparently.

Box 1.1. **IPCC Working Group I input to the Fifth Assessment Report - Climate change: The physical science basis**

Released in September 2013, the input of the United Nations Intergovernmental Panel on Climate Change (IPCC) Working Group I to the IPCC's Fifth Assessment Report assesses the current state of scientific understanding regarding climate change. It reviews the physical science basis, discusses climate change processes and seeks to clarify knowledge on the imputation and potential scale and scope of climate change. It captures the most current state of scientific knowledge relevant to climate change at the time of its release. According to this report: "Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen and the concentrations of greenhouse gases have increased" (IPCC, 2013).

The climate change transport infrastructure impact pathway

Of the six so-called greenhouse gases,[1] three play a predominant role given their volume of emissions (carbon dioxide) and/or elevated warming potential (methane and nitrous oxide). The emission of these gases leads to an observed or modelled series of interactions that have an impact on global average temperatures, weather patterns and, ultimately, human societies (see Figure 1.1). Figure 1.1 illustrates the pathway that links emissions of greenhouse gases to changes in climate and impacts on human activities and ecosystems:

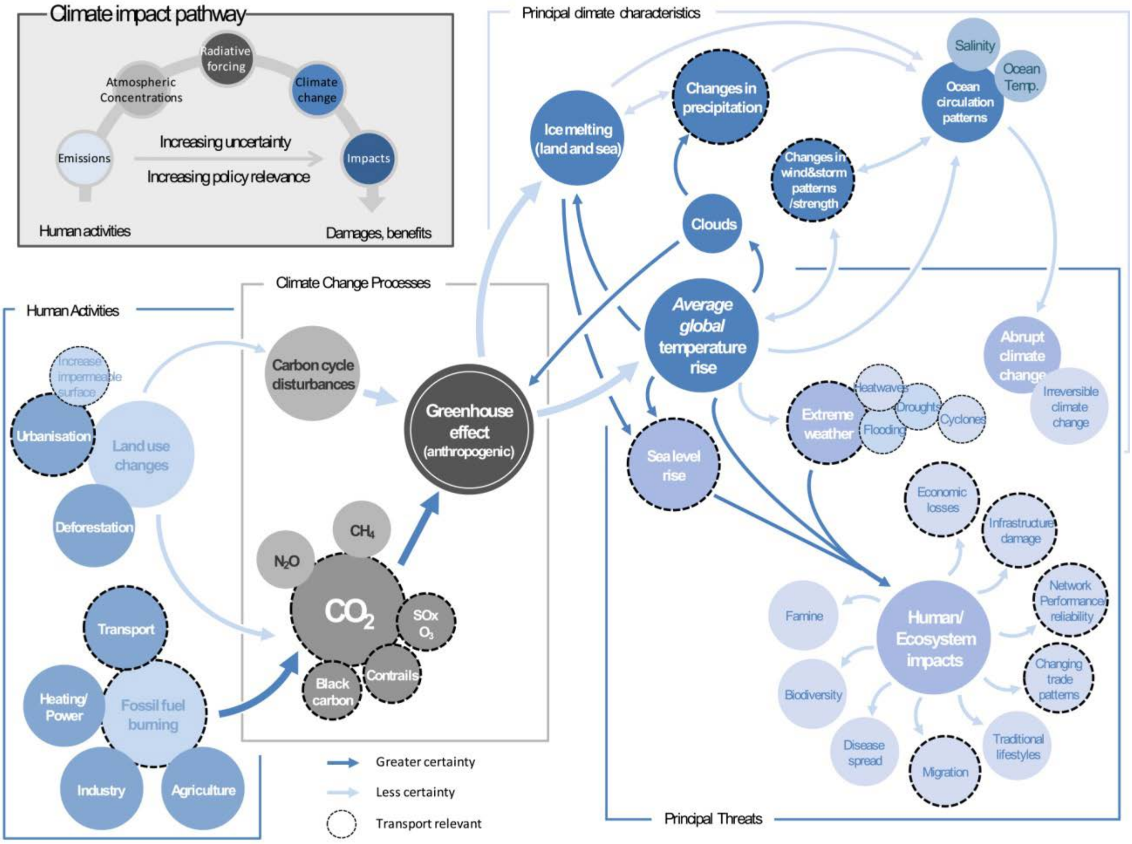
- Human activities give rise to a sustained pulse of emissions into the atmosphere.
- Not all of these emissions remain in the atmosphere – ultimate atmospheric concentrations of GHGs depend on the action of sinks in removing gases as well as reactions amongst gases in the atmosphere.
- At different time scales, these emissions have different relative warming or cooling impacts (e.g. radiative forcing) on the atmosphere according to the nature of the compound emitted and

its chemical and physical interactions within the atmosphere. For some compounds, the location of emissions matters.

- Numerous climate models indicate that changes in global average atmospheric temperatures lead to changes in the amount and pattern of precipitation, changes in wind patterns and strength, changes in soil moisture, changes in the frequency and strength of extreme weather and changes in sea level.
- These changes in turn may affect terrestrial systems as well as human settlements, activities and energy needs. Potential impacts range from changes in yields and spatial distribution of ecosystems, and agricultural and forest systems to losses of key ecosystems, changes in water resources, and changes in energy needs for heating and cooling.

Transport infrastructure, networks and services are placed at risk from the damaging impact of extreme weather and temperatures as well as rising sea levels. The pattern and distribution of transport demand may also shift alongside climate-impacted human activities placing new demands for infrastructure and posing the risk of stranded assets and capacity where demand falls off of projected levels.

Figure 1.1. **Anthropogenic climate change impact pathway**



Source: Adapted from UNEP-GRIDA, and den Elzen et al. (2005).

Crucially from the perspective of policy-making, this impact chain is characterised by increasing scientific uncertainty even as policy relevance increases (e.g. towards a quantified estimate of damages that could help to guide policy action). Despite improvements in the scientific understanding of the impact pathway, climate policy making is still characterised by the need to balance significant yet uncertain risks with immediate and consequent actions.

The global and regional climate is already changing in perceptible and measurable ways. The following sections first summarise the current state of understanding of observed changes in the climate system largely based on the report “Climate Change 2013: The Physical Science Basis” (IPCC, 2013). We then examine the state of knowledge about future climate conditions and discuss the use of this knowledge in formulating adaptation policies.

Box 1.2. **Characterising likelihood terms used in the IPCC Fifth Assessment Report**

The IPCC has adopted a carefully calibrated set of terms to characterise both agreement as well as confidence in scientific findings emerging from its Fifth Assessment Report. These are adopted in this section and should guide the reader in understanding these findings.

Virtually certain	**99-100% probability**
Very likely	90-100% probability
Likely	66-100% probability
About as likely as not	33-66% probability
Unlikely	0-33% probability
Very unlikely	0-10% probability
Exceptionally unlikely	0-1% probability

Source: IPCC, 2013.

Observed changes in the climate system

There are centuries (millennia) of observations of critical climate variables that have helped to characterise historic climate periods. These have only become systemic and more-or-less harmonised in the past century and even more so now that global ground-station monitoring has been supplemented by satellite observations.[2] The next few sections present current understanding of the historic climate trends for some transport infrastructure-relevant variables, discussing the evolution of averages as well as extremes, where relevant. Almost all of these phenomena are linked to generalised trends in atmospheric temperatures. These temperatures are changing and the evolution of atmospheric mean and extreme temperatures indicates both a rightward shift and a spreading of the distribution. This suggests more elevated temperatures on average, more frequent unusually warm days and less frequent unusually cold days (Figure 1.2).

Atmospheric temperature: Mean temperature

Why is mean atmospheric temperature relevant for transport infrastructure owners and network managers?

Atmospheric temperature is a fundamental climate variable for infrastructure since temperature means, distribution and extremes must be accounted for in infrastructure design and operational planning. Temperature is a key driver of other climate parameters as well. For instance, a warmer atmosphere holds more moisture and this, combined with differences in temperature (spatial or vertical differences in temperatures or temperature differences between air and sea generate atmospheric fluxes), is the fundamental driver of cloudiness, storminess and precipitation. Atmospheric temperature has an impact on the formation or melting of land and sea ice (including permafrost) and can contribute to thermal expansion of seawater. In the latter case and when land-ice melts, sea levels rise putting transport infrastructure and activity in danger, especially in the context of increased storm strength and frequency due to the damaging effect of storm surges. Increases in atmospheric mean temperature, when combined with elevated CO_2 levels in the atmosphere, lead to accelerated carbonation rates of concrete materials, contributing to accelerated degradation and loss of cohesion and strength. Elevated air temperatures in polluted areas will lead to increased peak levels of ozone and fine particulate matter due to atmospheric chemical feedback cycles.

What is the evidence regarding mean atmospheric temperature trends?

There is evidence of a robust and global warming trend over the period for which there are reliable global data sets. This warming is not uniform nor is the rate of warming steady, especially when considering averages of shorter year ranges. The record shows periods displaying a strong warming trend alternating with periods where the rate of warming has slowed. Recent data suggests that in the current period is displaying lower-than-average rates of warming. Nonetheless, decadal temperature data shows a consistent and increasing trend (Figure 1.3).

According to IPCC (2013), the globally averaged mean land and sea temperature has increased by 0.89°C from 1901 to 2012 (linear trend calculation using multiple independently produced datasets). There is 90% certainty that the temperature change over the period falls between +0.69°C and +1.08°C (90% certainty intervals will be expressed in brackets in the text that follows). The rise in temperature has been 0.72°C [+0.49°C to +0.89°C] from 1951 to 2012 (IPCC, 2013).

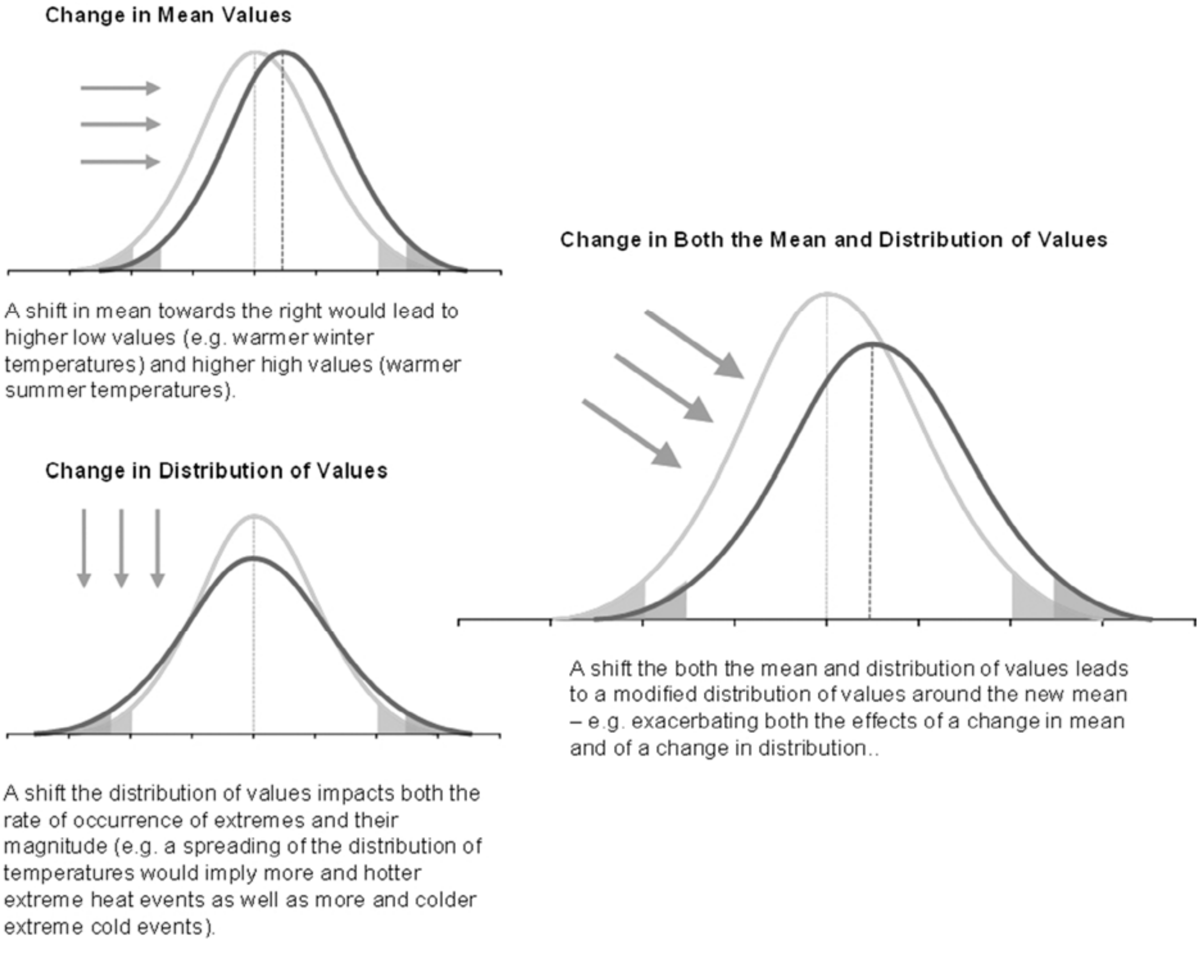
Gridded data for the period 1901 to 2012 indicate that the warming trend covers all regions though the Northern Hemisphere; the Arctic regions in particular display the strongest warming. Warming was not uniform across the atmospheric column either with the lower troposphere (0 to 10 kilometre [km] in altitude) warming since 1958 (the year where reliable global data became available) and the lower stratosphere generally cooling over the same period. The direction and patterns of temperature change in the lower troposphere and stratosphere were not spatially consistent with some regions displaying temperatures counter to global trends in both layers (AMS, 2013).

The IPCC notes that each of the last three decades has been successively warmer than any preceding decade since 1850 and that the thirty-year period from 1983 to 2012 was likely (66% to 100% likelihood) to be the warmest in the past 1 400 years. Global average land and sea temperature in 2012 was above the 1981-2010 average and was among one of the ten warmest years over the 1880-2012 period.

Annual temperature averages and decadal averages display significant variability. Trend analysis is also sensitive to starting and ending values as these may express exceptional values that may bias analysis. Short intervals are especially subject to non-representativeness due to natural variability and sensitivity to starting and ending values. Especially problematic are intervals starting or ending during the El Niño or La Niña Southern Oscillation events which result in unusual temperature records (as well as non-typical precipitation patterns and intensity). Isolating the impact of natural variability and identifying robust trends requires long record intervals (at least more than 30 years).

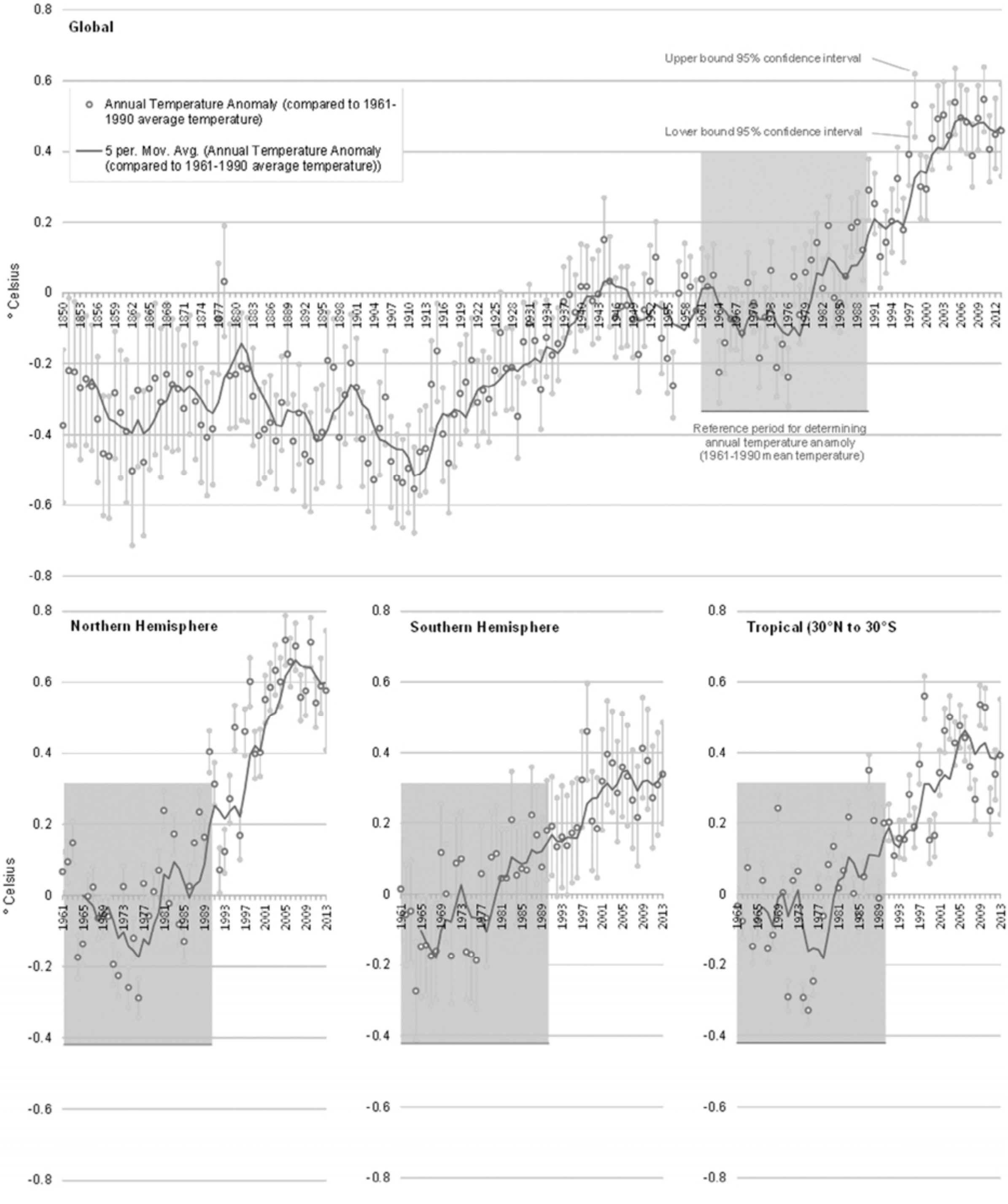
The trend of annual temperature anomalies from the 1961-1990 mean temperature displayed in Figure 1.2 illustrates the above-mentioned variability. This variability may be smoothed by averaging data in "binned" year ranges (e.g. 30, 20, 10 or 5-year "bins"), or by calculating *x*-year moving averages. Care should be made to understand the internal distribution of yearly average temperatures within a "bin" (e.g. what was the standard deviation of temperatures within the interval and what were the deviations from the mean for each year within the interval?) when using "binned" data to estimate a point measurement (e.g. was this decade substantially warmer or cooler than the previous decade?). Running averages can also help smooth some of the natural variability – shorter averaging periods have the advantage of being able to pick up recent changes but also run the risk of over-emphasising changes due to natural variability. Figure 1.3 also displays the 5-year running average of recorded temperature anomalies from the 1961-1990.

Figure 1.2. **Atmospheric temperature: Implications of changing mean values and their distribution**



Source: Adapted from IPCC (2013).

Figure 1.3. **Global and regional mean combined land and sea surface annual temperature anomalies compared to average 1961-1990 temperature**



Source: Data from Met Office Hadley Centre observations datasets (HadCRUT4).

Both the annual data and 5-year running average trend line underscores that non-uniform rise in global temperatures. Since 1850, there have been two approximately 30-year periods, where recorded temperature anomalies from the 1961-1990 mean have risen strongly (~1910-1945 and 1978-2006 using 5-year running averages). At other times, the rate of change of recorded anomalies has been much lower. This has been the case since approximately 2002 where the rate of change in recorded temperature anomalies has slowed considerably and has been nearly stationary (when considering the 5-year running average). IPCC also notes that the decadal rate of warming from 1998 to 2012 has been substantially lower than the average rate over the period from 1951-2012 – +0.05° C per decade [-0.05° C to +0.15°C] and +0.12°C per decade [+0.08°C to +0.14°C], respectively for the 1998-2012 and 1951-2012 (IPCC, 2013).

The recent slowdown in the rate of growth is not necessarily inconsistent with the observed long-term trend in rising global temperatures. There is limited understanding of the reasons for the observed drop in the growth rate and coupled climate models have failed to reproduce it. This may indicate that either the recent period is simply an expression of natural variability or that there is an unsuspected (and hitherto un-modelled) phenomenon at work. One possible explanation may involve heat exchanges between the upper and lower oceans but this has not been fully explored.

Atmospheric temperature: Extreme temperatures

Why are atmospheric temperature extremes relevant for transport infrastructure owners and network managers?

Extreme temperatures, be they hot or cold, have negative impacts on the physical properties of materials used in the construction of transport infrastructure as well as on the viability of geo-technical works associated with numerous transportation assets. Both extremes can also have impacts on transport demand and on operations and maintenance activities. Extreme heat events can also be associated with fire risk which can impact network performance, asset integrity and user safety.

What is the evidence regarding the evolution of atmospheric temperature extremes?

Evidence indicates a global shift in extreme temperatures with fewer and less pronounced cold extremes and more frequent and more pronounced heat extremes. This overall finding is subject to regional, diurnal and seasonal variability with some indications of regional counter-trend findings.

IPCC (2013) notes growing evidence that a large majority of global land areas have experienced broad warming trends for both cold and hot extremes since 1950. This means that there has been an increase in unusually warm days and a decrease in unusually colds days (and nights in particular) since the middle of the 20th century. In particular, cold extremes have warmed more than hot extremes and this warming is more pronounced for night-time versus daytime temperatures. In addition globally averaged multi-day heat spells are likely to have become more frequent but global findings are tempered by lack of data for Africa and South America. Confidence in regional evidence regarding the shift in extreme temperature indices is linked to data availability as well as to the level of understanding of regional climate behaviour. IPCC (2013) finds that it is likely that Europe, Australia and parts of Asia have experienced stronger and longer heat waves since the mid-20th century. North America has also likely experienced a similar trend though regional variations seem greater and the impact of temperature extremes in the early part of the 20th century skew findings regarding the evolution of temperature extremes.

Ocean temperature

Why is ocean temperature relevant for transport infrastructure owners and network managers?

Ocean temperature is linked to the volume of the oceans as well as to the patterns and strength of convective currents. Combined air-ocean warming also leads to atmospheric convective movements that contribute to atmospheric moisture content, precipitation and storminess. A warmer ocean has a larger volume and thus is associated with an increase in sea level (see below).

What is the evidence regarding ocean temperature trends?

It is virtually certain that surface ocean temperatures (above 700 metres) have increased with greater confidence in the trend observed in recent versus historical periods. Deeper ocean warming has also been observed but is variable with the most significant deep warming observed in the Southern Ocean.

On a global scale, more heat energy is being absorbed by the planet than is being released back into space with oceans absorbing 93% of the combined heat stored by the atmosphere, land, sea and melted ice. The significant heat storing capacity and slow circulation of oceans contribute to a slower thermal inertia than the atmosphere. This means that even if atmospheric warming were slowed or reversed, it is likely that oceans would continue to warm and expand for centuries to millennia with a concomitant rise in sea levels (IPCC, 2013).

IPCC (2013) concludes that it is virtually certain that the upper 700 metres of ocean have warmed since 1950 with the strongest warming occurring nearest to the surface. The global averaged warming from 1971 to 2010 was +0.11 [0.09 to 0.13] °C per decade in the upper 75 m decreasing to +0.015°C per decade at a depth of 700 m. There is some evidence that warming in the upper ocean has slowed from 2003 to 2010. The observed decrease in upper-ocean warming is consistent with a similar trend in globally averaged atmospheric temperatures but IPCC (2013) notes as well that this time period saw a change in ocean-observing systems which may have introduced spurious readings.

Evidence of ocean warming at greater depths is more scattered and difficult to gauge due to sparse and time-inconsistent data. IPCC (2013) finds that it is likely that ocean warming has occurred from 700 to 2 000 metres below the surface but that there much less conclusive evidence on warming at depths below 2 000 metres. Deep-ocean warming seems to have occurred more consistently in the Southern Ocean near Antarctica.

Sea level

Why is sea level relevant for transport infrastructure owners and network managers?

Increases in sea level will put unprotected low-lying infrastructure at risk of temporary or permanent inundation which will trigger significant asset protection, rehabilitation or relocation costs. Wave overtopping thresholds may be more frequently breached as sea level rises. In conjunction with increased storm frequency or storm strength, increased sea level rise will amplify the damaging impact and reach of storm surges leading to catastrophic asset failures and sudden transportation network interruptions. Average sea levels are also important in planning for port infrastructure and bridges over navigable tidal waterways.

What is the evidence regarding sea level trends?

IPCC (2013) finds that it is virtually certain that globally averaged sea level has risen over the course of the 20th century and that evidence supports that this increase has accelerated since the latter portion of the 20th century.

Relative increases in sea level result from the convergence of numerous, sometimes contradictory, factors at various time and geographic scales. Thermal expansion of the oceans and land-based ice loss has contributed most to the observed rise in sea levels. Measurements of globally averaged sea levels since 1993 have increased in accuracy and confidence as has monitoring of surface melting and runoff from the Greenland and the Antarctic ice sheets. Other factors that impact relative sea level rise include geographically constrained incidences of coastal land mass subsidence or uplift. At a regional level, subsidence exacerbates the impact of global sea level rise whereas uplift can partially counteract mean increases in sea level. On a shorter time frame, imperfect mixing between ocean basins can also lead to relative differences in global sea levels – especially as water released from land to ocean is redistributed among ocean basins.

On the basis of tide gauge data from 1900 supplemented by more precise satellite data from 1993 on, IPCC (2013) finds that global mean sea level has very likely increased by 1.7 (1.5 to 1.9) millimetres per year from 1900 to 2010. From 1993 to 2010, it is very likely that this rate has increased to 3.2 (2.8 and 3.6) millimetres per year.

Precipitation: Mean

Why is mean precipitation relevant for transport infrastructure owners and network managers?

The design of transportation assets must account for hydraulic forces, ambient humidity, ground humidity and therefore cohesiveness of soils and other precipitation-related phenomena such as corrosion. Transportation infrastructure must also be designed to handle prevailing patterns of precipitation (wet vs. frozen) and the average duration of precipitation events common to specific locations. This is especially important when considering average runoff in watersheds and the specific volume of stream and river flow at points intersecting transportation networks.

What is the evidence regarding trends in mean precipitations?

Evidence reviewed by IPCC (2013) is mixed. Globally precipitation seems to have increased in the 20th century though confidence is low for the period prior to 1951 and medium thereafter. Regionally, precipitation in the Northern Hemisphere has likely increased since 1951. It is however very likely that global mean near-surface and tropospheric air humidity have increased since the 1970s (IPCC, 2013). More wintertime precipitation is falling as rain rather than snow.

Evidence supports that globally averaged precipitation has increased over the last century but the large range in precipitation observations across the datasets examined lowers confidence in this finding. Incomplete data for several time periods and regions likely plays a role in the inconsistent findings regarding the magnitude of globally averaged precipitation levels. Confidence is low in findings prior to 1951 and medium in findings since then, largely due to more complete observations.

Missing precipitation data makes it difficult to uncover statistically significant regional trends as well. There is evidence that tropical mean precipitation levels show no significant trend from 1951 to 2008 but have perhaps increased in the most recent decades. Mean precipitation levels have likely increased in the Northern Hemisphere but confidence in this finding is tempered by missing data and is variable by latitude band (higher confidence over the mid-latitudes, lower over the upper-latitudes for the period 1901 to 2008). Statistically significant precipitation trends cannot be discerned with confidence for southern latitudes.

The warming of average and extreme winter temperatures has been led to more wintertime precipitation falling as rain rather than snow. This is especially true for regions where average winter temperatures are near 0°C. Regional variation exists due to localised climate interactions – e.g. lake-effect snow has increased in the area east of the North American Great Lakes.

As temperatures warm, atmospheric water vapour levels increase as well by 7% for every degree Celsius. In keeping with observed increases in globally averaged atmospheric temperatures, IPCC (2013) finds that ambient humidity levels have very likely increased since the 1970s near the surface and in the troposphere.

Precipitation: Extreme

Why are precipitation extremes relevant for transport infrastructure owners and network managers?

Extreme precipitation leads to heightened stream and river flow, increased soil runoff as well as flooding. Extreme (or unusually prolonged) precipitation can also lead to a loss of soil cohesion and result in land and mudslides. These hydraulic hazards are among the most damaging for transportation assets and can lead to significant asset damage and sudden failure which interrupt, sometimes significantly so, transport networks.

What is the evidence regarding extreme precipitation trends?

IPCC (2013) notes regional variability in both extreme precipitation and confidence in trend observation. Nonetheless, there have been statistically significant increases in heavy precipitation events in more regions than there have been statistically significant decreases. This holds despite difficulty in establishing a harmonised definition of what constitutes an extreme precipitation event.

Establishing a harmonised global definition of extreme precipitation is difficult given variation in regional climates. Deviation from mean precipitation patterns and intensity is linked to a shift in the mean as well as a possible spread of the distribution of precipitation events. It may also be that many highly-localised extreme precipitation events (e.g. stormbursts) occur at a scale that cannot be captured by current observation systems. Nonetheless, IPCC (2013) finds that more regions have experienced a statistically significant *increase* in extreme precipitation events than have experienced a statistically significant *decrease* in extreme precipitation events. Evidence supporting increased extreme precipitation events is most consistent in central North America and Europe. Findings for winter extreme precipitation events are more consistent than for summer events where seasonal effects have been assessed.

Extreme storms

Why are extreme storms relevant for transport infrastructure owners and network managers?

Extreme storms are accompanied by high winds, extreme precipitation, storm surges in coastal areas, lightning and increased wave energy and amplitude. Cyclones and hurricanes are among the most damaging storm phenomena known but more localised thunderstorms can also result in asset damage and network interruption.

What is the evidence regarding trends in extreme storminess?

IPCC (2013) finds that there is low confidence that tropical storms have increased in number over the last century but that it is virtually certain that extreme storms have become more frequent and that their intensity has increased in the North Atlantic Basin. No significant trend has been observed in thunderstorms and hail.

Large-scale tropical and extra-tropical storms are especially damaging for transport networks. Evidence reviewed in IPCC (2013) does not reveal a statistically significant increase in the frequency of these storm events. However, there is robust regional evidence indicating that the frequency of exceptionally strong storms has increased in the North Atlantic Basin, especially since the early 1970s. There is disagreement on the causes of this trend and whether or not it is a durable one. Evidence from other basins fails to discern significant trends neither in storm frequency nor in extreme storm frequency.

Many smaller-scale extreme storms and related phenomena such as hail and lightening also can disrupt transport activity and networks. These events are much more frequent than large-scale storms but observation networks are often too coarse to adequately record these. With this caveat in mind, IPCC (2013) finds low confidence in the trend of localised extreme storms.

Cryosphere

Why is the state of the cryosphere (snow, river and lake ice, sea ice, glaciers, ice shelves, ice sheets and frozen ground) relevant for transport infrastructure owners and network managers?

The cryosphere is especially sensitive to increases in both average and extreme temperature extremes. Warming trends, and especially winter and polar warming trends, lead to accelerated melting, runoff and frozen soil dynamics. These changes impact transport networks and assets in numerous ways. Shortened snow and ice seasons can lead to a decrease in snow and ice removal costs and snow/ice-related crashes. Less river and lake ice and shorter periods of freezing can increase the accessibility and productivity of inland waterways. Conversely shorter ice seasons cut the period of use of locally important river and lake ice roads in the upper Northern Hemisphere.

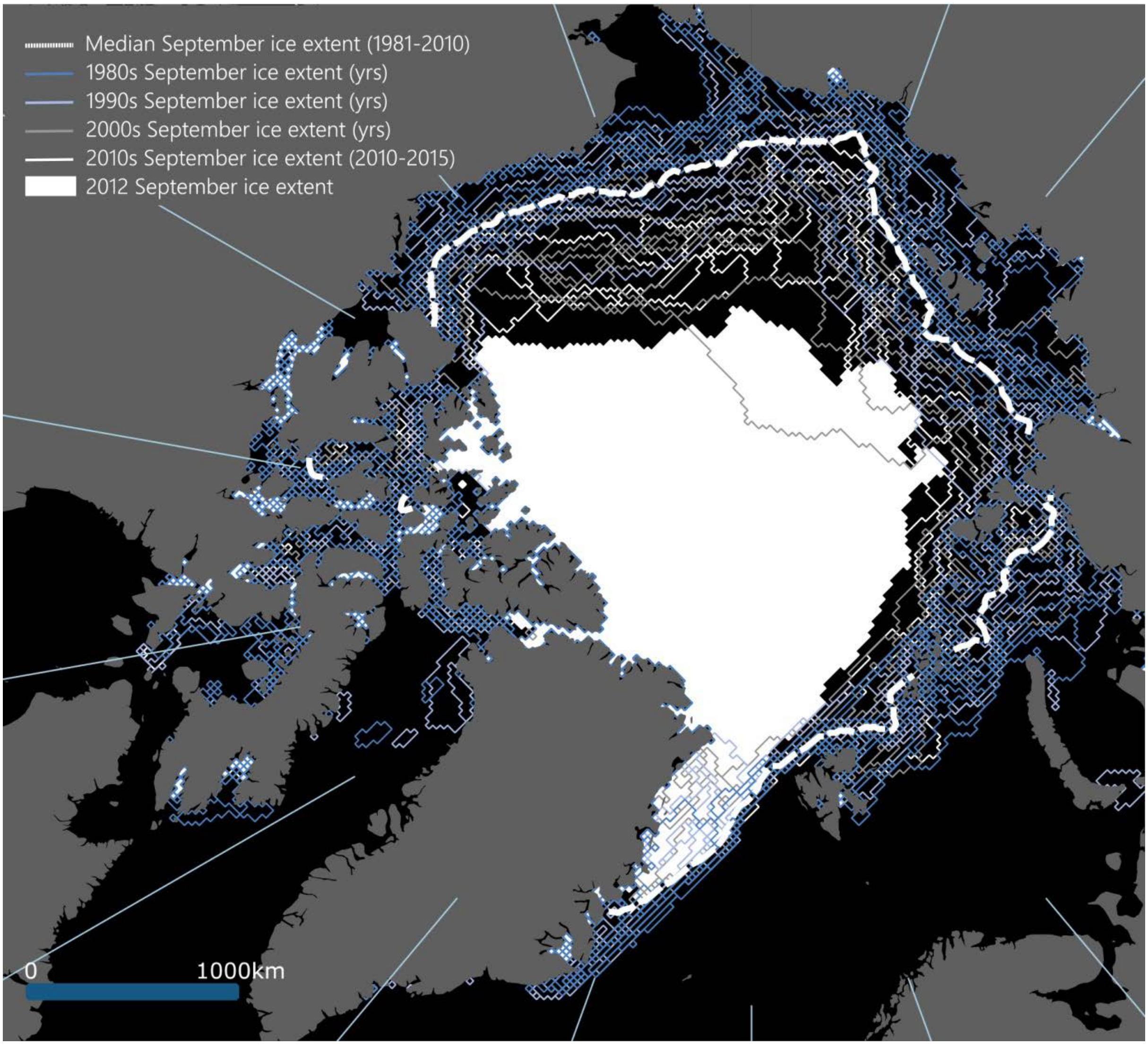
Reduced sea ice, and less Arctic ice cover in particular, can potentially open new northern sea routes. At the same time, loss of Arctic sea ice increases heat absorption by the Arctic Ocean and contributes to increased convective fluxes and extreme storminess.

Seasonal melting of frozen soils (permafrost) can lead to loss of slope cohesion and result in landslides in alpine environments. Permafrost instability can lead to soil upheaval which can have a widespread damaging effect for roads, pipelines, railroads and airfields. Indirectly, large-scale melting of land ice contributes to an increase in global sea levels which also jeopardises coastal infrastructure.

What is the evidence regarding changes in the cryosphere?

IPCC (2013) finds that the cryosphere is undergoing major changes. Northern Hemisphere snow cover has decreased, river and lake ice is decreasing and seasonal coverage is shortening, permafrost temperatures and dynamics are increasing, glaciers are shrinking, the Greenland ice sheet is melting and retreating, annual and permanent Arctic ice cover is decreasing (Figure 1.4).

Figure 1.4. **September Arctic Sea ice extent 1980-2015**



Source: Data from US National Snow and Ice Data Center.

The cryosphere refers to terrestrial components that contain a significant share of frozen water – these include snow cover, lake and river ice, glaciers, ice sheets and shelves, sea ice, ice caps and frozen ground (permafrost). These elements can be transient in nature such as seasonal snow and ice cover or longer-lasting (glaciers, ice sheets, etc.). Their distribution varies but they generally increase in prevalence away from the equator and in altitude. They comprise defining elements of polar regions. Because of their nature, they are sensitive to a rise in global and more localised warming. IPCC (2013) finds broad evidence of significant perturbations to most elements of the cryosphere.

According to the evidence reviewed by the IPCC, Arctic sea ice cover has very likely decreased by 3.1% to 4.1% per decade from 1979 to 2012. The summer minimum Arctic ice cover has decreased at a higher rate of approximately 11.5% per decade over the same period. Average winter Arctic ice thickness has decreased between 1980 and 2008. Antarctic sea ice, on the other hand, has very likely increased by 1.2 to 1.8% per decade from 1979-2012.

Glaciers worldwide have shrunk and lost mass. This loss has very likely led to an increase in sea level of 0.62 ± 0.37 mm yr^{-1} from 1971 to 2009 and this increase has accelerated in recent years accompanying higher rates of ice loss (IPCC, 2013). Momentum in glacial systems means that glaciers will continue to lose mass in the future even if temperatures stabilise.

IPCC (2013) notes with high confidence that the Greenland ice sheet has lost mass over the past twenty years and that this loss has accelerated in recent years. This loss has very likely led to a sea level increase of 0.09 [–0.02 to 0.20] mm yr^{-1} from 1992 to 2001 to 0.59 [0.43 to 0.76] mm yr^{-1} from 2002-2011. The Antarctic ice sheet has similarly lost mass over the past two decades and this loss has also accelerated in recent years. It is likely that Antarctic ice loss has led to an increase in global sea level of 0.08 [–0.10 to 0.27] mm yr^{-1} from 1992–2001, to 0.40 [0.20 to 0.61] mm $yr^{-1}$from 2002-2011.

Where it is well-monitored in the Northern Hemisphere, the seasonal extent of snow cover has decreased over the past twenty years with very high confidence, especially in the spring. IPCC (2013) also finds that Northern Hemisphere winter ice cover of freshwater bodies has also generally decreased in spring. Freeze-up of freshwater bodies has generally occurred later and later with breakup of frozen freshwater bodies occurring sooner and sooner.

Evidence regarding changes in permafrost indicates that frozen soil temperatures have increased in most concerned regions since the 1980s. The rate and depth of seasonal and permanent warming varies according to region with significant warming and permafrost degradation taking place in the Siberia. Findings regarding the depth of the active layer (the layer exposed to seasonal freeze-thaw cycles) vary by region as well and in many areas, active layer depth has increased by a few centimetres to tens of centimetres on average.

Atmospheric and oceanic CO_2 concentration

Why are atmospheric and oceanic CO_2 levels relevant for transport infrastructure owners and network managers?

Alongside other greenhouse gases, atmospheric concentration of CO_2 drives global warming. However, atmospheric concentrations of CO_2 also contribute to chemical reactions that can degrade the coherence and strength of cementitious materials and of concrete in particular. CO_2 absorbed by oceans decreases their pH, increases acidification, which can also contribute to the accelerated degradation of cementitious coastal infrastructure. Climate change impacts stemming from atmospheric concentrations of CO_2 are indifferent to the point of emission but this is not the case for the corrosive impact of CO_2 on vulnerable materials. In particular, increased concentrations of CO_2 in urban areas multiply the corrosive impact of this gas on vulnerable infrastructure elements (Stewart, Wang and Nguyen, 2011).

What is the evidence regarding changes in CO_2 concentrations?

It is certain that atmospheric concentrations of CO_2 have risen since the onset of industrialisation. Atmospheric CO_2 levels were 390.5 ppm in 2011 representing a 40% increase over concentrations in 1750 (IPCC, 2013). Concentrations have likely increased disproportionately in urban areas alongside increases in fossil fuel combustion (Peng and Stewart, 2014). Oceans are also absorbing more CO_2 as atmospheric concentrations of CO_2 rise (Raven et al., 2005).

Future climate projections: Modelling, predicting and describing future climate

Climate change is not new and there are historic periods where changes in prevailing climate have led to unanticipated changes in the scope and strength of weather phenomena that have disrupted, sometimes severely, human activities and infrastructure networks. Generally, however, these changes have not operated on a global scale and have not presented such a wide range of potentially disrupting impacts as have been documented in the previous section. At present, it seems clear that the historical climate record can no longer adequately guide the understanding of the likely future weather conditions, especially past 2050.

If accurately measuring historic and present climate trends is an inherently difficult task, predicting future climate trends is even more challenging and uncertain. From a practical perspective, it is impossible at present (and for the foreseeable future) to predict specific weather phenomena beyond relatively short time frames. This of course would be the most useful information for infrastructure managers to have since it is weather phenomena, and not climate, which are directly responsible for infrastructure damage and failure and ensuing service perturbations. The averaged historic record of weather phenomena instructs this report's understanding of the present climate and gives infrastructure designers and managers a good understanding of the range of climate stressors they will have to account for as well as an idea of the scale and scope of the extreme weather incidents they will face. Traditionally this type of information has been collected by meteorological agencies and provided either directly to engineers or embedded in infrastructure design standards. Historical meteorological data is also used by insurance companies to calculate risk exposure and to set premiums. Since this data is at best an imperfect and worsening predictor of future climate (and at worst, largely irrelevant to describing future climate), planners and engineers must turn to alternative sources of data to guide their designs and investments.

One approach is to look to at other regions of the world that have climate patterns that are analogous to those which are emerging at present. Using such a "climate analogue" approach, planners and engineers witnessing an upwards shift in temperature might look to warmer regions as a way of capturing the range of future climate parameters. Likewise those seeing an increase in atmospheric moisture and wet (e.g. not frozen) precipitation might look to more humid climes for guidance on possible future climate phenomena. The difficulty with this approach is twofold. The first is that there is little statistical certainty that an evolving climate will match that found in a putative "climate analogue". The second is that many transportation assets are longed lived and that under an evolving climate regime, a particular zone might pass through several climate analogue zones (Hallegatte, 2009). At some point in the future, the climate in Barcelona may ultimately become more analogous to that of Casablanca. In that illustrative case, building infrastructure adapted to Casablanca vs. Barcelona is not inherently more difficult. Building long-lived infrastructure capable of handling the both the climate of Barcelona and Casablanca (and points between) is a much more challenging and potentially expensive proposition.

Another option is to look to model outputs regarding future climate variables and use these to guide infrastructure planning, design and investment decisions. Multiple Atmosphere-ocean general circulation models (AOGCMs) that capture interactions between atmospheric composition, radiative forcing and ocean circulation have been developed and are used in co-ordinated manner to simulate future climate conditions. More recently, state-of-the-art Earth System Models (ESMs) extend the modelling environment of AOGCMs to include representations of certain biogeochemical cycles such as the carbon and sulphur cycles and ozone. These model families divide the world into grids (and sometimes stratify these grids vertically into the atmosphere and ocean) at various spatial scales ranging from hundreds of kilometres across to tens of kilometres across. For each cell, the models simulate future climate parameters (e.g. temperature, humidity, and precipitation) after iterative runs that capture inter-cell interactions.

These models must allow scientists to approximate the natural variability of climate systems in order to isolate those climate variables that are evolving out of the historic norm. This is done by running single models multiple times, sometimes with different starting conditions ("ensemble" runs), and averaging the results. Different models are used with their own ensemble runs and the outputs of these are averaged across models. Nonetheless, AOGCM/EOMs models have difficulty in capturing the full extent of natural climate variability, especially for poorly understood phenomena that operate on daily, monthly, annual or decadal time scales. A good example is the challenge of accounting for the effects of the highly disruptive El Niño Southern Ocean Oscillation (ENSO) or its counterpart La Niña. As with other cyclical but poorly understood drivers of regional climate, current global climate model frameworks cannot provide clear guidance on the evolution of these in both frequency and strength as the global climate evolves (Meyer et al., 2014).

Global climate models are complex, computationally demanding, subject to inherent limitations and sometimes compound biases or errors. In particular, they are sensitive to a number of factors that include (Dessai et al., 2009; IPCC, 2013):

- inaccurate specification of climate mechanisms (e.g. lack of scientific understanding or uncertainty in process representation)
- inherent randomness (e.g. stemming from cloud physics)
- error propagation
- uncertainty in observational data
- sensitivity to model resolution
- uncertainty regarding human actions that impact climate (e.g. actions leading to emissions and/or having an impact on sinks).

Because of these limitations, it may very well be that models may produce consistent findings and yet still have low skill in describing the future climate. Model outputs may agree and yet still be in error (Power et al., 2012). Furthermore, while many models display skill at replicating past climate regimes (and thus seem to adequately capture climate dynamics), no scientific assessment can be made as to their ability to capture future climate regimes. In some cases the impact of these limitations can be quantified but in many cases they simply cannot. This results in "some level of irreducible ignorance in our understanding of future climate" (Dessai et al., 2009).

Temperature, humidity and precipitation outputs expressed in absolute terms are generally not a good basis on which to predict future climate. A better approach is to take the relative changes in these three (or other) variables and apply these to observed climate data in order to create climate change scenarios. This allows for the correction of the bias inherent in the simulated and observed climates (Fordham et al., 2011).

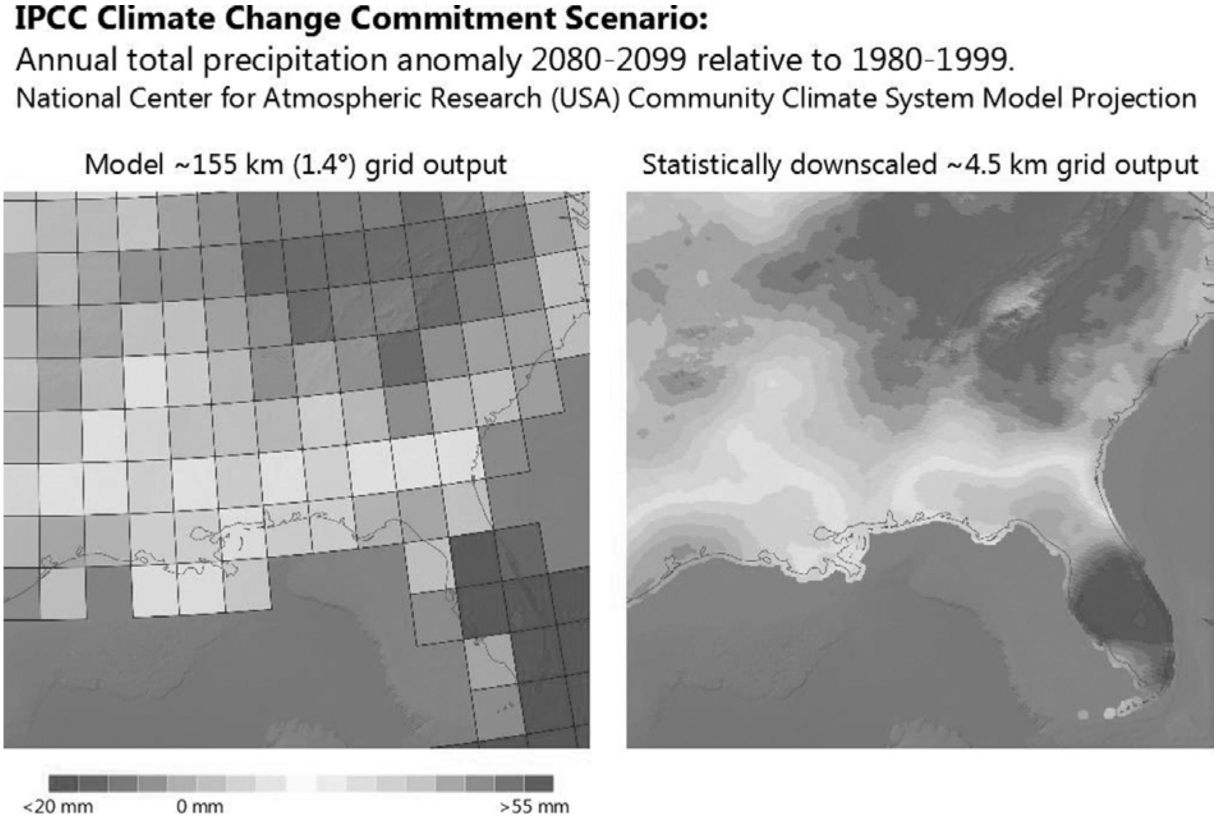
From a transport policy perspective, one clear limitation in the current generation of AOGCMs and ESMs is the spatial mismatch between model outputs and relevant spatial scales for asset planning and design purposes. Data regarding general climate parameters in a 100 km by 100 km cell, or even a 30 km by 30 km cell is simply not fine enough for assessing the risk posed by many specific weather phenomena (e.g. thunderstorms, extreme precipitation, flash floods) under an evolving climate.

Various downscaling techniques and regional models can and have been used to deliver more policy-relevant climate data for regional and local applications but these inherit many of the limitations of AOGCMs and ESMs (especially when regional or downscaled models use global model inputs). Compared to the coarse grid of many global climate models, downscaled outputs seem more suited to local infrastructure design and planning uses (see Figure 1.5). However, downscaling may compound limitations inherent to the original model output and is dependent on the continued validity of linkages between local scale and global scale climate variables. Under a changing climate, it is not certain that these linkages will remain constant, or at least remain roughly similar, to what has been observed in the past. More importantly, climate data resulting from global, regional and/or downscaled models may seem analogous to historic climate data. They are not the same and model-based data should not simply be used to replace historic meteorological data by asset planners, designer and managers.

Fundamentally, while regionalisation and downscaling can provide more precision to model outputs, at present these techniques cannot and do not provide more accuracy (Meyer et al., 2014). What these models *do* provide is a range of plausible future climate scenarios that could emerge given the report's present understanding of climate mechanisms and the inherent and sometimes deep uncertainty embedded in the Earth's climate system.

Despite the inherent limitations to the modelling approach and the degree of deep uncertainty that accompanies model outputs, the current generation of ESMs and AOGCMs, and the co-ordinated modelling efforts built around them, are at present the best available source of insight into future climate (IPCC, 2013). Climate models are continually improving, their skill at replicating many historical climate regimes is increasing and they are able to capture many more dynamic elements in the Earth climate mechanism. With the caveats outlined above, they can be used to guide policy – but not necessarily to optimise asset design for one particular climate future.

Figure 1.5. **Spatial grid coverage: Global climate model output vs. downscaled output**



Source: Data from National Center for Atmospheric Research.

Global climate models use scenarios to model the pathway linking human activities, emissions, atmospheric concentrations, radiative forcing (warming/cooling) and ultimately climate impacts.

According to the IPCC, the goal of using scenarios "is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures" (IPCC, 2014). In the last two reports prior to the current Fifth IPCC Assessment Report, global climate models used a set of five socio-economic scenarios for population, energy use, industrial development and agricultural activity that were developed in 2000 – the Special Report on Emission Scenarios (SRES) (Nakicenovic et al., 2000). These are now replaced in the most recent Fifth Assessment Report of the IPCC by four so-called "Representative Concentration Pathways" (RCPs) that are conceptually different than the SRES scenarios.

The four RCP scenarios represent different levels or targets for radiative forcing (signalled by the scenario number) and each is associated with an indicative atmospheric concentration of greenhouse gasses that would result in each level of radiative forcing (see Table 1.1). The key difference between the RCP scenarios and the SRES scenarios that preceded them is that there are multiple potential socio-economic scenarios that can lead to each RCP scenario end-point whereas each SRES scenario embodied only one specific socio-economic scenario. This means that socio-economic trajectories can be much more realistically and flexibly addressed in the RCP approach and in particular, adaptation decisions can become a component of the scenario modelling exercise.

Table 1.1. **Atmospheric concentration of greenhouse gases and radiative forcing of each IPCC representative concentration pathway (RCP) scenario**

RCP scenario	Radiative forcing 2100 compared to pre-industrial values (W/m^2)	Atmospheric concentration of GHG, CO_2 equivalent (ppm)
Current situation (2011)		*390.5*
RCP 2.6	+2.6	453
RCP 4.5	+4.5	586
RCP 6	+6	779
RCP 8.5	+8.5	1396

Source*:* IPCC, 2013.

The modelling framework and scenarios described above are used by the scientific community to project future climate conditions. Crucially, however, these scenarios have no likelihoods associated with them – at this time no basis exists for determining if one scenario is more likely than any other. Therefore projections made in IPCC (2013) are conditioned to specific scenarios. IPCC (2013) discusses these projections on two different timescales. The first is comprised of the near term (2016-2035) and the second for the mid to long term (from 2035 to 2100 and beyond). The following sections discuss the main findings emerging from the Fifth Assessment Report regarding future climate for each of these time scales and for transport-relevant climate variables.

How might climate-related variables evolve in the near-term future?

One important finding from the IPCC's Fifth Assessment Report is that the sensitivity of near-term climate projections to different scenario specifications (in this case the four RCP scenarios) is relatively low. This means that through 2035, the four different RCP scenarios give rise to broadly similar patterns and magnitudes of climate change (IPCC, 2013). This is important for asset owners and transport network managers to understand since it means that range of modelled near-term climate impacts are similar across the range of scenarios. This inherently qualifies some of the deep uncertainty faced by asset owners and network managers since even if probabilities cannot be ascribed to near-term climate outcomes, they are at least similar in scope.

Another finding relates to some of the uncertainties that have not been or at least only partially addressed in the near-term projections – notably the impact of aerosols and uncertainty regarding methane emissions from human activities and land cover change. In the former case, efforts to reduce local air pollution could have a near-term but uncertain cooling impact. In the latter case, including non-natural methane emissions results in a spread of CO_2 equivalent concentrations that is 30% wider than those characterised by the RCP scenarios.

Generally, however, there is higher confidence in some trends than for others. Higher confidence exists (in roughly descending order) for projections regarding global mean temperature and extreme temperatures, surface ocean temperature, sea level rise, permafrost melting and loss of sea and land ice since these stem from well-understood mechanisms that are more readily modelled using the current generation of AOGCMs and ESMs. Less confidence generally exists for projections regarding mean and extreme precipitation as well as large and small-scale storminess. This matters for asset managers and network managers since it is these types of climate-related phenomena that can be most damaging to transport infrastructure.

Near-term trends: Global mean surface temperature

IPCC (2013) projects that globally averaged mean surface air temperatures will likely increase by 0.3°C to 0.7°C by 2035. This finding is sensitive to potential major climate-altering volcanic or solar activity but the impacts of these potential events is considered to be small when compared to radiative forcing brought on by rising greenhouse gas concentrations. Though model runs for all RCP scenarios project increasing temperatures through 2050, the rate of projected warming differs among model runs and between scenarios and the spread between projections increase over time. The indicative likely range of mean temperatures for all RCPs lies in the lower half of the range of all 299 model ensembles (Figure 1.6) but this is conditioned by a number of uncertainties outlined previously, including the evolution of the current slowdown in the rate of temperature increase experienced over the past few years.

The IPCC Fifth Assessment Report finds that it is more likely than not that the global mean surface air temperature for the period 2016 to 2035 will be more than 1°C over the mean for the period ranging from 1850-1900 and very unlikely that this temperature will be more than 1.5°C over the 1850-1900 mean (IPCC, 2013). It is very likely that the rate of warming will be more rapid over land than over sea and that warming over the Arctic will be disproportionately higher than the global mean.

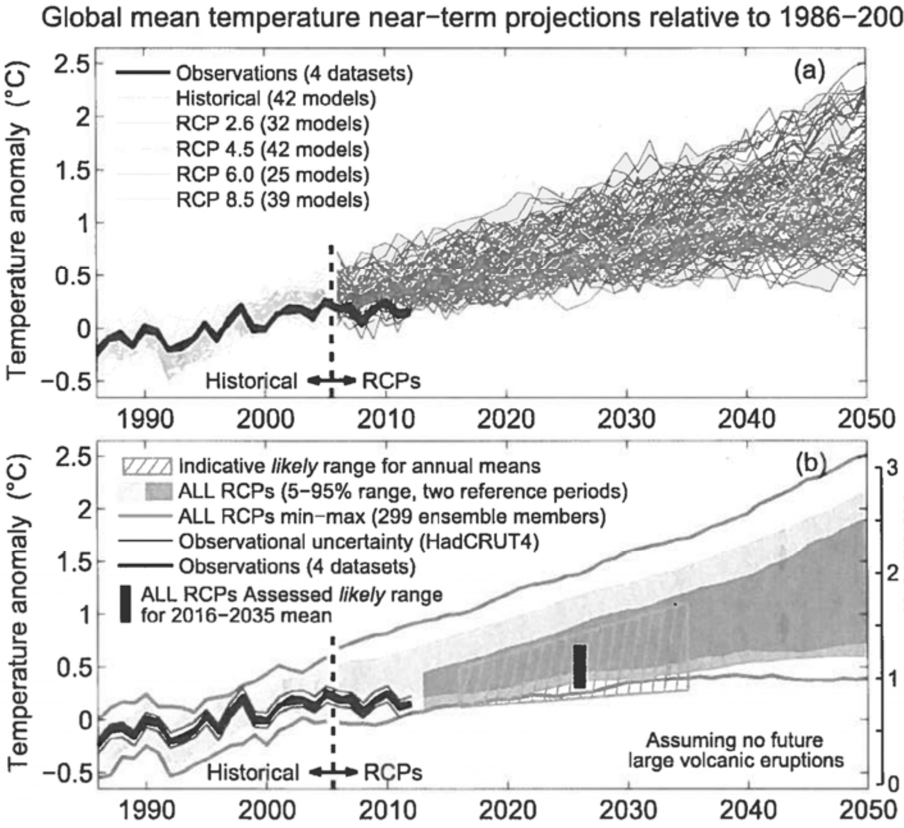
Near-term trends: Ocean temperature

In the absence of major volcanic eruptions which would otherwise lower atmospheric and surface ocean surface temperatures, the Fifth Assessment Report finds that globally averaged surface and near-surface ocean temperatures for the period 2016 to 2035 will be warmer those averaged from 1986 to 2005. This generalised ocean warming will contribute to thermal expansion of the oceans and rising sea levels.

Near-term trends: Extreme surface temperature

Consistent with the recent observed record, the IPCC Fifth Assessment Report finds likely that most land regions will experience more frequent warm days and nights and fewer cold days and nights by 2035 (IPCC, 2013). Evidence supports that the duration of warm spells will increase. As for mean temperatures, these findings are strongly insensitive to the RCP scenario considered over the near term to 2035. The Fifth Assessment Report finds that regional variations exist in the trend of extreme temperature events. In Europe, extreme daytime summer temperatures are projected to increase significantly faster than daytime mean temperatures. In North America, some evidence suggests that the ratio of extremely hot days to extremely cold days will shift from 2 to 1 in the early 2000s to 20 to 1 by 2050 (IPCC, 2013).

Figure 1.6. **Near-term model-based projections for global mean temperature for all four RCP scenarios including likely annual means**



Note: RCP = Representative Concentration Pathway.
Source: Adapted from IPCC, 2013.

Near-term trends: Precipitation

Mean precipitation is very likely to increase in the mid to upper latitudes and in wet regions like the tropics whereas mean precipitation levels are more likely than not to decrease in subtropical zones. Natural regional variability and the emissions of anthropogenic aerosols will have an impact on precipitation. Findings regarding precipitation are more consistent at large scales and less so at smaller scales. Near-surface specific humidity is very likely to increase over land. Generally, and especially at smaller scales and nearer-term periods, the magnitude of projected mean precipitation levels is smaller than the magnitude of natural variability – e.g. there is a low signal-to-noise ratio (IPCC, 2013).

Near-term trends: Extreme precipitation

Evidence reviewed by (IPCC, 2013) confirms a clear upwards trend in the frequency of extreme precipitation events on average but highlights significant regional variations in extreme precipitation patterns in the near-term. These extreme events will increase as atmospheric water vapour content increases in reaction to atmospheric warming. Short-term extreme events like thunderstorms may also increase in frequency and strength but current modelling approaches cannot establish confidence in these localised trends.

Near-term trends: Extreme storms

Due to a range of complicating factors, insufficient data and conflicting projections, IPCC (2013) finds low confidence in regional and global projections of tropical cyclone trends at present. Findings are inconclusive as to whether the frequency of these storms will increase, remain steady or decrease. Likewise, there is also low confidence in near-term tropical storm intensity projections. These findings do not indicate that tropical cyclone frequency and strength will not increase (or decrease) but that there is simply not sufficient confidence in backing either claim.

Near-term trends: Cryosphere

As near-term global mean temperatures rise, it is very likely that observed trends in the cryosphere will continue unabated. This means that it is likely that further shrinking of Arctic sea ice will take place and in some projections may lead to a nearly ice-free summer in the near-term. Further decreases in northern high-latitude springtime snow cover and more dynamic and deep thawing of permafrost soils are also likely. With the decrease in cold extremes and the later onset and earlier breakup onset of frozen conditions, there will likely be a shortening of the ice season for northern latitude rivers and lakes (IPCC, 2013).

How might climate-related variables evolve in the mid- to long-term future?

Projecting the evolution of climate variables past 2035 and to 2100 and beyond necessarily involves increasing uncertainty linked to the model and knowledge-based limitations outlined in the previous section. The accuracy of longer-term model-based projections is inherently unknown at the time of the projection. Given the challenge of correctly capturing the complex phenomena at work in the Earth's climate system and the fact that key uncertainties regarding the mid- to long-term future may be irreducible. This is not to say that there is no value in scenario-based modelling exercises looking at the long-term – there is. For one, there is no better way to try to understand the interplay between emission levels and potential future climate regimes. Modelling allows us to better grasp the relative sensitivity of the climate system and its component elements to emissions and activities. It also allows us to understand the limitations of our knowledge regarding the future and, crucially, areas expected to have no actionable information regarding the evolution of critical climate variables.

The modelling undertaken in support of the IPCC's Fifth Assessment Report indicates that there is broad consistency in projections regarding both the large-scale patterns and magnitude of change. This consistency does not necessarily imply accuracy but it does indicate that the models employed are in agreement about the broad parameters of longer-term future climate change. (IPCC, 2013) notes that model agreement and confidence in projections depends on the variable in question and the level of spatial or temporal averaging. Confidence is generally higher for large-scale mean temperature and precipitation trends as well as sea level projections over longer averaging periods. Confidence is generally lower for other climate-related variables (e.g. extreme precipitation, storminess, etc.) and for smaller-scale spatial extents and shorter averaging periods.

Long-term trends: Mean and extreme global mean surface temperatures

According to IPCC (2013) global mean surface temperatures will continue to increase should greenhouse gas emissions continue to rise. Projected global mean temperature increases are related to the radiative forcing implied in each of the RCP scenarios and are likely to vary from 0.3°C to 1.7°C for

RCP 2.6 to 2.6°C to 4.8°C for RCP 8.5 for the period 2081 to 2100 and in relation to the period 1986-2005. Given the current GHG emissions trajectory and about the current understanding of atmospheric and ocean cycles, this warming trend has significant and durable momentum. The global increase in mean temperatures will not be uniform – more warming will occur over land than over sea and faster warming will likely occur in the Northern Hemisphere[3] and certainly occur in the Arctic. There is evidence linking accelerated Arctic warming to greater instability in Northern Hemisphere atmospheric circulation. So-called "Arctic amplification" effects are linked to the emergence of more extreme and unstable weather patterns in the Northern Hemisphere (Francis and Skific, 2015).

The short-term trend of more frequent and hotter temperature extremes and fewer cold temperature extremes will virtually certainly continue through to the end of the 21st Century (and likely beyond). Twenty-year return values for both hot and cold extremes will increase at rates greater than the respective rates of change for mean summer and winter temperatures. Hot extremes will occur more frequently, last longer and be warmer than in the past (IPCC, 2013). Cold extremes will be less frequent but they may be as cold as or colder still than today's cold extremes, especially in the upper latitudes.

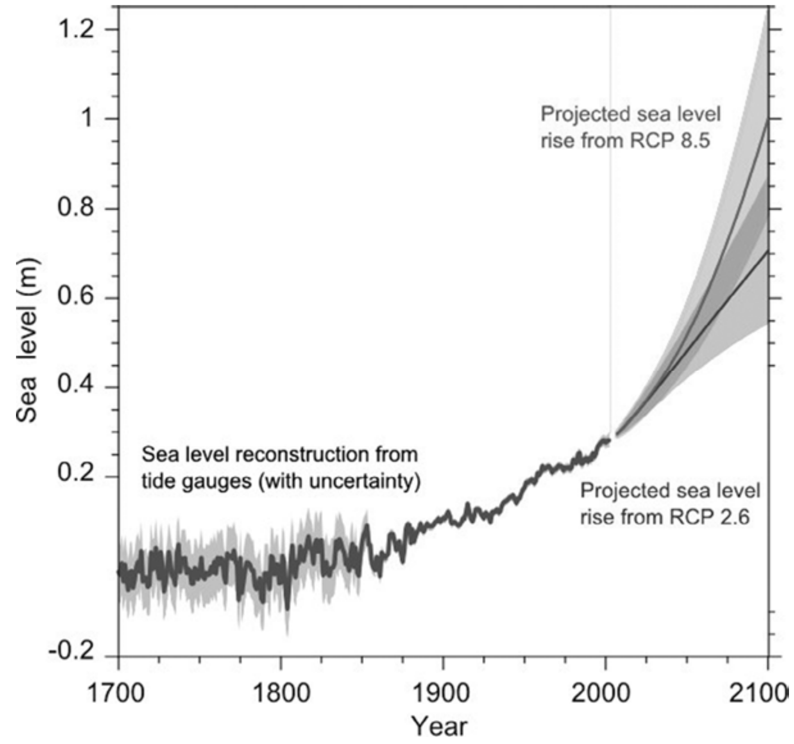
Long-term trends: Ocean temperature

The short- to mid-term warming of the upper layer of the ocean is projected to warm for all four RCP scenarios. Storage of atmospheric heat by the ocean will only slowly dissipate leading to some long-term phenomena like sea level rise. Changes in ocean circulatory patterns brought about by ice melt and thermal changes could have severe and lasting impacts on global climate but current evidence is does not support a sudden or abrupt change of these in the 21st century.

Long-term trends: Global sea level rise

The rate of global sea level rise during the 21st century is very likely to surpass the rate of sea level rise experienced from 1971 to 2010 for all of the four RCP scenarios. This increase is due both to continued thermal expansion of the sea due to the increase in mean global temperature as well as to the melting of land-based glaciers and ice sheets (especially that covering Greenland). IPCC (2013) finds that the likely range of global mean sea level rise will span from an estimated +0.26 to +0.55 metre increase in 2081-2100 compared to 1986-2005 levels (5% and 95% values for all projections) for RCP 2.6 to +0.52 to +0.98 metres for RCP 8.5 (See Figure 1.7). Sea level rise may be higher still but insufficient evidence exists to determine the probability of such an occurrence. Even more so than with the trend in mean temperatures, the oceans' thermal momentum means that this rise is already committed and will virtually certainly continue beyond the 21st century (and possibly for several more centuries). Sustained warming between 2°C and 4°C over pre-industrial global mean temperatures would result in the complete loss of the Greenland ice sheet and a sea level rise of approximately 7 metres over a millennium or more. Crucially, IPCC (2013) notes that abrupt and irreversible sea level rise resulting from warming-related instability of the Antarctic ice sheet is possible but that insufficient information exists to assess this probability.

Figure 1.7. **Historic sea level from tide gauges and projections for RCP 2.6 and RCP 2.8**



Note: RCP = Representative Concentration Pathway
Source: Adapted from IPCC, 2013.

Long-term trends: Mean and extreme global precipitation

Warming temperatures will increase in the amount of water vapour in the atmosphere and lead to a concomitant increase in the amount of global mean precipitation. The virtually certain increase in global mean precipitation will be uneven however with some regions seeing an increase, some a decrease and some no change at all. Land masses in the Northern Hemisphere, especially at upper latitudes, are likely to experience more precipitation than now. IPCC (2013) finds that conversely, many mid-latitude and subtropical dry regions will see less precipitation than now. Generally, the change in contrast between wet and dry regions and between wet and dry seasons within regions will increase through the 21st century.

The increase in global mean temperatures will likely contribute to more frequent and more extreme short-duration storms. This is especially true for most of the mid-latitude and wet tropical land masses that will very likely see more intense and frequent precipitation events. Even regions that are expected to see less overall precipitation may see more intense and damaging extreme precipitation events (IPCC, 2013). Damage from these events to transport infrastructure in arid areas may be multiplied due to runoff characteristics on very dry soils.

Long-term trends: Cryosphere

Loss of seasonal and perennial Arctic sea ice is very likely to continue through the 21st century leading to a nearly ice-free polar region in RCP 8.5 by 2081-2100. There is evidence suggesting that changes in ocean and atmospheric circulatory regimes induced by the loss of Arctic ice cover will contribute to more frequent and extreme Arctic cyclones (Vavrus, 2013). The Antarctic is also expected to experience a reduction in sea ice extent and volume though there is less confidence in this finding (IPCC, 2013). Northern Hemisphere snow cover is very likely to diminish through to the end of the 21st century. The global extent of permafrost coverage is very likely to retreat and the amplitude of the active layer in permafrost soils is likely to increase.

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Notes

1 The six greenhouse gases tracked under the Kyoto protocol are: Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Perfluocarbons (PFCs), Hydrofluorocarbons (HFCs) and Sulphur hexafluoride (SF_6). Other greenhouse gases include ozone-depleting substances as well as several other compounds that lead to changes in atmospheric temperatures (see Chapter 2).

2 Even so, there remain sources of uncertainty in the recent historic record spanning from the mid-19th century to present and even in the very recent historic records from the middle of the 20th century on. These uncertainties relate to biases inherent in different datasets, biases inherent from measurement (instruments) and sampling and biases stemming from incomplete coverage.

3 Not all models agree though, with one in particular indicating the potential for cooling across significant portions of the Northern Hemisphere for 2081-2100 (IPCC, 2013).