Impacts of climate change on transport and infrastructure, relevant to the coastal and marine environment around the UK

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EXECUTIVE SUMMARY

Transport and infrastructure is potentially vulnerable to a wide range of climate-change impacts, in particular sea-level rise, storms and waves. These all have the potential to modify asset risk profiles for flooding and coastal erosion. It is generally the case that UK industry recognises the potential impacts associated with climate change although has to weigh up these longer term risks against the costs associated with implementing more-immediate adaptation plans.

A number of strategic initiatives are now in place to help improve quantitative understanding of potential impacts on the physical environment arising from climate change. These include the development of sophisticated numerical models looking at the morphological response of coastal systems to rising sea level, as well as consideration of the potential for enhanced levels of scour around marine structures. Infrastructure providers are also including climate-change assessments within their planning and project analyses.

Major risks to transport and infrastructure associated with climate change include:

- Enhanced erosion and flood risk resulting from sea-level rise, leading to a requirement for (costly) coastal defence improvements and/or re-siting of coastal infrastructure;
- Greater potential for damage to structures associated with larger extreme waves; and
- Disruption to operations (especially in ports) which are potentially sensitive to weather-related disruption (including wind, heat, cold and fog).

However, climate change also has the potential to bring some benefit. For instance, whilst annual maximum significant wave height may increase in places, UKCP18 suggests that average significant wave height may reduce and this could improve access windows for at-sea working to be conducted

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safely (Palmer *et al*., 2018). The potential for transit shipping through the Arctic could also result in large fuel savings and associated reductions in greenhouse gas emissions.

Although understanding of climate change impacts is improving, considerable uncertainty still remains with regards to how a number of weather parameters that determine infrastructure risk profiles may be affected. This is particularly the case for patterns of atmospheric circulation which control wind (and wave) regimes. Any change in these parameters could have significant implications for the reliability of infrastructure assets with a long design life. There is also a requirement for improved understanding of correlated risks, such as flood events across large sections of coast or clustered in time.

1. WHAT IS ALEADY HAPPENING?

This MCCIP report card is an amalgamation and update to three 2013 MCCIP report cards (Built Structures (onshore and coastal): Wadey *et al*., 2013; Built Structures (offshore): Side *et al*., 2013; and Ports and Shipping: Wright, 2013). As such it covers a wide range of marine and coastal sectors from coastal defences to oil and gas platforms to ports to offshore wind farms. It draws heavily upon key marine climate change information presented in accompanying MCCIP report cards, in particular:

- Storms and waves;
- Coastal geomorphology;
- Sea-level rise; and
- Coastal flooding.

The report also uses outputs from UKCP18 (Palmer *et al*., 2018) to inform understanding of potential climate change impacts on transport and infrastructure. UKCP18 represents the most up-to-date assessment of how the climate of the UK may change over the 21st century and supersedes UKCP09 (Lowe *et al*., 2018) (which was used to inform previous MCCIP report cards). The UKCP18 projections are based on greenhouse gas (GHG) Representative Concentration Pathways (RCPs) developed for the Intergovernmental Panel on Climate Change's (IPCC) latest 5th assessment report and are informed by the global climate model simulations from Phase 5 of the Coupled Model Intercomparison Project (CMIP5). Representative Concentration Pathways (RCPs) are time- and space-dependent trajectories of concentrations of greenhouse gases and pollutants resulting from human activities. Four RCPs (2.6, 4.5, 6.0 and 8.5) are used in the IPCC's (latest) 5th assessment report as a basis for the climate predictions and projections. The numbers refer to radiative forcings (change in the net, downward minus upward, radiative flux), measured in watts per square metre, by the year 2100 (IPCC, 2013).

These models represent substantial improvements over their predecessor CMIP3 models which informed UKCP09 (Meehl *et al*., 2007).

All of the above information has subsequently been considered alongside the relevant climate change impact research on the built environment (especially the 2017 Climate Change Risk Assessment (CCRA) published by the UK Committee of Climate Change) to arrive at the most up-to-date picture (Dawson *et al*., 2016a).

It is noted here that the report's focus is on marine and coastal impacts: coastal transport and infrastructure will still be prone to some of the same potential hazards to which non-coastal transport and infrastructure is potentially susceptible (such as rail buckling under higher temperatures), but these are not covered here.

What is happening to key impact drivers?

Storms and waves

Decadal variability in terms of storms and waves within the north-east Atlantic Ocean is mainly related to the North Atlantic Oscillation (NAO), and affects the west-facing coasts of the UK, but its effects can also be detected in the North Sea (Wolf *et al*., 2020). There is some evidence for an increase in wave height for the North-East Atlantic over the whole 20th Century and there is very strong evidence that storm activity has increased in the North Atlantic since the 1970s, at least into the 1990s. Interestingly, trends in wind speed around the UK were much weaker during this period, and therefore most of the increase in wave heights is attributed to Atlantic swell (waves generated far outside of UK waters but propagating here from the ocean) rather than locally generated wind sea. Wave heights may also have been enhanced by an increase in persistence of westerly winds (Wolf *et al*., 2020).

In addition to the NAO, the Atlantic Multidecadal Oscillation (AMO) is a pattern of long-term variability in sea-surface temperature in the North Atlantic which is also known to influence the climate over much of the northern hemisphere including the level of storminess in Europe (Peings and Magnusdottir, 2014). Because north–south gradients of heat in the Atlantic can be associated with the development of extra-tropical storms (Shaffrey and Sutton, 2006) these longer-term changes in sea-surface temperature can alter the odds of extreme storm occurrence over multidecadal timescales.

Coastal geomorphology

A large proportion of the coastline of the UK and Ireland is currently suffering from erosion (17% in the UK; 20% in Ireland) and of the 3700 km coastline of England and Wales 28% is experiencing erosion greater than 0.1 metre per year (Masselink and Russell, 2013). In Scotland, the National Coastal Change Assessment (NCCA) has mapped the physical susceptibility of the coast and identifies that soft coastline (i.e. coasts with the potential to erode) make up 19% (3802 km) of the coast (Hansom *et al*., 2017). However, between a half and a third of all coastal buildings, roads, rail and water network lie in these erodible sections. Where coastal changes occur, the NCCA identifies that they are faster than before: nationally average erosion rates around the Scottish coastline have doubled since the 1970s to 1.0 metre per year whilst accretion rates have almost doubled to 1.5 metres per year.

Where the coast is protected by engineering structures, rising sea levels have the potential to cause a steepening of the intertidal profile, often referred to as 'coastal squeeze'. According to Taylor *et al*. (2004) almost two-thirds of intertidal profiles in England and Wales have steepened over the past hundred years although some authors have questioned the extent to which this has occurred (e.g. Dornbush *et al*., 2008). It has also been shown that that coastal narrowing has occurred on undefended as well as defended profiles. This is consistent with there being a number of other factors responsible for changes in the width of the coastal zone in addition to the presence of defences and sea-level rise (Pontee, 2011, 2017).

Sea-level rise

Sea level has risen globally by around 0.2 m from 1901 to 2010, at an average rate of 1.7 mm per year (IPCC, 2013). Because of the wide range in future projections (and the possibility of very large increases in mean sea level by 2100), there is considerable interest in recently observed records of sea-level rise and whether they reveal acceleration in the rate of change. A number of studies looking at observational (satellite and tide gauge) records of global mean sea level reveal an apparent change in rate to ~3 mm per year over the past 30 years or so (e.g. Cazenave and Nerem, 2004; Church and White, 2006; Menendez and Woodworth, 2010; Chambers *et al*., 2017). In fact, the recent study of Nerem *et al*. (2018) finds that sea level is accelerating at rates which are consistent with the process-based model projections of sea level for RCP 8.5, which is considered to represent a 'business as usual' pathway.

The IPCC (2013) 20th century estimate of sea-level rise is consistent with a best estimate trend of 1.4 ± 0.2 mm/yr for sea-level rise based on UK tide gauge records, once corrected for land movement (Woodworth *et al*., 2009). It is also in agreement with the analysis of Wahl *et al*. (2013) who considered tide gauge records from around the North Sea and obtained estimates of sea level rise of 1.5 ± 0.1 mm /year with slight, but not significant, variations in different locations.

Importantly however, regional differences in isostatic rebound around the UK serve to moderate or amplify the global mean values of sea-level rise. Indeed when vertical and movement (from geological data or GPS measurements) is included then the combined effects lead to relative rates of sea level that are up to *c*. 2 mm per year lower in Scotland and the north of the UK, and up to 1 mm per year greater for the south of England (Horsburgh *et al*., in press).

Coastal flooding

Coastal flooding can arise from ‘functional’ defence failures when wave and extreme high water-level conditions exceed those for which the defence was designed, or structural defence failure where some element or components of the defence do not perform as intended. Functional failures arise from society’s need to compromise between the cost of the defence and the consequences of a flood, and can feature waves overtopping or still-water levels overflowing defences. These may progress to structural failures known as ‘breaching’, where the crest of the defence is lowered or an aperture forms. Each year, the Expected Annual Damages (EAD) from coastal flooding is £320M, which represents 24% of total UK EAD from all sources of flooding (Sayers *et al*., 2015).

Extreme high waters around the UK are typically caused by a combination of exceptionally high tides and severe weather events. While changes in the most severe weather events could therefore contribute to changes in sea-level extremes, there is no clear observational evidence for either systematic long-term changes in the intensity and frequency of storms (‘storminess’) or any detectable change in the magnitude of surge events associated with storms. As reported by Horsburgh *et al*. (2019), the scientific consensus is that any changes in extreme sea levels in the UK and worldwide have been driven by the observed rise in mean sea level (e.g. Marcos *et al*., 2015; Wahl and Chambers, 2015).

Observed impacts of climate change on transport and infrastructure

Each of the main factors of extreme sea levels exhibit considerable natural variability, which influences the frequency of flooding on inter-annual and multi-decadal timescales. This makes isolating changes due to climate change difficult. Notwithstanding this, over the last decade a growing number of studies, at both national and global scale, have found evidence for an increase in extreme sea levels over the last 150 years due to climate change (Haigh and Nicholls, 2017). However, while sea levels are now greater than they have been in the past due to climate change, there has been growing recognition that this has not led to a corresponding increase in coastal flooding (Stevens *et al*., 2016). This is because of continued improvements in flood defences, together with advances in flood forecasting and warning and emergency planning (Haigh and Nicholls, 2017).

The Arctic is warming faster than anywhere else on Earth and since satellite observations of Arctic sea ice began in the late 1970s, the Arctic has, on average, lost an area of 3000 km^3/decade of sea ice (Melia *et al*., 2017). Recent (2015) Arctic shipping transit statistics available from the Arctic Logistics Information Office and Canadian Coast Guard show an overall increase in trans-Arctic voyages from less than 10 in 2007 to around 70 in 2013. It is understood that these voyages are exploratory in nature, to establish whether Arctic routes are economically viable (Melia *et al*., 2017).

As previously discussed, there is some evidence for an increase in wave height for the North-East Atlantic over the whole 20th century and there is very strong evidence that storm activity has increased in the North Atlantic since the 1970s, at least into the 1990s. However, it is unclear whether recent behaviour is driven by global climate change or is simply natural variation and there is no clear evidence that these changes have directly impacted offshore infrastructure or their operation.

Responses by industry

Offshore infrastructure

Offshore infrastructure s potentially vulnerable to high wind speeds, large wave-heights and strong currents. These have the potential to cause disruptions to maintenance, operations and movements of the infrastructure and personnel, as well as presenting increasing challenges for energy production and transmission (HSE, 2005; WEC, 2014). Due to more-intense weather conditions than originally anticipated, a large number of offshore wind turbines in Europe have required extensive repair over the past few years. Many of these repairs are attributable to the turbines' designs, which were not engineered to withstand the force and duration of certain metocean (meteorological and oceanographic) conditions and extreme weather to which they have been exposed. Indeed, it has been estimated that extreme weather conditions have caused about 80% of all North Sea offshore turbines to sustain failing grouted connections. This has primarily been in monopole turbines, which can experience bending movement in the grouted joints between the monopole and the transition piece (Diamond, 2012). This has resulted in the need for urgent repairs to be carried out, such as at Greater Gabbard offshore wind farm in the southern North Sea. Measures are now being taken to address these grouting issues. One such measure includes DNV KEMA modifying its industry guidelines to lower the acceptable load threshold that can be placed on grouted connections (Diamond, 2012).

Although renewable energy sources like wind power are increasingly used in the fight against climate change, the generation capacity, availability and intermittency of such alternative technologies are also impacted by climate change. The growing realisation of the potential threat to offshore structures resulting from climate change has led to increased research efforts in recent years. For instance, the EU-funded HYDRALAB-PLUS project has been focusing on experimental hydraulic research to better address climate change adaptation issues. A key element of this project is the PRotection of Offshore wind Turbine monopilEs against Scouring (PROTEUS) study (Chavez *et al*., 2019), with large-scale experiments aimed at improving the design of scour protection around offshore wind turbine monopiles as well as future-proofing them against the impacts of climate change. This has the potential to increase the design storm conditions and influence the scour-protection stability.

In England and Wales, an overarching National Policy Statement (NPS) exists for new energy infrastructure (EN-1) (DECC, 2011a), together with a separate NPS for gas supply infrastructure and gas and oil pipelines (EN-4) (DECC, 2011b). For existing and new oil and gas offshore industry, guidance on the preparation of safety cases include consideration of the structural standards of offshore infrastructure and the weather events to which it may be exposed. New energy infrastructure and extensions to existing schemes typically require an Environmental Impact Assessment under the Infrastructure Planning (EIA) Regulations 2009. The 2014 update of the EU EIA Directive extends the list of impacts to be considered to include climate-change vulnerability impacts where this may go on to cause environmental impact if the site were affected (Dawson *et al*., 2016a).

Coastal infrastructure

Government research of relevance to coastal assets has been the Environment Agency's Collaborative Research Programme which has supported projects which improve our ability to replicate the coastal processes (with and without climate change) and hence provide robust predictions of change under different climate-change scenarios to support adaptive management. Projects include iCOASST (www.channelcoast.org/iCOASST/introduction) which considers large-scale geomorphological changes as well as using the information gathered from Pathfinder Projects which trialled new and innovative approaches to planning and managing for coastal change. Its current research (2016 to 2020) is seeking to improve the modelling of mixed beaches (and hence improving understanding of risk to coastal infrastructure behind these beaches).

Other relevant notable research initiatives include the Adaptation and Resilience of Coastal Energy Supply (ARCoES) project. This was a contribution to the wider Adaptation and Resilience in the Context of Change network (ARCC) although this project has now ended. The ARCoES project considered the challenges facing the future security of the UK nuclear energy sector and coastal energy supply in the north-west region of the UK as a result of a changing climate. A key aim was to produce an integrated model of the coast that can predict coastal changes for estuaries, gravel beaches, sandy beaches and dunes, and cliffs comprising both hard and soft rock. The model incorporates climate projections to the 2020s, 2050s, 2080s and best understanding of long-term coastal change to 2100, 2200 and 2500 CE. ARCC also has an Infrastructure operator's adaptation forum (IOAF). Coordinated by the Environment Agency, this forum enables members to work together to reduce vulnerability to climate change and realise opportunities presented by points of dependency between infrastructure systems.

In support of the Climate Change (Scotland) Act, research has included the National Coastal Change Assessment (NCCA) (Hansom *et al*., 2017) which aims to create a shared evidence-base for decision making in light of climate change (2015 to 2017). The study maps the physical susceptibility of the coast and will be used in the development of an Adaptation Programme for coastal assets.

A number of projects related to the understanding and mitigation of coastal flooding and erosion risk have been funded through The Environmental Risks to Infrastructure Innovation Programme (ERIPP) since 2014. ERIIP is a collaboration between the Natural Environmental Research Council (NERC) and infrastructure owners, operators, policy makers and regulators to fund innovation and translational projects which use environmental science to identify, quantify and manage environmental risks, such as those from extreme weather and climate change. Information on projects awarded grants (including case study outputs) can be accessed via http://nerc.ciria.org/.

Around 95% of all goods entering and leaving Britain are moved by sea and the port sector directly contributes £1.7 billion to the UK economy. Accordingly, ports are of great strategic importance to the UK (Defra, 2018). The UK Climate Change Act 2008 introduced a requirement for 'reporting authorities' to report on how they are addressing and acting on the risks and opportunities from a changing climate, in the context of their business risks. This included Port Authorities with an annual throughput of more than 10 million tonnes of commercial cargo (of which there were 10 in the UK in 2017 (DfT, 2018)). The latest available adaptation reports are from 2015 although are due to be updated by the end of 2021.

Shipping

The Arctic is in transition to a seasonally ice-free state and could be largely free of sea ice in summer as early as the late 2030s (AMAP, 2017). The reduction in summer Arctic sea ice has led to increased interest in the possibility of transit shipping, using the Arctic Ocean as a shortcut between Pacific and Atlantic ports. The substantial reductions in distance compared with Suez and Panama Canal routes result in large cost savings due to reduced fuel consumption and increased trip frequency (Lasserre, 2014). Shorter shipping routes also have the potential to reduce global shipping emissions (Browse *et al*., 2013) although increased Arctic shipping may pose potential impacts on its ecosystem. For instance, the migration corridor used by marine mammals and birds correspond broadly with the main shipping routes into and out of the Arctic (Eger, 2010).

Currently, the fastest available routes between North Atlantic and Asian Pacific ports for non-specialised (or open water) vessels are along the Northern Sea Route (NSR) and North West Passage (NWP) and voyage statistics for the NSR and NWP show increasing traffic (Eguíluz *et al*., 2016). Whilst activity today is still mostly destination traffic to and from ports within the Arctic (Eguíluz *et al*., 2016; Stephenson *et al*., 2013), the NSR has seen growing traffic during summer months already, with cargos of oil and gas regularly making the journey. Notably, in 2018 a commercial container ship has for the first time successfully navigated the NSR of the Arctic Ocean. Also in 2016, China's COSCO shipping company (one of the world's largest) sent five vessels through the NSR, one of which delivered wind power equipment to the UK (Humpert, 2016).

Whilst ship traffic in the Arctic regions is increasing, there are significant operational challenges. As a result, recent years have seen a sharp rise in marine casualties (SEDNA, 2017). In response to this, the SEDNA ('Safe maritime operations under extreme conditions: the Arctic case') research project has been established to develop an innovative and integrated risk-based approach to safe Arctic navigation, ship design and operation. The project was established in 2017 and is due to run to 2020.

Although shipping accounts for only about 2.5% of global carbon emissions (IMO, 2015), the industry has come under concerted pressure to reduce this contribution. This is partly in response to the increasing need for global seaborne transport, but also because of the wide-spread use of carbon-rich fuels, such as heavy diesel. In response to this pressure, in 2018 it was agreed that carbon dioxide originating from ships at sea will now be regulated. Shipping companies will halve their greenhouse gas emissions by 2050 under the plan, brokered by the International Maritime Organisation and binding its 170 member states. Recently (May 2019), the Committee on Climate change has recommended to UK Government that legislation should be implemented as soon as possible to reach net-zero greenhouse gas (GHG) emissions by 2050 and that this target should cover all sectors of the economy, including shipping (CCC, 2019).

In order to achieve this, the agreement will require substantial changes to vessel propulsion which at present, are largely fuelled by heavy oils. In the short term, use of Liquid Natural Gas (LNG) may provide a means to reduce GHG emissions although the environmental advantages have been called into question (Baresic *et al*., 2018). Renewable energy may also be used as an augment to the main propulsion and auxiliary power requirements of a ship. In the medium-longer term, further propulsion options include alternative fuel options, fuel cells, batteries, solar and wind electricity generation, and possibly the use of sail in some cases. Indeed, the shipping industry has begun to experiment with rotating towers on ships that can harness wind power, potentially cutting fuel bills by 10% (WSJ, 2018). Nuclear power may also be an option, but would require a major change to ship owning and operation infrastructure and practices (Royal Academy of Engineering, 2013).

In addition to the above, a mandatory data collection system for fuel oil consumption of ships entered into force in March 2018. This will provide robust data and information on which future decisions on additional measures can be made. The mandatory data collection system is regarded as an important step in the IMO's Marine Environment Protection Committee roadmap (2016 through to 2023) for developing a "Comprehensive IMO strategy on reduction of greenhouse gas emissions from ships".

2. WHAT COULD HAPPEN IN THE FUTURE?

Storms and waves

Climate change may affect storminess, storm tracks and hence winds and wave heights. Future projections in UK waters are very sensitive to climate model projections for the North Atlantic storm track, which remains an area of considerable uncertainty (Wolf *et al*., 2020). UKCP18 21st century projections of average significant wave height suggest a general tendency towards lower average significant wave heights around the UK, under the RCP 8.5 scenario (Figure 1; wave-height projections associated with other RCPs are not available). However, the annual maximum significant wave height is projected to change by up to about +/– 1m or 20% by the end of the 21st century: increases are found to occur off the south-west of the UK, in parts of the Irish Sea and to the north of the UK but reductions are seen off the west of Ireland and in the southern North Sea. High-resolution wave simulations suggest that the changes in wave climate over the 21st century on exposed coasts will be dominated by the global response to climate change. However, more sheltered coastal regions are likely to remain dominated by local weather variability over the 21st century. Levels of uncertainty associated with all projections remains high (Palmer *et al*., 2018).

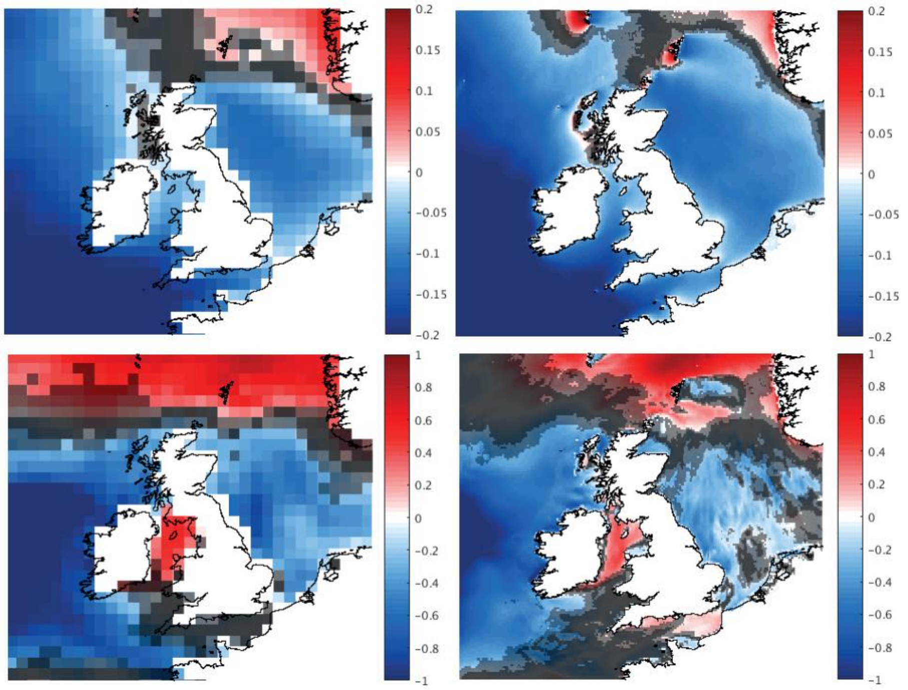


Figure 1: RCP 8.5 (high emissions) end century change in mean significant wave height (top) and mean annual maxima (below). Global model (left) and regional (right). All plots show an absolute change, in metres. Grey masking indicates where natural variability is high. Where there is no

masking, there is higher than a 75% chance that the future wave conditions are different to the historical conditions, rather than masked by natural variability. (From Palmer et al.*, 2018.)*

Coastal geomorphology

The two main consequences of climate change that have an impact on coastal geomorphology are sea-level rise and changes to the wave climate (storminess and prevailing wave direction). However, predicting future coastal erosion rates remains problematic: coastal response to sea-level rise is strongly determined by site-specific factors (such as geology, human influence and sediment supply) and usually it is these factors that determine the precise coastal response, rather than a global change in sea level or a regional change in wave climate (Masselink and Russell, 2013).

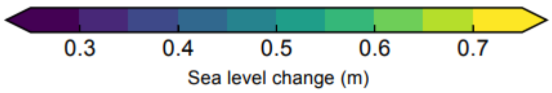
Notwithstanding the above, it is very likely that stretches of coast currently undergoing erosion will experience increased erosion rates as a direct consequence of sea-level rise. Furthermore, the removal of coastal defences as part of managed realignment coastal management strategies will also increase coastal erosion rates. Therefore, the proportion of coastlines undergoing erosion, and the average coastal recession rates in the UK, are expected to increase in the future (Masselink and Russell, 2013).

Sea-level rise

UKCP18 21st century projections of time-mean sea-level change around the UK vary substantially by climate change scenario and geographic location. By 2100, sea levels around the UK are expected to have risen by between approximately 0.3 and 1.2 metres above the 1981 to 2000 average level, with the greatest increases observed in the south of the UK (Table 1). These sea-level projections are consistently larger than in the previous set of UK climate projections, UKCP09 (see Lowe *et al.*, 2009), for similar future GHG scenarios (Palmer *et al.*, 2018). It is noted that UK sea-level rise is slightly lower than global mean sea level rise across all RCP scenarios throughout this century. For example, under RCP4.5 the UK average value at 2100 is 89% of the global value. This is because of the proximity of the UK to the Greenland ice sheet: As ice sheets lose mass their gravitational pull weakens, causing a local lowering of sea level and movement of water away from the ice sheet. For the UK, the contribution of the Greenland meltwater component is therefore reduced compared to the global mean (Horsburgh *et al.*, 2019).

Table 1: Range of sea-level change (m) at UK capital cities in 2100 relative to 1981 to 2000 average for a low (RCP2.6), medium (RCP4.5) and high (RCP8.5) scenario. (From Palmer et al.*, 2018).*

	RCP2.6		RCP4.5		RCP8.5	
	5th	95th	5th	95th	5th	95th
London	0.29	0.70	0.37	0.83	0.53	1.15
Cardiff	0.27	0.69	0.35	0.81	0.51	1.13
Edinburgh	0.08	0.49	0.15	0.61	0.30	0.90
Belfast	0.11	0.52	0.18	0.64	0.33	0.94



Exploratory, time-mean relative sea-level projections to 2300 undertaken as part of UKCP18 suggest that UK sea levels will continue to rise over the coming centuries under all climate change scenarios. For London and Cardiff, the projection ranges at 2300 are approximately 0.5 to 2.2 m, 0.8 to 2.6 m and 1.4 to 4.3 m for RCP2.6, RCP4.5 and RCP8.5, respectively, above the 1981 to 2000 average level. The values for Edinburgh and Belfast are substantially lower, with corresponding ranges at 2300 of approximately 0.0 to 1.7 m, 0.2 to 2.1 m and 0.7 to 3.6 m (Palmer *et al*., 2018). Spatial variation in the glacio-isostatic adjustment and Greenland meltwater components account for the differences in projected sea-level rise between the sites.

Coastal flooding

Coastal flooding is caused by the occurrence of high water-levels that exceed the elevation of the land, including any coastal defence infrastructure. Extreme high water-levels typically arise from a combination of high tides and/or storm surges. If present, waves can also contribute to the landward transfer of flood water. The magnitude of the surge effect is controlled by the large-scale patterns of air pressure and wind associated with a storm. On the basis of modelling undertaken for UKCP18, the frequency and magnitude of extreme water levels around the UK coastline is expected to increase over the 21st century and beyond under all RCP climate change scenarios. However, this increase will be dominated by the effects of mean sea-level rise (increasing the overall water level generally), rather than changes in tidal water levels, or storminess (affecting the magnitude of surge or wave contributions) (Palmer *et al*., 2018). In fact, because of the wide disagreement between model simulations of potential future changes to surge water levels, UKCP18 proposes a best overall estimate of zero change in surge over the 21st century.

It is noted that the greatest increases in sea level are expected to occur in the south of the UK with rates of sea-level rise becoming increasingly non-linear throughout the 21st century under higher-emissions scenarios. The extent to which this leads to an increase in coastal flooding will be spatially variable and highly dependent upon coastal management policies as well as other local-scale factors, especially coastal elevation/ topography.

For contingency planning, UKCP18 has produced an illustrative, high-end storm surge projection. Using this model, depending on location around the UK, a trend of –0.5 to 1.3 mm/yr was found for the 1-year return level and for the 200-year return level the trend was –1.1 to 2.7 mm/year. However, even for this high-end scenario, typical projected rates of mean sea level rise over the 21st century are around twice this value (Palmer *et al*., 2018).

Implications for industry

Offshore infrastructure

Wind-power production depends very strongly on wind speed, and to a lesser extent, the wind direction. Changes that affect the mean wind speed in a particular location would therefore be expected to influence the power generation and possibly the finances of a wind farm. Wind turbines have an associated power distribution curve: a typical 5 MW turbine will generally start producing power when the wind speed reaches around 3 m/s, reach peak output at around 15 m/s and cut out and stop producing power at speeds greater than about 25 m/s to prevent damage to the turbine in these very high wind speeds. A change in the characteristic wind distribution due to climate change could lead to a different amount of energy being generated over a given period of time (Cradden *et al*., 2015). However, it is noted that future projections of the wind climate are highly uncertain: Any small potential signals in UK wind speed projections are very difficult to distinguish from the high levels of background 'noise' associated with natural system variability.

In addition to climate-related changes in average wind speed, a shift in the storm track paths or in the strength of the driving forces could lead to a change in the spatial distribution of wind speeds around the country (Cradden *et al*., 2015). There is some evidence to suggest that the paths of incoming Atlantic storms may change under future climate change scenarios (e.g. Jiang and Perrie, 2007; Woollings *et al*., 2012; Zappa *et al*., 2013) although confidence in such projections is low.

Additionally, seafloor conditions, such as scour and sand-wave migration, often present poorly understood risks, as do extreme weather impacts on such conditions (Diamond, 2012). Seafloor dynamics, including wave conditions, tides, currents and water flow velocity, can create chronic scour, or the depletion of seabed sediment. Scour can cause erosion around turbine bases located in sandy soils, making turbine foundation anchoring less sturdy and reducing turbine stability.

Extreme weather causing seafloor sediment to be more mobile than anticipated could result in higher cable-scour incidents than currently envisaged, potentially causing exposure. Relaying or repairing cables requires highly specialised vessels and personnel, and the global increase in the demand for these vessels for wind farm installations may make access to them at short notice both difficult and costly (Dawson *et al.*, 2016a).

In 2011, the Department of Energy and Climate Change (DECC) stated that a wave and tidal stream capacity of 27 GW could be deployed in the UK by 2050 assuming a high deployment scenario (DECC, 2011c). Although the capacity of the UK's shoreline wave and tidal technologies grew from 13 MW in 2016, to 18 MW in 2017 – an increase of 36.4% – the sector remains in its infancy. Notwithstanding this, important steps towards commercialisation have taken place in the past few years and a range of research, development and innovation projects have been progressing (OES, 2018). The main focus for wave and tidal energy resource exploitation is off the north coast of Scotland with a number of prototype designs being tested at EMEC (European Marine Energy Centre) in Orkney. Lease rights have also been issued by the Crown Estate (Scotland) in these waters. As previously stated, wave modelling undertaken for UKCP18 suggests that in almost all areas average significant wave height is projected to marginally reduce, whilst annual maximum significant wave-height may increase in places. These changes have the potential to alter the long term energy output from wave-energy convertors although it is noted that confidence in these future wave climate projections remains low. Larger extreme waves could theoretically increase the risk of direct damage to the devices although this risk may be mitigated through good device design, reducing the wave induced forces on the structure by stopping energy generation during such events. Tidal stream energy convertors are also capable of ceasing generation during extreme events (Side *et al.*, 2013). Increased scour around mooring systems and seabed electricity transmission infrastructure is also possible with larger waves. However, this risk is likely to be limited to wave energy conversion devices since by their nature, tidal stream devices are located in areas experiencing fast currents which are therefore likely to be characterised by naturally scoured seabed environments.

Offshore petroleum industry structures (both fixed and floating) also have the potential to be impacted by climate change. An increase in significant wave height will place greater stresses on these structures where design considerations focus also on extreme events. However as previously discussed, uncertainty with future projections of wave climate remains high. Scour (either around the base of offshore structures and/or along pipelines) may also be exacerbated by any increase in seabed currents. In deeper offshore areas, the influence of wave induced currents on the bed is more limited although currents associated with storm surges may contribute to scour. However, in shallower areas (especially where pipelines approach the shore) wave-induced scour may be significant. Remedial measures (such as the use of rock protection) are available, although may be costly and require regular inspection (Side *et al*., 2013).

Importantly, many aspects of the deployment, operation and maintenance and decommissioning of offshore oil and gas (as well as other) structures will depend on 'weather windows' for at-sea working to be conducted safely. These may alter under a changing climate, bringing both risks and (potentially) benefits. The potential for impact will be dependent upon a range of factors including the nature of operations and type of vessels involved in carrying these out.

Coastal infrastructure

Coastal defences

Wave conditions around much of the UK coast are limited in size by the nearshore water depth. Because of this, relative sea level rise has a dominant influence on coastal flooding, (increasing both wave-driven overtopping, the probability of a breach and, in more-extreme climate change projections, tidal overflow (Sayers *et al*. 2015).

Along the UK coastline, the impacts of climate change on coastal infrastructure will vary according to structure type and location. However, even lower projected rises in mean sea-level could increase overtopping volumes by 50–150%, depending on structure type and location. Sayers *et al*. (2015) consider the potential vulnerability of current coastal-defence lines to failing as mean sea-levels rise to the 'toe' height of defence foundations (leading to stronger and near continual wave action on the weakest point of defence structures). The length of coastal defences in England that will be highly vulnerable to failure is expected to double under 1 m mean sea-level rise, from 110 km to 220 km in the absence of additional adaptation action. This would mean that 20% of the total length of coastal defences in England would be highly vulnerable

Properties on the coast

In England, 520,000 properties (including 370,000 homes) are located in areas with a 0.5% or greater annual risk from coastal flooding and 8900 properties are located in areas at risk from coastal erosion, not taking into

account coastal defences. The direct economic damages from flooding and erosion are over £260 million per year (CCC, 2018).
The extent of the impacts of coastal erosion on homes and communities will depend on the degree of future warming, and what future adaptations are undertaken. Even if the shoreline management plans are fully implemented, there will still be an estimated 700 properties lost to coastal erosion in England over the next 20 years, and a further 2000 after 50 years. Without these interventions, about 5000 properties could be affected within 20 years and about 28,000 within 50 years (Environment Agency, 2018). By the 2080s, up to 1.5 million properties (including 1.2 million homes) may be in areas with a 0.5% of greater annual level of flood risk and over 100,000 properties may be at risk from coastal erosion (CCC, 2018).

The NCCA for Scotland identified that 30,000 buildings are sited close to potentially erodible coasts. If recent erosion rates were to continue in the future, by 2050 at least 50 residential and non-residential buildings (along with 1.6 km of railway, 5.2 km of road and 2.4 km of clean-water networks) are expected to be affected by coastal erosion. However, these numbers are likely to be underestimates as erosion rates are expected to increase in future due primarily as a result of increases in the rate of sea level rise (Hansom *et al*., 2017).

Road and Rail

Currently 12,000 km of UK transport infrastructure is considered to be at risk of flooding (Defra, 2012) and Hooper and Chapman (2012) suggest that the threat of flooding from sea-level rise combined with that from more extreme precipitation events renders coastal-transport infrastructure more at risk than its equivalent inland. In the UK alone, there are several vulnerable stretches of railway track, including the main lines in North and South Wales, the Cambrian Coast line in mid-Wales, the Chatham main line in south-east England, the Cumbrian coast line in north-west England and the Ayrshire line in south-west Scotland (Dawson *et al*., 2016b). One of the most vulnerable is the London–Penzance line which has a long history of closure at Dawlish during high seas and storm events. This vulnerability was illustrated during the winter storms in 2014 which breached the sea wall, leaving the railway tracks unsupported and closing the line for two months (Figure 2). Using a semi-empirical modelling approach, Dawson *et al*. (2016b) considered potential sea-level rise impacts on the London-Penzance line at Dawlish, using sea-level rise projections from UKCP09 in their work. They identified a relationship between sea-level change and rail incidents over the last 150 years and then used model-based sea-level predictions to extrapolate this relationship into the future. It was found that without substantial improvements to the coastal defences, days with line restrictions look set to increase by up to 1170%, to as many as 84 to 120 per year, by 2100 under a high sea level rise scenario (0.55 to 0.81 m).

Figure 2: Section of rail track dangles over the sea after the wall collapsed at Dawlish, Devon. (Source: BBC.)

Energy

The Climate Change Risk Assessment (2017) identifies energy as one of six key areas of climate change risk that need to be managed as a priority (Committee on Climate Change, 2017). The UK energy industry provides the country with around 200 Mtoe each year (million tonnes of oil equivalent), dominated by fossil fuels – 84.5% in 2014 – and has exported 70–80 Mtoe (930MWh) annually over the last five years (DECC, 2015). The main risk to coastal energy infrastructure posed by flooding from the sea is to power stations; in particular, all the UK's nuclear reactors are currently located at coastal sites. Electricity transmission and primary distribution substations are at greater risk of river flooding. Increased ambient seawater temperatures may also reduce the efficiency of thermal power plants by lowering the ratio of electricity produced to the amount of fuel used in the processing (Linnerud *et al*., 2011).

The coastal infrastructure that supports energy operations (oil, gas and renewables) includes gas terminals, refineries and ports. As noted by Dawson *et al*. (2016a), rough seas can prevent ships docking, limiting arrivals of fuel (and other cargoes) to the UK. Disruptions to road or rail networks could affect fuel distribution from ports, whilst port infrastructure is also potentially exposed to coastal erosion, sea-level rise and flood risk. Of note is the fact that half of the UK’s port capacity is located on the east coast, where the risk of damage from a tidal surge is greatest (Dawson et al., 2016a). This risk will be enhanced with rising sea levels.

Waste water

In order to minimize the costs of treating waste water, treatment plants serving coastal populations have typically been constructed at low elevations near the coast. This facilitates the conveyance of waste-water flows to the plant by gravity and thus minimizes the number of pumping stations required. In addition, coastal locations allow for efficient discharge of treated effluent to adjacent water bodies (Hummel *et al*., 2018).

Despite the benefits of locating waste-water treatment plants in coastal settings, such siting can also leave plants exposed to flooding which can be expected to occur more frequently in future if adequate coastal defences are not in place. The risk of flooding may also be exacerbated by more intense rainfall. Flood waters are often polluted by sewage, which leads to additional risks to health, higher repair costs and longer periods of disruption. In addition to flooding, higher sea levels can also prevent outfalls from functioning properly or interfere with underwater discharges of treated effluent, requiring larger pumps to overcome the increase in pressure above the outfall location. The salinity of marine floodwaters could also potentially lead to corrosion of critical plant components (Hummel *et al*., 2018).

Ports

UK Climate Change Act 2008 introduced a requirement for ‘reporting authorities’ to report on how they are addressing and acting on the risks and opportunities from a changing climate. Some of the main identified risks include:

- An increase in the risk of flooding, especially related to sea level rise;
- Significant changes in weather paths affecting cargo operations and transport. Extreme heat and cold also has the potential to adversely affect these operations;
- Power outages caused by damage to the distribution network;
- Greater pressure on drainage systems and pluvial flooding associated with extreme rainfall events;
- Increased water demand; summer water shortages potentially affecting locking activities;
- Increased summer cooling demands, especially buildings becoming uncomfortably hot;
- International supply chain effects on impacts and exports; and
- Weather-related disruption to inland distribution networks that could result in knock-on effects within the port.

In addition to the above, changes to flows from altered rainfall patterns could result in the seaward migration of the turbidity maximum during the winter and landward during the summer (or *vice versa*). This could affect sediment deposition patterns affecting navigation and dredging with resulting increases in costs of surveying and maintenance dredging. Similarly, storm events may also result in short term episodes of enhanced erosion and deposition, with consequential impacts on channel navigability. As well as potential changes in sedimentation, there may also be a morphological response of (navigation) channels to sea-level rise and storminess. However, this response is likely to be very much influenced by site-specific factors, including local geology, wave and tide conditions, sediment transport, human impacts and the interactions between different coastal systems.

Amongst other potential impacts, any changes in storminess and storm tracks and hence significant changes in wind speeds or wave heights will impact on operations such as berthing, pilot boarding and cargo handling (i.e. crane operations) (ABP, 2016). Any local increases in the number of fog days will similarly have implications not only for pilotage activities but also for safety generally, especially in areas intensively used by recreational as well as commercial vessels as in the case of the Thames through London (Boorman *et al*., 2010; PLA, 2015).

Warmer air and water temperatures could also affect biology and water chemistry with various potential direct and indirect impacts for ports and other coastal infrastructure or activities. Both increased growth rates and desiccation can have implications for vegetation management in navigable upstream waterways within harbour areas. Increased water temperature and changes in salinity/acidity can affect suitability for certain species, not only those at the edge of their range (with potential implications for harbour-based activities such as fishing or wildlife watching) but also for non-native species, including those that adversely impact on infrastructure e.g. through fouling/smothering or burrowing. It is noted here that fouling and related processes have the potential to similarly impact offshore infrastructure.

One of the main challenges of climate adaptation for ports is that many future climate-change impacts may fall outside the planning horizon of the ports, but investment in long-lived assets needs to be considered now (particularly in the case of hard infrastructure). Moreover, given the multiplicity of port decision-makers (policymakers, private, terminal operators, and others) alongside budgetary constraints, it is not always straightforward to determine how climate-change impacts should best be addressed. For instance, a private terminal operator on a medium-term (say 20 years) lease is unlikely to invest in items that would mainly benefit the future holders of the concession (Becker *et al*., 2018).

Shipping

It is uncertain how future climate change will impact the extreme-sea states that will be encountered by ocean-going vessels. Available observational evidence suggests that there has been an increase in significant wave height from the middle of the twentieth century to the early twenty-first century in the northern hemisphere winter in high latitudes, although it is unclear if the increase observed during the past 4 to 5 decades is caused by anthropogenic climate change or just a consequence of long-term natural variability. Regardless of cause, it has been shown that in order to maintain the same safety level, the steel weight of the deck in the mid-ship region should be increased by 5–8 % if the extreme significant wave height were to increase by 1 m (Bitner-Gregersen *et al*., 2013). However, it should also be noted that weather forecasts are also improving, increasing the ships ability to avoid extreme metocean conditions by using weather routing systems.

As previously stated, the reduction in summer Arctic sea ice has led to increased interest in the possibility of transit shipping, using the Arctic Ocean as a shortcut between Pacific and Atlantic ports. Melia *et al* (2016) used global climate model simulations to consider how projected sea-ice loss might increase opportunities for Arctic transit shipping. The authors find that by mid-century, the frequency of navigable periods doubles, with routes across the central Arctic becoming available (Figure 3). European routes to Asia are typically found to become 10 days faster via the Arctic than alternatives by mid-21st century, and 13 days faster by late 21st century. The analysis also finds that the shipping season reaches 4 to 8 months under RCP8.5. Despite these trends, inter-annual variability will remain a significant factor in route availability throughout the 21st century.

It is possible that trans-Arctic shipping will reduce Arctic warming by nearly 1 °C by 2099, due to sulphate-driven liquid water-cloud formation (Stephenson *et al*., 2018). However, the magnitude of this cooling effect (~1 °C) is around an order of magnitude smaller than the overall regional warming in RCP 8.5 (~10 °C) and therefore the projections of Melia *et al*., (2016) should remain broadly unchanged.

The UK is well positioned, geographically, geopolitically, and commercially, to benefit from increasing Arctic shipping: potential opportunities for the UK include the development of a UK-based trans-shipment port – transferring goods from ice-classed vessels to conventional carriers. Indeed due to this opportunity and their strategic location for European bound trans-Arctic shipping, Stornoway Port Authority has proposed their long-term vision to become an Arctic gateway hub in 20 years (Melia *et al*., 2017).

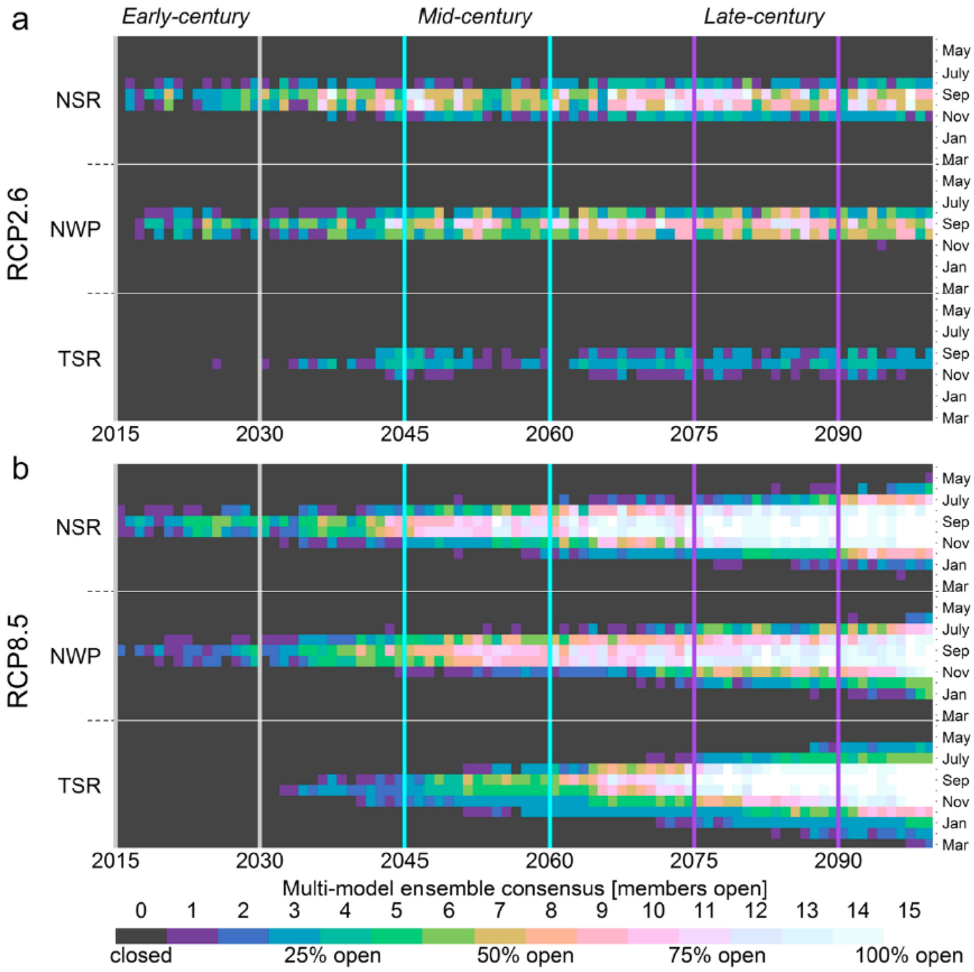
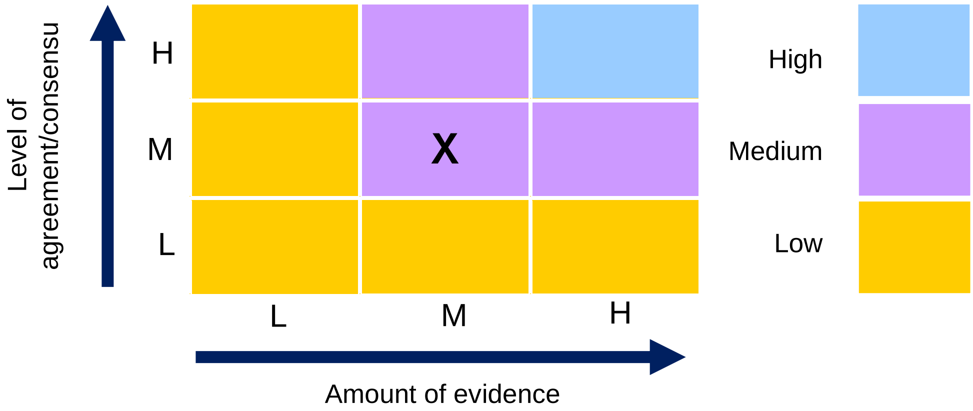


Figure 3: Year-round trans-Arctic projections for open-water vessels. The different arctic routes (Northern Sea Route (NSR), North-West Passage (NWP) and Transpolar Sea Route) are shown in three horizontal bands for (a) RCP2.6 (low emissions) and (b) RCP8.5 (high emissions). (From Melia et al. *2016.)*

3. CONFIDENCE ASSESSMENT

What is already happening?

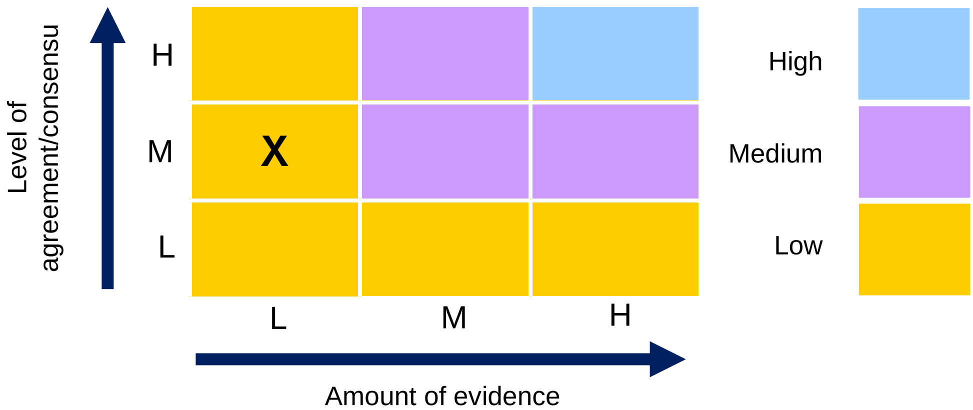
In recent years, there have been a number of efforts to develop a better picture of the geographic distribution of infrastructure assets to help inform understanding of potential vulnerability to climate change. The impacts on these assets from extreme weather (especially flood events) are also being recorded more comprehensively. However, detailed monitoring and recording of the performance, deterioration and thresholds of failure of infrastructure is not yet being carried out in a systematic manner which complicates attempts to determine vulnerability to key forcing mechanisms (Dawson *et al*., 2016a).



What could happen in the future?

Confidence with regards to assessments of potential future impacts to transport and infrastructure is intrinsically linked to the robustness of future climate change projections. In terms of sea level, there is a very high degree of confidence that it will continue to rise throughout the 21st century although the range in future projections remains large. (This relates to both uncertainty with regards to future emissions trajectories and the behaviour-response of the polar ice sheets to rising sea levels and ocean warming). With regards to future patterns of storms and waves, confidence in projections remains low, with substantial differences between climate models. However, new higher-resolution models promise better representation of storms (Wolf *et al*., 2019).

Rising sea levels and (potential) increases in maximum significant wave heights could have important consequences such as enhanced/accelerated erosion and more frequent flooding in estuaries, deltas and embayments. Increasingly sophisticated numerical models are being used to consider the morphological response of coastal systems to these potential hydrodynamic changes. However, the complexity of coastal systems means the range of possible outcomes is high and confidence in predictions remains low.



4. KEY CHALLENGES AND EMERGING ISSUES

Key knowledge gaps regarding the potential impacts of climate change on transport and infrastructure have previously been considered by Dawson *et al*. (2016a), for the 2017 UK Climate Change Risk Assessment and by Edwards (2017), as part of the UK government's Foresight Future of the Sea project. The following knowledge gaps identified in these reports are particularly pertinent for marine infrastructure:

- Considerable uncertainty exists with regards to how climate change may affect a number of weather parameters that determine infrastructure risk profiles. This is particularly the case for patterns of atmospheric circulation which control wind (and wave) regimes. Any change in these parameters could have significant implications for the reliability of infrastructure assets with long design lives, especially when considered alongside other climate variables, notably sea-level rise.
- There is a requirement for improved understanding of correlated risks, such as flood events across large sections of coast or clustered in time (e.g. Haigh *et al*., 2016) and risks of multiple types of flooding simultaneously, e.g. coastal and river. This requirement for improved understanding of change to joint probabilities of extreme water levels over the next century is particularly needed in estuarine settings, where the relationship between increases in sea level and extreme water level may be non-linear, and also influenced by other factors, such as morphological change.
- Monitoring and recording of the performance, deterioration and thresholds of failure of infrastructure needs to be undertaken over the long term in order to construct a comprehensive database of infrastructure fragility. This needs to be carried out in a consistent manner to enable cross comparison between assets/ locations.

Climate-change adaptation is also not only about infrastructure: operations and activities will also be affected and measures to improve resilience will be needed. The Cabinet Office (2011) identified four strategies to manage infrastructure risks and build resilience:

- Increase the resistance of infrastructure components by providing enhanced protection;
- Improve the reliability of infrastructure components so they are able to operate under a range of possible conditions;
- Provide redundancy to increase the capacity, number of alternative connections and diversity of backup systems; and
- Build capacity in organisations and communities to deliver a fast and effective response to, and recovery from, climate disruption.

Monitoring and recording of operational threshold exceedances will also help to understand local trends and hence when adaptation measures need to be introduced.

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