Impacts of Climate Change on Transport and Infrastructure relevant to the coastal and marine environment around the UK and Ireland

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KEY FACTS

What is already happening?

- Increasing construction activity at sea means a greater proportion of our critical infrastructure, particularly offshore renewable energy, is exposed to the effects of climate change on the marine environment.
- Sea levels are rising around the UK at an accelerating rate, increasing flood and erosion risk to critical coastal assets (e.g. energy, transport and water).
- Water temperatures in our seas and estuaries are increasing around the UK, impacting marine species distribution and the efficacy of cold-water cooling applications.
- Higher sea levels and more severe storms are increasing the risk to operations which are sensitive to weather-related disruption. These include disruption to ports and shipping through flooding, high winds and waves, heatwaves, cold snaps and fog, and disruption to operation and maintenance of marine infrastructure from weather downtime.

What could happen in the future?

- Sea level is likely to continue to rise at an accelerated rate with an associated increase in flood and coastal erosion risks to ports and coastal infrastructure.
- Increased frequency and severity of storms is anticipated to result in increased disruption to shipping affecting port operations, and greater costs for operation and maintenance of marine structures.
- Increased need for forecasting and early warning systems to manage marine risk, for example ferry services, and operation and maintenance of marine infrastructure.

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- The trans-Arctic shipping route, currently only navigable during summers with limited ice sheet extent, could be navigable four to eight months of the year by 2100.
- Increasing seawater temperatures, particularly in semi-enclosed shallow coastal areas such as estuaries, are expected to affect the design and licensing of cooling and wastewater discharge systems.

SUPPORTING EVIDENCE

Overview

A growing proportion of the UK's infrastructure, particularly for energy generation, is situated in the sea and coastal zone. This trend will continue with the British Energy Security Strategy measure to deliver 50 GW of offshore wind energy by 2030, including 5 GW from floating technology (UK Government, 2022b). This infrastructure contributes to a significant proportion of GDP; offshore oil and gas – £20Bn (OEUK, 2023); Offshore wind – £6Bn (ONS, 2021); aquaculture – £0.8Bn (Salmon Scotland, 2022); £116Bn generated by through-port trade (Maritime UK 2022) and supports significant direct and indirect employment around the UK. This paper discusses the climate risk (now and in the future) to marine transport and infrastructure and is an update to the previous MCCIP Report Card by Brooks et al. (2020). It should be read in conjunction with MCCIP papers on storms and waves, coastal geomorphology, sea-level rise and marine temperature. Information on the impacts on coastal flooding can be found in Haigh et al. (2022).

What is already happening?

Sea-level rise

Sea levels around the UK are rising, with around 18.5cm of sea-level rise recorded along UK coastlines since the 1900s (Kendon et al., 2022), compared to a global mean sea-level rise of 20 cm for the same period (Fox-Kemper et al., 2021). There is now sufficient evidence that the rate of sea-level rise around the UK is accelerating, with rates between 3.0 ± 0.9 mm per year and 5.2 ± 0.9 mm per year recorded over the period from 1991 to 2020 (when corrected for vertical land movement), which is significantly larger than the longer-term increase rate of 1.5 ± 0.1 mm/year observed since the 1900s (Hogarth et al., 2020; Fox-Kemper et al., 2021; Kendon et al., 2022).

Sea-level rise is not occurring uniformly around the UK but varies regionally, primarily due to differences in isostatic adjustment (vertical land movement following the last deglaciation) (Palmer et al., 2018; Kendon et al., 2022). For example, tide gauge measurements in Wick (northern Scotland) have recorded increases of 2.9 ± 0.6 mm/year between 1991 to 2020, while Newlyn (south-west England) has measured a rise of 4.2 ± 0.8 mm/year for the same period (Kendon et al., 2022).

Winds, storms and waves

While sea-level rise is a primary concern, extreme water level events, which are usually caused by a combination of storm surges, wave conditions and local tides, can have highly damaging impacts and pose an increasing risk to UK coastlines as the underlying mean sea level continues to increase (Palmer et al., 2018; Haigh et al., 2022). Additionally, high winds, storms and large waves are key hazards to offshore infrastructure.

Over the last 30 years in the south of the UK, significant wave height (approximately equal to the average of the highest one-third of wave heights) has increased, whilst decreasing in the north (Bricheno et al., 2023). These trends are generally attributed to variability in large-scale atmospheric set-up rather than locally generated waves around the UK (Castelle et al., 2017; Hochet et al., 2021; Bricheno et al., 2023). Notwithstanding this significant variability (Earl et al., 2013), HadUK-Grid observations show peak windspeeds around the UK show a broadly downward trend compared to the 1980s and 1990s, with mean windspeed also showing a downward trend since the 1960s (Kendon et al., 2022). However, any trends must be treated with caution due to the large day-to-day and year-to-year variability (Zeng et al., 2019; Wohland et al., 2021). Additionally other studies which use alternate observation datasets (e.g. ERA-interim, Murphy et al., 2018; ERA5, Laurila et al., 2021) find there is no consistent trend in daily mean windspeeds over the UK (Pirret et al., 2023). Elsewhere changes in wave conditions will have implications for shipping to and from UK ports with sea ice loss leading to increased wave heights in the Arctic (data between 1992 and 2014) (Collins et al., 2019; Fox-Kemper et al., 2021).

Extra-tropical cyclones, also called ‘mid-latitude depressions’, are the prevailing weather systems for the UK and can produce storm surges (Horsburgh et al., 2020). The North Atlantic storm track brings these storms and associated extreme waves originating over the Atlantic to the UK region. A northward shift in the North Atlantic storm track and mid-latitude depressions is evident over the past 50 years (Gulev et al., 2021; Seneviratne et al., 2021; Bricheno et al., 2023). There is very strong evidence that storminess has increased in the North Atlantic since the 1970s, into at least the 1990s (IPCC, 2013), potentially increasing the occurrence and severity of these systems in the UK, although the degree of natural variability in these systems means confidence in this trend is comparatively low. In fact, when looking at the observations since the mid-20th century, there is no trend in observed windstorms over the UK (Pirret et al., 2023). However, recent work indicates a pattern of increasing storm surge magnitudes along UK coastlines north of 52°N and a decreasing pattern along UK coastlines south of 52°N from 1960 to 2018 (Calafat et al., 2022). Calafat et al. (2022) challenge the scientific consensus that observed increases in extreme water levels around the UK are primarily driven by changes in mean sea level (Haigh et al., 2022). Instead, the study finds the magnitude of the surges is comparable to sea-level change in influencing extreme water levels from 1960 to 2018, having a variable impact around the UK, increasing the likelihood of an extreme storm surge along northern UK coastlines and decreasing the likelihood of extreme storms surges along southern UK coastlines (Calafat et al., 2022).

Coastal geomorphology

Coastal geomorphology is a product of the governing oceanographic, sedimentological and geological processes that are present at a given time/location. As these processes exhibit daily, seasonal, annual, and decadal variability, deriving a trend attributable to climate change is challenging. Currently 28% of the shoreline in the in England and Wales is considered vulnerable to erosion with, 19.5% vulnerable in Northern Ireland and 19% in Scotland (Jaroszweski et al., 2021). When considered nationally, greater than 20% of the coast is susceptible to erosion with a high proportion of this active coastal retreat (17% of the UK coastline and 19.9% of the Irish coastline, Masselink et al., 2020).

In locations where the shoreline cannot retreat due to hard coastal infrastructure, coastal habitats are unable to naturally roll back landwards with sea-level rise, resulting in the loss of these habitats (coastal squeeze). The loss of buffer coastal habitats, such as dune systems, saltmarsh and machair (saltmarsh-like habitat found in Scotland), represents degradation of natural inundation and erosion prevention mechanisms, which further increases the risk of erosion and inundation of the coastline and the built environment.

Sea surface temperature

Increases in global air temperatures lead to increases in sea-surface temperature in most global ocean basins (Collins et al., 2019), with UK near-coast temperatures between 2012 and 2021, 0.7°C warmer than the 1961–1990 average (Kendon et al., 2022). Mean ocean-surface warming is also correlated to longer and more frequent short-term extreme warming events, called marine heatwaves (Oliver et al., 2018). In the North East Atlantic region, these marine heatwaves can spread across millions of square kilometres of sea area, persist for weeks to months, and occur at the subsurface (Fox-Kemper et al., 2021). One recent example is the 2023 marine heatwave, where the North Atlantic, including waters around the British Isles, experienced record-breaking sea-surface temperatures in June (Copernicus Climate Change Service, 2023; Met Office, 2023). This event was identified as a category 4 marine heatwave with sea-surface temperatures 5°C higher than the 1985–1993 average (European Space Agency, 2023).

Impacts of climate change on transport and infrastructure

Climate change has had a wide-ranging impact on marine and coastal industry, and this is set to become increasingly acute as the influence of climate change increases.

Ports and Shipping

The UK's ports and harbours are currently at risk from climate change-related disruption. As noted by Dawson et al. (2016), rough seas can prevent ships docking, limiting arrivals of fuel (and other cargoes) to the UK. Flood, storm or heat-related disruptions to road or rail networks affect the distribution of fuels and other cargos to and from ports, whilst port infrastructure is also exposed to coastal erosion and flood risk. Half of the UK's port capacity is located on the east coast, where the risk of damage from storm surge is greatest (Dawson et al., 2016). These UK-wide impacts will increase the risks potential port closures, downtime and associated revenue losses and increased operational costs.

Ten out of 14 port authorities have voluntarily reported to the Climate Change Committee under the UK Climate Change Act 2008 third round of Adaptation Reporting Power (ARP3), including those managed by Dover Harbour Board (Port of Dover, 2021), Mersey Docks and Harbour Company and Port of Sheerness Ltd (Peel Ports, 2021), Port of London Authority (Port of London Authority, PLA 2021) and Associated British Ports (ABP, 2021). All these reports identified risks from increases in significant wave height, changes in wind speed or direction, and storm surge on top of rises in sea level to disrupt operations and/or damage port infrastructure.

Some ports also highlighted risks to shipping, impacting windows for safe navigation including pilotage, or changes in hydrography affecting dredging requirements. Other issues include possible extreme heat impacts on older structures and the implications of reduced summer rainfall for safety of operations/navigation in upstream sections on the River Thames (PLA, 2021). London and Dover ports (PLA, 2021, Port of Dover, 2021) highlighted the impacts of increases in the frequency of winter fog conditions, and Liverpool port (Peel Ports, 2021) identified potential impacts on lock gate operations. Most of the ports that prepared reports identified or alluded to important interdependencies and/or highlighted the increased risk of cascading failures, for example in transport, electricity or water supply (refer to coastal structures below). Some pointed to the wider potential impacts of climate change disruption in global supply chains.

Offshore structures and infrastructure

Offshore infrastructure includes assets of the oil and gas and the renewable energy industries, telecommunications and interconnector cables and aquaculture. They may be fixed or floating and include platforms, rigs, turbines etc., producing or transporting product from the reservoirs to processing terminals on the UK's coastline or moving product between countries. Since 2010, there has been substantial growth of the marine renewable energy sector including wind, tidal stream and wave energy. Much of this growth has focused on the expansion of offshore wind farms and is leading to an exponential increase of offshore infrastructure and the services on which they rely (i.e. survey vessels, cable installation, port infrastructure). Offshore windfarm assets include those with fixed foundations to ~60m depth and floating offshore wind turbines. Additionally, renewable energy assets (marine and coastal) are now being designed to include hydrogen production and energy storage battery facilities to enable continued energy generation during unfavourable generation conditions (Murray, 2022).

Offshore infrastructure above or below water, whether on fixed foundations, or floating and moored through catenary lines and anchors, is potentially vulnerable to high wind speeds, large wave heights, and strong currents. Due to a changing climate, these assets may be exposed to more extreme weather conditions than originally anticipated. A large number of offshore wind turbines in Europe have required extensive repair over the past few years. Indeed, it has been estimated that extreme weather conditions have caused about 80% of all North Sea offshore turbines to sustain failing grouted connections (Diamond, 2012).

As an island nation, the UK is heavily dependent on the uninterrupted provision of telecommunication, energy and electricity services delivered by subsea cables and pipelines. Protection of the subsea power cable network, in particular, is a key consideration with approximately 80% of all financial losses and insurance claims in the offshore wind industry attributed to electricity transmission cable failures, this is because most of the infrastructure consists of hundreds of miles of power cables (Arikan and Campbell, 2021). Climate change can lead to increased risk of exposure, scour and failure of these assets.

Significant investment is focusing on more robust and durable high-voltage energy transmission cables, transferring electricity between countries (interconnectors), with four new ones online since 2019 and five more planned for completion by 2025 (Ofgem, 2022). These infrastructure assets play an important role in ensuring national energy security and are key to enabling the UK to reach the target of 50 GW of offshore wind energy by 2030, set by the British Energy Security Strategy (BESS), published in April 2022 (UK Government, 2022b).

Currently, more than 97% of all intercontinental digital data traffic is carried by subsea telecommunications cables due to the limitations of satellite transmission. Trillions of dollars are traded along this network each day, which also enables internet services by supporting remote working and a host of virtual digital data transfer and storage applications (Bueger et al., 2022). As a consequence, the UK relies heavily on over 70 subsea fibre optic cable systems comprising many hundreds of individual cables, that help facilitate national and international communications by internet and telephone traffic (The Crown Estate, 2023).. The UK, as an island nation, is thus vulnerable to cascading failures of the global communications network with marine climate related impacts to global communication systems potentially having acute impact to UK connectivity (Clare et al., 2022), demonstrated by the failure of underwater communications to Orkney and Shetland in 2022 (BBC, 2022). While this event was likely related to fishing activity, climate-driven hazards, such as extreme weather, pose an increasingly important threat. Telecommunication cables are laid water depths of less than 1500 m and are generally buried to protect them from damage by bottom fishing, anchor drops as well as natural processes such as storms and seafloor sediment mobility. Approximately 10% of instances of damage to seafloor cables result from scour abrasion or chaffing, that can occur due to the action of vigorous seafloor currents, particularly where cables cannot be buried and must be surface laid (e.g. where seafloor comprises bedrock) (Kordahi et al., 2016). Cable-landing locations (where cables come ashore) are additionally vulnerable to climate-related stressors similar to other coastal infrastructure, such as extreme weather events (Clare et al., 2022).

Coastal structures and infrastructure

Within the UK, 35 power stations, 34 electricity substations, 22 clean water facilities and 91 sewage treatment works are currently at significant risk from coastal flooding and erosion (Jaroszweski et al., 2021). 511km of vital coastal rail links (e.g., the Dawlish railway line) are also at risk, including 25 railway stations (Jaroszweski et al., 2021). In recent years, high temperatures, strong winds and flooding have had a significant effect on the UK's railways. These adverse conditions are accelerating asset deterioration and increasing the likelihood of critical coping thresholds for railway operators being exceeded, such as on rail temperatures, resulting in buckling, or drainage capacity exceedance, causing flooding (Joint Committee on the National Security Strategy, JCNSS, 2022), with coastal stretches of rail at greatest risk from flooding.

The main climate-change related risk to coastal energy infrastructure, particularly power stations, is coastal inundation. All the UK's nuclear reactor plants are currently located at coastal sites. However, the risk of nuclear reactor plants being inundated is judged as low due to the sites having very high standards of protection (Jaroszweski et al., 2021). For example, Sizewell C Nuclear power station and access road is being designed to withstand a 1-in-10,000-year storm and 1-in-100,000-year surge events (EDF and CGN, 2021).

Much of the wastewater infrastructure around the UK combines rainfall and sewerage. As a result, intense runoff events commonly exceed the capacity of treatment plants. Increases in the intensity and frequency of intense rainfall events is a significant factor in any increases in combined sewer overflows (discharge of raw sewage) to fluvial systems and/or the marine environment (Ofwat, 2011). Following the new legal duties on water companies and government to reduce sewage discharged into waterways set out in the Environment Bill 2020 (UK Government, 2020), the Storm Overflows Taskforce was formed to eliminate harm from storm overflows, through a review of options to mitigate untreated discharge and offset increases in storm-related discharges (Gill et al., 2021) and Scottish Water published an investment route map to mitigate the impact of overflows in 2021, outlining improvements to 108 Scottish assets (Scottish Water, 2021).

Individual infrastructure assets do not operate in isolation but are interdependent due to reliance on other assets for access, power, fuel and communications. These critical infrastructure networks are often co-located and therefore they experience the same hazards; are managed and used by the same organisations (Dawson et al., 2016); or are at risk of failure propagation (Arrighi et al., 2021) and cascading risks. For example, the rail line between the Port of Immingham and Drax Power Station was damaged by flooding in

February 2020 which also threatened the supply of biofuel to the power station (DRAX, 2022).

What could happen in the future?

Winds, storms and waves

In the North Atlantic, towards the end of the century, under higher-emission scenarios, an overall reduction in mean significant wave height is projected, although heights of the most extreme wave are projected to increase (Bricheno and Wolf, 2018; Palmer et al., 2018; Morim et al., 2019; Bricheno et al., 2023). The UK Climate Projections (UKCP) show UK daily mean wind speeds are projected to slightly increase in winter and slightly decrease in summer (Murphy et al., 2018), however there are large uncertainties associated with this as the projected changes are small compared to interannual variability and other projections e.g. the Couple Model Intercomparison Project (CMIP) 5, show even less of a trend in winter (Pirret et al., 2023). Meanwhile, CMIP5, CMIP6 and UKCP show the frequency of winter windstorms over the UK is projected to increase (2061-2080 compared to 1981-2000) under a high emissions scenario, RCP8.5 (Zappa et al., 2013; Priestley and Catto, 2022; Pirret et al., 2023). As future winters are projected to be increasingly dominated by cyclonic weather systems, western coasts of the UK are anticipated to preferentially impacted by a higher incidence of strong winds and waves (Slingo et al., 2021). Additionally, the Atlantic Meridional Overturning Circulation plays an important role in the regulation of Northern Europe weather systems, it is projected to weaken over the 21st century (Fox-Kemper et al., 2021), which may cause an increase in winter storminess in the UK (Jackson et al., 2015; Bellomo et al., 2023). However, despite these projected changes in winds, storminess and waves, future extreme sea levels are projected to be dominated by the underlying mean sea-level rise (Horsburgh et al., 2020).

Sea-level rise

Sea-level rise is already occurring and is accelerating, with projections indicating that even with large reductions in greenhouse gas emissions we are committed to continued sea-level rise beyond 2100 (Palmer et al., 2018; Palmer et al., 2020; Fox-Kemper et al., 2021). For example, under the high emissions scenario RCP8.5 London is projected to experience between 0.53 m and 1.15 m increase in sea level by 2100, relative to a 1981-2000 average sea-level baseline (Palmer et al., 2018). Due to large uncertainty, the sea level projections for individual emission scenarios do not fully consider scenarios of significant ice sheet melt/collapse (DeConto et al., 2021; Herr, 2023). Under scenarios of ice sheet collapse, global sea-level rise could reach up to 2 m by 2100, although there is high uncertainty around these projections (Oppenheimer et al., 2019; Fox-Kemper et al., 2021; Slingo, 2021).

Coastal morphology

Changes to coastal morphology associated with climate change are anticipated to continue with increases in sea levels causing accelerated rollback or squeeze of coastal habitats. As sea-level rise continues, potential erosion rates are anticipated to increase and have a progressively disruptive impact on coastal assets (Rennie et al., 2021). For example, the erosion of vulnerable coastlines in Scotland could increase from 46% of the present-day 'soft coast' extents to 84% in 2100 under a high emission scenario, with a total of £1.3 bn of Scottish assets potentially at risk (Rennie et al., 2021). Changes in wave climate, storm severity and water levels are anticipated to stimulate change in coastal and inshore morphology at a local scale. The impact of coastal erosion is expected to remain highly variable along the UK coastline and dependent on the governing physical conditions locally and the coastal defences or management strategies in place.

Sea-surface temperature

Sea-surface temperatures have risen over the past few decades and under various climate-change scenarios sea-surface temperatures are projected to continue to rise. The UK's National Oceanography Centre (NOC) outlines that temperatures have risen by 0.3°C per decade since 1980 and predict future rises of 3.11°C by 2100 (Cornes et al., 2023). Additionally, the frequency, duration, spatial extent and intensity of marine heatwaves are very likely to increase under all emission scenarios (Collins et al., 2019).

Implications for industry

For all marine and coastal industries, climate change is likely to result in a more-harsh environment. This will make infrastructure more vulnerable to damage, increase health and safety risks to operatives, and increase periods of weather downtime. This will in turn increase the costs associated with the design, operation, maintenance and decommissioning of infrastructure.

National and global policies for the reduction in greenhouse gas emissions and decarbonisation of economies means there will be increasing amounts and types marine infrastructure. These include the British Energy Security Strategy (UK Government, 2022b) which sets out the Government's ambition to deliver up to 50 GW of offshore wind by 2030, including up to 5 GW of innovative floating wind. The planned expansion of renewable energy arrays, such as floating wind turbines into deeper, more exposed locations, means that there is greater exposure to climate related marine risk.

There is also a global drive for industrial decarbonisation resulting in emerging marine industries. Examples include carbon capture and storage (Viking, 2023), offshore hydrogen production, e-fuel (renewable synthetic fuels) or other fuel generation (DNV, 2023), and underwater datacentres (Microsoft, 2023). The risks associated with the design, operation and decommissioning associated with this infrastructure in a changing climate will become more evident with increasing application.

This broadening of application along with the increasing severity of climate change impacts, means that the risks and financial costs associated with successful operation in marine and offshore industry sectors are expected to increase. This diversification is anticipated to provide opportunities for new and novel offshore infrastructure and marine monitoring technologies with recent innovations such as using fibre optic cables as seafloor sensors (Marra et al., 2022), allowing increased data collection and ocean conditions.

In addition to adapting to the impacts from climate change, it is also important to mitigate. The International Maritime Organisation's (IMO) ambitions for greenhouse gas (GHG) emissions targets (40% reduction by 2040 and 70% by 2050) have gathered pace since the publication of the previous MCCIP paper (Brooks et al., 2020) and IMO Member States have adopted a strategy for the reduction of GHG emissions from ships in July 2023. This strategy is supported by a data collection exercise reviewing fuel consumption on ships with a gross tonnage more than 5,000 tons and outlines progressive, mandatory GHG emission targets for new ships supported by a comprehensive research and development program (IMO, 2023). This builds international capacity for the implementation of greenhouse gas reduction strategies and includes transition to biofuels, hydrogen, electric and hybrid, propulsion, combined with efficiencies in planning and optimising of shipping logistics. The targets set by the IMO and its partner organisations encourages further investment into GHG reductions and climate-change mitigation. Other industries are also following this precedent, with global aquaculture moving toward hybrid energy operations (Digre, 2020).

Financial institutions (including banks and investment funds) are becoming more aware of climate-related risks, and assets holders within the marine and offshore industry are seeking to better understand and mitigate climate associated risk. There are also new regulations for climate disclosures including those associated with the Financial Stability Board's Task Force on Climate-related Financial Disclosures (TCFD) and The Companies (Strategic Report) Climate-related Financial Disclosure Regulations 2022 (UK Government, 2022a). These require public disclosure of a company's climate-related risk along with targets and key performance indicators for managing that risk. This increased awareness in climate-related risks encourages operators to review and identify the potential impacts of climate change to their operation and to devise and implement appropriate mitigation strategies, increasing preparedness.

A recent report by the Joint Committee on the National Security Strategy (JCNSS) from the House of Lords and House of Commons recommended the use of a range of mechanisms to improve collaboration on interdependencies and oversight of adaptation and resilience relating to critical national infrastructure (CNI) sectors. Their suggested mechanisms include establishing a statutory forum for CNI regulators on climate adaptation, establishing clear resilience standards for CNI operators, and setting up a programme of stress testing CNI against extreme weather and other effects of climate change, as well as ensuring that all operators have access to high quality weather, climate and impact forecasting and modelling (Joint Committee on the National Security Strategy, JCNSS, 2022).

Ports and shipping

The analysis in Brooks et al. (2020) and BPA (2021) highlight some specific future risks to port assets and operations which still stand. Additionally, publications by the Environmental Defence Fund (2022) and Izaguirre et al. (2021) highlight the potential for climate change to lead to significant adverse impacts on port assets and operations. While there will be differences associated with the specific location (exposure) and characteristics of individual ports; many of the risks identified in these papers as well as in BPA (2021) and PIANC (2020, 2022a) will be relevant to most UK ports. These include:

- Increased risk of coastal flooding, especially related to sea-level rise (Haigh et al., 2022).
- More-intense rainfall putting greater pressure on drainage systems; causing pluvial flooding of coastal infrastructure.
- Extreme heat and cold adversely affecting port operations and some infrastructure, for example lock or bridge mechanisms may be impacted by extreme heat; extreme heat/humidity or extreme cold can impact on stored commodities, either directly or indirectly due to power failure.
- Sediment transport, siltation, and scour changes due to altered rainfall patterns or storm events (in-combination with sea-level rise) impacting navigation safety/dredging needs (ABP, 2021).
- Changes in storminess and storm tracks/wind speeds/wave heights affecting berthing, pilotage and cargo handling including crane operations (ABP, 2021).
- Increase in winter fog days in the south-east of the UK, impacting pilotage activities and safety generally, especially in areas used by both recreational and commercial vessels (PLA, 2015).
- Warmer air and water temperatures increasing rates of vegetation growth, desiccation, etc.; facilitating establishment of invasive alien species that can adversely impact on assets and equipment fouling/smothering or burrowing etc.
- Climate change-induced changes in salinity/acidity affecting species at the edge of their range with implications for recreation and tourism related industry such as fishing or wildlife watching, Barange et al. (2018). Changing port activity.
- Weather-related disruption to inland distribution networks (road, rail, waterborne) resulting in knock-on effects within the port (Arrighi et al., 2021).
- Long-term intentions of third-parties responsible for critical infrastructure assets within the port hinterland (e.g. commitment to maintenance of flood defences or erosion protection).
- Increased water demand and summer water shortages potentially affecting locking activities.
- Increased summer cooling demands as storage units and workspaces overheat.
- Power outages caused by damage to the distribution network.
- Climate-related disruption in global supply chains can impact on ports. Currently 95% of all goods entering and leaving Britain are moved by sea (Department for Transport, 2022). Disruption at ports has the potential to compromise global supply chains and maritime trade, with local-global geo-political and economic/financial consequences (IPCC, 2022).

- Disruption associated with extreme weather may damage goods directly, (flood damage to goods in storage), cause delays in the shipping of perishable goods (foodstuffs and medicines), through spoiling. This prospective loss represents increased financial risk associated with shipping for relevant industries.
- Impacts on international trade of climate-related changes in population; agriculture; industrial production and similar.

Very few ports are expected to remain unaffected by the changing climate, so those that are currently wholly or partly unprepared will need to act to ensure the resilience of both new and existing infrastructure and operations. For new infrastructure, this may mean designing to withstand or otherwise accommodate both slow onset changes and more-frequent extreme events, paying attention to the resilience of linked systems including transport, energy and supply chains (Pery et al., 2021). For many existing ports, this may mean retrofitting or replacing existing infrastructure and/or improving operational resilience. For some, facing existential threats, it may involve transformational change such as relocation. Most importantly, for existing facilities, climate risks need to be mainstreamed into corporate strategies and into organisations' risk registers so that both threats and opportunities can be identified, and appropriate responses developed (PIANC, 2022b), including contingency plans and early warning systems alongside structural retrofitting or operational change.

Much of the work required to support increased attention to preparedness focuses on better understanding risk. As indicated by Jaroszweski et al. (2021), comprehensive data on the scale of risk from coastal erosion and flood risk for transport infrastructure, including ports, is among the data required. The same is the case for changes in waves, wind and storminess; extreme heat and humidity; fog; and so on. However, evidence-based risk and vulnerability assessment relies on a combination of data (including time-series data) and relevant projections, which are typically more uncertain for select marine parameters such as wind, waves, fog, and sediment transport, than for air temperature, precipitation or sea level. The ability to understand and reliably accommodate uncertainty, for example through sensitivity testing, is therefore vital (PIANC, 2022a).

Ferries and vital transport infrastructure are at a unique risk to increased climate change with a high proportion of UK ferry routes only partially sheltered from significant wave conditions, particularly the Scottish Western Isles (Coll et al., 2013) and Scilly Isles. Presently, isolated island and coastal communities are heavily reliant on these routes for commodities and employment but also schooling and healthcare. This uncertainty hinders commercial investment with conditions on Islay already becoming more challenging for whisky exporters (Roberts and Maslin, 2021) due to weather downtime for ferry operations.

Smaller harbours and marinas will also experience effects from climate change associated with increased periods of adverse weather conditions and potential reduction in periods and volumes of recreational boating and tourism.

Warming seas are projected to cause a poleward shift in marine ecosystems, modifying existing opportunities for commercial fisheries (and port income). Modelling has predicted a global reduction in fishery catch potential from 2000 levels by 12.1% by 2050 under a high-emission scenario (RCP8.5) (Barange et al., 2018). However, the direct impact of this to UK waters, fishing, and dependent industry remains uncertain (Berry and Brown, 2021).

Climate change will bring opportunities as well as risks. The projected increase in the marine renewable energy sector will increase the demand for port services with the need for construction, operation and maintenance bases as well as require accommodation for new commodities including hydrogen, ammonia and carbon for capture and storage. Some UK ports may benefit from the increase in trans-Arctic shipping route traffic with predictions of significant transit windows of up to 200 days per year simulated by Mudryk et al. (2021) through the North-West Passage and Northern Sea Route. Others may benefit from changes in global trade associated with climate-driven changes in population, agriculture or manufacturing (Hanson and Nicholls, 2020). More locally, some ports and harbours may gain, while others lose due to the migration of commercial fish stocks or other types of marine wildlife.

Offshore structures and industry

Wind-power production depends very strongly on wind speed and subsequently, change in the characteristic wind distribution due to climate change could lead to variable energy yields (Doddy Clarke et al., 2022), increasing uncertainty and impacting energy production. It is noted that future projections of the wind climate are variable and highly uncertain (Palmer et al., 2018, with changes in offshore wind yield likely occurring both spatially (i.e. regionally) and temporally (i.e. seasonally). Extreme weather periods, such as heatwaves, cold snaps and droughts could lead to demand-driven overstress of energy infrastructure especially offshore and coastal locations, thus threatening national energy security (Clare et al., 2022). During the winter of 2022–23 we have seen long periods of high pressure/low wind with energy generators having to turn to emergency coal-fired power stations to avoid interruption to the energy supply (Climate Change Committee, 2023) as reported in the national news (BBC, 2023). To better understand the risk from extreme weather on current and future renewable generation and demand, the Met Office, in collaboration with the National Infrastructure Commission and the Climate Change Committee, developed the Adverse Weather Scenarios for Future Electricity Systems dataset (National Infrastructure Commission, 2022). It comprises adverse weather scenarios, based on physically plausible weather conditions, representing a range of possible extreme events and can be used to stress test proposed future highly renewable electricity systems to inform resilience planning. The future risk to offshore infrastructure from storms and high waves is judged “medium magnitude” by the UK’s Third Climate Change Risk Assessment in part due to increased vulnerability with increased dependence on offshore wind energy production as well as the oil and gas platforms in UK waters, which may remain operational beyond their initially intended lifespan due to repurposing for carbon sequestration and storage (Jaroszweski et al., 2019).

Climate-change induced variability in the oceanographic climate is modifying the risk profile of many marine assets on the UK's continental shelf, heightening risk of damage to, and failure of, these assets (Clare et al., 2022). Wilkie and Galasso (2020) found increased risk of structural failure of offshore floating wind components under climate-change scenarios. Additionally, fixed structures and anchors are sensitive to changes in bathymetry such as scour, sand-wave migration and extreme weather impacts (Diamond, 2012). Climate-change induced modifications in scour patterns, particularly wave induced scour, may increase erosion around structures, cables, pipelines and anchors, increasing uncertainty in structure stability, particularly in nearshore areas and at the landfall. In deeper offshore areas, the influence of wave induced currents on the bed is more limited although currents associated with storm surges may also contribute to scour. These changes and increased variability may result in the need for additional scour protection on the seabed (rock armour). Adapting to these increased risks is anticipated to increase operation and maintenance costs, requiring more-frequent structural checks, increased engineering costs associated with construction, maintenance and repair and additional spend associated with added redundancy.

Many aspects of the deployment, operation and maintenance, and decommissioning of offshore structures depend on 'weather windows' for at-sea working to be conducted safely. Current weather window patterns are projected to alter under a changing climate, bringing both risks and (potentially) opportunities. The increased potential for weather downtime affects all marine industries including renewable energy generation, oil and gas, aggregate extraction, and other industries. The potential for impact will be dependent upon a range of factors including location, nature of operations and type of vessels involved. This has led to increasing uptake of metocean forecasting capability in offshore industries as an attempt to better define weather windows and mitigate this impact (Acton, 2021).

Coastal structures and infrastructure

The impact of climate change on coastal flooding is presented in MCCIP paper "Impacts of climate change on coastal flooding, relevant to the coastal and marine environment around the UK" (Haigh et al., 2022). Here we focus on the key impacts to UK coastal structures and infrastructure.

Projected sea-level rise is anticipated to exacerbate existing pressures on coastal infrastructure and defences and challenge the existing management of coastal resilience. Hooper and Chapman (2012) suggest that the threat of flooding from sea-level rise combined with pluvial flooding from extreme precipitation events is expected to further expose coastal road and rail transport links and infrastructure to a higher risk compared to inland. Sayers et al. (2020) found that by 2100 and under a 4°C global warming scenario, the length of rail track at risk from coastal flooding could increase by 400% in England, 50% in Northern Ireland, and 75% in Scotland. Similarly, in

England, the coastal flood risk to sewage works and electricity substations could increase by 200% and 55%, respectively, by the 2080s. Additionally, Brand et al., (2018) outline that without intervention, 80 out of the 1200 known landfill sites in low-lying coastal areas in England are projected to become exposed to erosion within the next 40 years.

In order to minimise the costs of treating wastewater, sewage treatment plants serving coastal populations have typically been constructed at low elevations near the coast. This facilitates the conveyance of wastewater flows to the plant by gravity and minimises the number of pumping stations required. In addition, coastal locations allow for efficient discharge of treated effluent to adjacent coastal water bodies, although increases in sea levels may require a transition from gravity to pumped discharge systems. During prolonged warm periods, wastewater treating plants may incur higher energy requirements and there may also be changes to the performance of biological systems, oxidation ponds and sludge management, resulting in changes to effluent discharge characteristics and odour increase (Hughes et al., 2021). Additionally, extreme rainfall and runoff events are projected to increase, putting the UK's combined wastewater treatment and storm overflow systems under increased pressure. This increases the risk of wastewater overflows and pollution events (Gill et al., 2021) which affect water quality through bacterial pollution and increased nitrogen and ammonia, as well as depletion of dissolved oxygen in riverine and coastal waters as a result of eutrophication. These risks can be reduced by upgrading of infrastructure (including smarter designs and improved stormwater storage) and sustainable water management techniques.

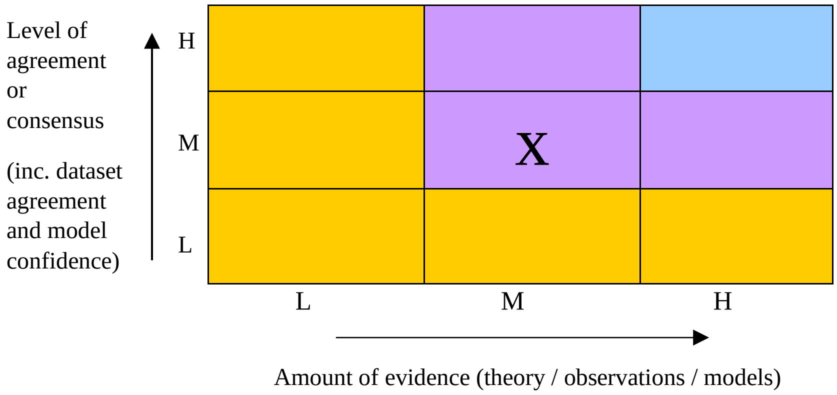
Under the Natura 2000 framework for designated areas (a network of sites protected for nature conservation designated under EU legislation and retained post-Brexit), there is a requirement to restore or recreate habitats (Pontee, 2013) which has led to sustained and increasing investments in the restoration of coastal habitats, mainly through Managed Realignment or Regulated Tidal Exchange schemes seeking to offset habitat losses. As sea levels continue to rise, the creation or rehabilitation of these coastal habitats will be required to maintain current extents.

Cooling of most coastal power plants in the UK, and specifically nuclear reactor power plants, is achieved through direct cooling by running seawater via inlets through the plant and discharging it at a slightly higher temperature. Warming sea-surface temperatures may reduce the power efficiency of thermal power plants by reducing the temperature differential of cooling water, lowering the ratio of electricity produced to the amount of fuel used in the processing (Linnerud et al., 2011), increasing costs and lowering yield. Environmental regulations also impose limits on the temperature of the returned water (typically 30°C) as well as on the temperature differential between inlet and discharge. Therefore, increasing water temperature may also require power stations to change their cooling methods to comply with their environmental permits, as occurred in Finland, Sweden and Germany in 2018 (Hersher, 2018). If the inlet water approaches the limit set for discharge, or the cooling waters are unable to effectively cool reactors, the plant will be unable to run at full power. This may become a more frequent consideration in the future when extreme prolonged heatwave conditions are combined with rising sea-surface temperatures. This may lead to an uptake in alternative cooling methods, such as at Barking Reach Power Station, on the tidal section of the River Thames. When active, this station ran for much of the year on direct cooling but is required under its consents to switch to tower cooling during the summer months when the river temperature exceeds 21.5°C (Turnpenny et al., 2010).

New industries are moving into the offshore space. For example, Norway and Scotland are some of the first countries to approve licences for open-ocean finfish aquaculture in increasingly exposed locations (Morro et al., 2022). Future increases in sea-surface temperature could increase productivity, but warmer conditions may also increase the frequency and magnitude of welfare risks to farmed species (e.g., harmful algal blooms, Amoebic gill disease and jellyfish: Morro et al., 2022) and also introduce greater pressures from invasive species due to changing marine habitat extents. Potential increases in storminess are anticipated to expose offshore-aquaculture setups to pen failures and escapes, increasing maintenance costs and presenting escalated risk to endemic populations (Føre and Thorvaldsen, 2021). However, the role of climate change in future operation in this emerging industry sector remains uncertain and highly dependent on the sector's ability to adapt to environmental challenges (Barange et al., 2018). Climate change also presents opportunities for increased productivity as it facilitates the northward migration of species, potentially opening new cultivation opportunities (Surminski, 2021).

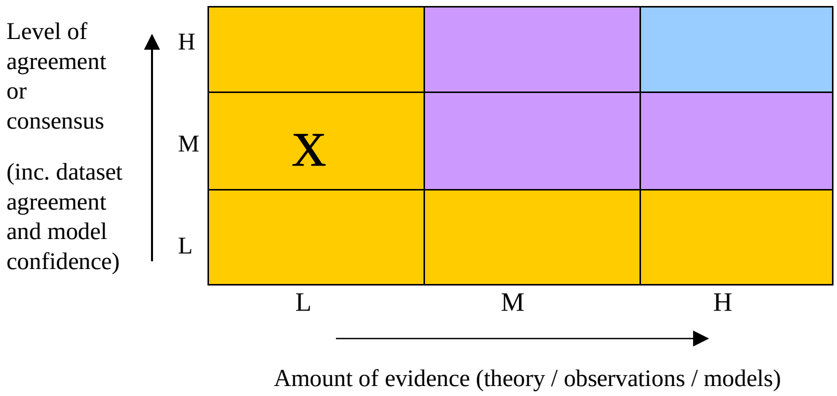
CONFIDENCE ASSESSMENT

What is already happening?



Access to data and information remains difficult. Industry (consultancy and private companies) have difficulty accessing contemporary academic literature. Additionally, much of the progress in understanding of climate associated risk to infrastructure is undertaken within companies and is considered commercially sensitive and not published. As a result, the exchange, review and dissemination of emerging understanding between the scientific community and industry is poor, with the primary source of collaboration between those two groups being restricted to discrete research funding projects and word of mouth.

What could happen in the future?



Confidence with regards to assessments of potential future impacts to coastal and marine transport and infrastructure is intrinsically linked to the robustness of future climate change projections. For sea-level rise, projections have relatively high levels of confidence irrespective of emission scenario and there is a recognition of reductions in sea-ice extents and sea-surface temperatures. Conversely, while industry is aware of the broad risks associated with climate change, confidence in the projected future patterns of some impacts (including changes to storms and waves) remains low, with significant spatial variability and conflicting model simulations. Notwithstanding that low confidence, with significantly more of our energy infrastructure in the marine environment, including offshore windfarms, tide and wave power generators, electricity transmission infrastructure as well as telecommunications cables, the risk of climate-related damage is expected to increase.

The overall confidence assessment has not changed from the previous paper, and we conclude that the amount of evidence remains low on the future impacts of climate change on marine and coastal transport and infrastructure.

KEY CHALLENGES AND EMERGING ISSUES

Top challenges

1. The accelerated expansion of the marine renewable energy sector means a significant proportion of nationally critical infrastructure is being built in the marine environment. This infrastructure is also being deployed in deeper and more-exposed offshore locations, along with an increasing network of associated transmission cables and interconnectors. The risk of damage to our energy network from climate change related storm events is therefore increasing.
2. As the lifespan of the marine infrastructure is extended, there is a need for improved data and models on changes to weather parameters, most notably wind and wave regimes, to adapt designs to a changing climate.
3. There is also a need to better understand and share the information on how climate change affects infrastructure performance, deterioration, and threshold failure.

Top emerging issues

1. The growth in marine renewable energy is significantly increasing demand for port area needed for the construction, operation, and maintenance of offshore windfarms. The ongoing expansion of the marine renewable energy sector and the advancement of decarbonisation technologies are expected to further increase the need for port facilities and infrastructure.
2. There is a call from industry to understand the interdependencies and cascading risks to nationally critical infrastructure, and to the UK Government to provide the mechanisms for these to be investigated and mitigated (The Joint Committee on the National Security Strategy, 2022).
3. The level of understanding of climate-related impacts is increasing unevenly across sectors. Whilst evidence and data on flood damage

and coastal erosion is abundant and available, information on storm damage to offshore infrastructure remains limited. This knowledge gap may be addressed from 2023, as companies are required to report climate risks under The Companies (Strategic Report) (Climate-related Financial Disclosure) Regulations 2022. Financial institutions are also seeking a greater understanding of these issues for borrowing and insurance, making understanding climate-associate risk increasingly business-critical.

4. Warming seawater temperatures may have a significant impact on the operation of marine cooling and outfall systems as well as present challenges for marine aquaculture and fisheries activities. The impact of increasing temperatures on the viability of sea farming operations however remains poorly understood.

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