Risks of sea-level rise to ports and associated facilities aligning with the Trident programme: A focus on Coulport, Faslane, Barrow-in-Furness and Devonport

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EXECUTIVE SUMMARY

Climate change has the potential to threaten many areas of our lives. The Trident programme, the UK's independent nuclear deterrent programme, has been in place for decades and is intended to be replaced so to maintain a credible deterrent to the 2060s and beyond. A question was posed as to the possibility of the threat of sea-level rise to the associated sites over this timescale, with a specific focus on 2060 and, moreover, to consider what the long-term effects of sea-level rise could be on Trident replacement programmes. This report considers how sea-levels will change and the potential effects of flooding and sea-level rise in four localities relevant to the Trident replacement programme: Coulport and Faslane in western Scotland, Barrow-in-Furness in Cumbria and Devonport in Devon.

Presently, according to the Scottish Environment Protection Agency, flood risk at Coulport ranges from low to high, and at Faslane present flood risk is low. From Environment Agency flood risk maps, flood risk at Barrow-in-Furness and Devonport is less likely due to the standard of protection already afforded. However, with sea-level rise, flood risk may need to be reconsidered.

Global sea-level rise has been reported as being 1.4mm/yr from 1901 to 1990 and 3.2mm/yr from 1993 to 2015. Considering a linear trend of relative sea-level rise (including changes in land levels), the nearest tide gauge locations for Coulport and Faslane indicate a rise of 1.5mm/yr from 1969 to 2015, the nearest station to Barrow-in-Furness indicated an increase of 1.8mm/yr from 1962 to 2019, and at Plymouth 2.4mm/yr between 1962 to 2020.

Future sea-level rise is complex and highly uncertain. Taking a range of mitigation and non-mitigation climate change scenarios and the associated 5th to 95th percentiles of uncertainty from the UK Climate Projection Programme, relative sea-level rise in 2060 is projected to be between 0.05m to 0.37m for Coulport and Faslane, 0.10m to 0.43m for Barrow-in-Furness and 0.19m to 0.53m for Devonport. Multi-metre sea-level rise is considered possible over more than a century. Without action, this will lead to increasing levels of flood risk.

One way to reduce flood risk is to adapt. For coastal locations, adaptation would need to consider slow onset events (such as sea-level rise) and fast onset events (such as a storm leading to an extreme water level event), where the latter normally causes the most damage to infrastructure. Potential damage includes that on sea walls, associated port operating infrastructure and also buildings. Due to the long-term commitment of rising sea-levels and increased likelihood of flooding, a range of adaptation approaches, such as raising of docks or protection of key infrastructure could be considered.

When infrastructure requires periodic renewal, adaptation could consider the highest possible sea-levels (i.e. a non-mitigation scenario, including high impact low probability (H++) events which project up to 1.9m of sea-level rise by 2100) and extreme events within the design life of the infrastructure affected to ensure effective and safe working of Trident-type sites over many decades to come. Communicating clearly with the public the standards of protection for potential flooding with future sea-level rise for high-risk sites within climate change risk assessments would be welcomed.

CONTENTS

1. SETTING

1.1 Scope

This report assesses the hazards and risks associated with climate change; in particular, rising sea-levels, at localities aligning with the UK Trident replacement programme. Rising sea-levels, storm surge heights, changes to the intensity of rainfall and increasing mean and extreme temperatures (Chhetri et al. 2013; Townend and Burgess, 2001) are all potential impacts. Coastal locations, including ports, will need to be prepared for climate change and potentially adapt.

The UK's policy of maintaining an independent nuclear deterrent has been in place for over 60 years (Defence Nuclear Organisation and Ministry of Defence, 2021), well before climate change was a concern. This policy is currently delivered through the deployment of four nuclear-armed submarines, often referred to as 'Trident'. In 2007, the government initiated the process of purchasing Dreadnought-class submarines (to replace the current Vanguard-class) in order to maintain the UK's Trident nuclear system beyond the early 2030s (Defence Nuclear Organisation and Ministry of Defence, 2020). In 2016, Parliament voted to formally authorise this process and maintain a 'continuous at sea deterrence' posture, through replacing submarines plus existing nuclear warheads (Defence Nuclear Organisation and Ministry of Defence, 2021). It also decided to maintain a 'credible, independent and capable deterrent out to the 2060s and beyond' (Defence Nuclear Organisation and Ministry of Defence, 2020). This long timescale is important, as this is when rising sea-levels could lead to a significant increase in flood risk due to more rapid rates of sea-level rise.

This report will first describe the setting (Section 1.2), then present flood risk (Section 2), a background to sea-level rise (Section 3), future sea-level rise (Section 4) and climate change adaptation (Section 5). Importantly, this report does not provide an opinion on the programme or precise details on hazards or risks at each Trident site; rather, it provides an overview of the generic issues that could be faced in the broad localities of the sites studied.

1.2 Setting

At the request of British Pugwash, this report focuses on the sites of:

- Coulport on the eastern edge of Loch Long in Argyll and Bute, Scotland;
- Faslane located on the western shore of the Clyde in Argyll and Bute, Scotland;
- Barrow-in-Furness located on the north-west English coastline in Cumbria;
- Devonport, to the west of Plymouth, Devon in the south-west of England.

Localities are shown in Figure 1.1. Coulport is situated on the shore of Loch Long, at the base of a hill, with a small stream debouching into the loch. By the 1920s, a sea wall had been constructed in front of Coulport House (now the far buildings on the south-east of the site) to protect the road. This may indicate that the shoreline was eroding, but based on Historic Ordnance Survey maps there is no long-term indication that this could relate to instability. The area in front of the site has been subject to land claim and raising (up to 13m above Ordnance Datum, Ordnance Survey 2020b), presumably to shoreline is rockier, with old groynes with the shoreline remaining stable or accreting. The B822 access road to the south is between 4m and 6m above Ordnance Datum (Ordnance Survey 2020b), and may be liable to flood.

Faslane port is built on reclaimed land, jutting out approximately 120m from the north-west coast of Gare Loch. Jetties, including a travelling crane, protrude out into the water. Land elevation is below the 10m contour line. Behind the port's operations area, the land to the north and east form a hill, whilst the south of the port comprises reclaimed land, rolling into hills.

Barrow-in-Furness is located on Furness peninsula. Fronting the coastline is Walney Island, a low lying populated island with saltmarsh, shingle and sand dunes. The island protects the town and port facilities from extreme wave events across the Irish Sea and, therefore, offers protection to the town. Ordnance Survey maps indicate benchmarks of elevation of between 0m to 14m above Ordnance Datum[1] (Ordnance Survey, 2020a). The southern end of the port is on reclaimed land. Entrance to the dock is via a lock. Dredging of the Walney Channel is necessary to maintain port access.

Devonport, Plymouth is located in the River Tamar, an estuary to the west of Plymouth. The historic port area is highly built up, with engineering structures having been present for a very significant length of time. The height of the land is approximately 4-5m above Ordnance Datum (Ordnance Survey, 2020a). The dockyard is restricted by a caisson, which could potentially be used to limit overall water levels on a temporary basis.

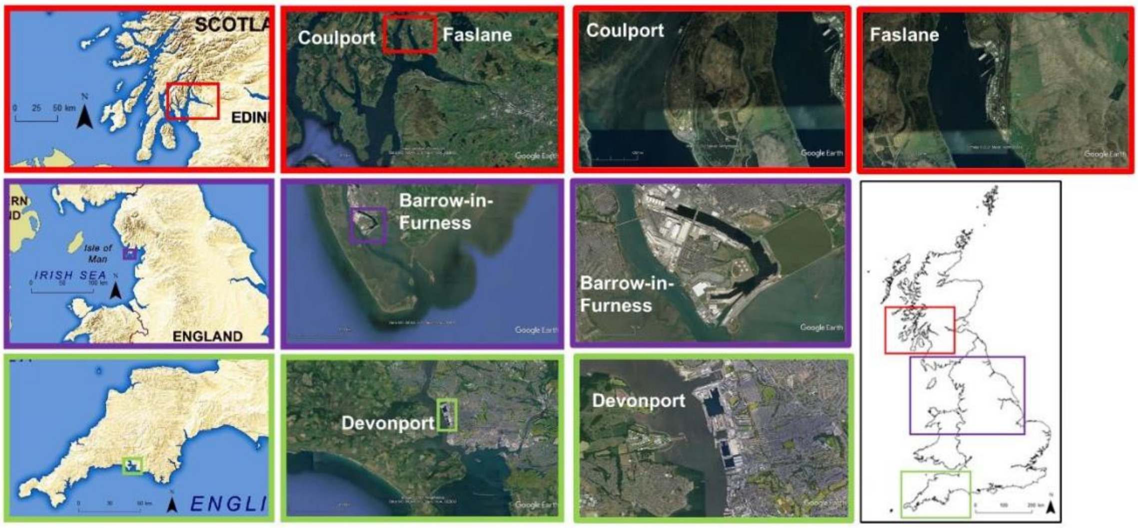

Figure 1.1. Location and setting in the UK, and at Coulport, Faslane, Barrow-in-Furness and Devonport. Maps: Digimap published under the Open Government Licence v3.0 (GB National Outlines 1:250,000. GB Overview 1:5,000,000) and Google Earth http://www.earth.google.com

[1] Ordnance Datum represents a measurement of mean sea-level at Newlyn, Cornwall from 1915 to 1921. Mean sea-level has changed since this time (Ordnance Survey, 2021).

2. PRESENT FLOOD RISK

2.1 Flood risk

According to the Environment Agency and the Scottish Environment Protection Agency, due to their coastal locations, Coulport, Faslane and Barrow-in-Furness are at risk from flooding. The Scottish Environmental Protection Agency (2021) assesses flood risk on a scale of high, medium or low risk from coastal rivers and surface water flooding. Within the Coulport site, flood risk ranges from low to high, including the access road to the south (a figure is unable to be displayed due to scale). In Faslane, there is low risk of flooding to a few selected parts of the north of site, with a wider expanse of low risk flooding to the south (a figure is unable to be displayed due to scale). Flood risk extends to coastal infrastructure and outbuildings in the affected areas.

The Environment Agency assesses present flood risk in terms of Flood Zones (named 1, 2 and 3), indicating the risk of flooding from rivers and the sea in England (Environment Agency 2015). These are defined as follows:

- Flood Zone 1 indicates 'land assessed as having a less than 1 in 1,000 annual probability of river or sea flooding (<0.1%)'
- Flood Zone 2 indicates 'land assessed as having between a 1 in 100 and 1 in 1,000 annual probability of river flooding (1% – 0.1%), or between a 1 in 200 and 1 in 1,000 annual probability of sea flooding (0.5% – 0.1%) in any year'
- Flood Zone 3 indicates 'land assessed as having a 1 in 100 or greater annual probability of river flooding (>1%), or a 1 in 200 or greater annual probability of flooding from the sea (>0.5%) in any year'

Flood Zone 3, therefore, has a higher likelihood of flooding than Food Zone 1. Barrow-in-Furness is largely protected, with a few parts of the wider port area situated in Flood Zone 3 (Figure 2.1). Devonport is located in Flood Zone 1, with part of the outer sea wall in Flood Zone 3 (Figure 2.2).

These results indicate that Coulport has a range of coastal flood risk adjacent to the coast, Faslane is generally at low risk from flooding, Devonport and Barrow-in-Furness are less likely to flood as a whole, but do have parts of sea walls that have a 1-in-100 annual probability of flooding (Flood Zone 3). With sea-level rise, the likelihood of flooding increases unless protection standards are raised.

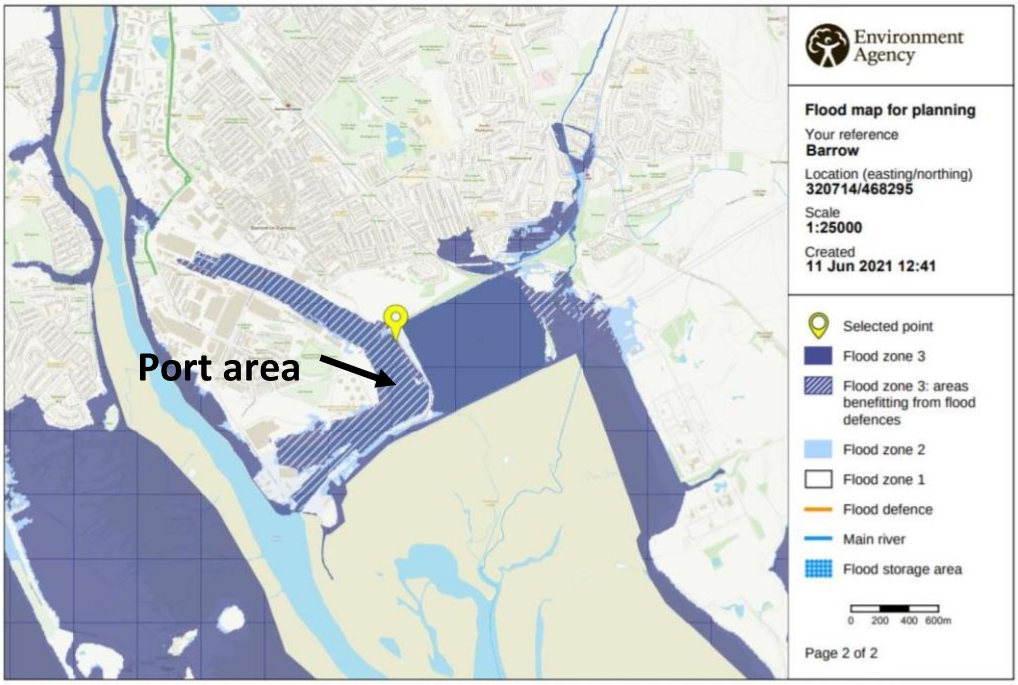

Figure 2.1. Flood zones of Barrow-in-Furness according to Environment Agency (2021). Published under an Open Government Licence (LINK).

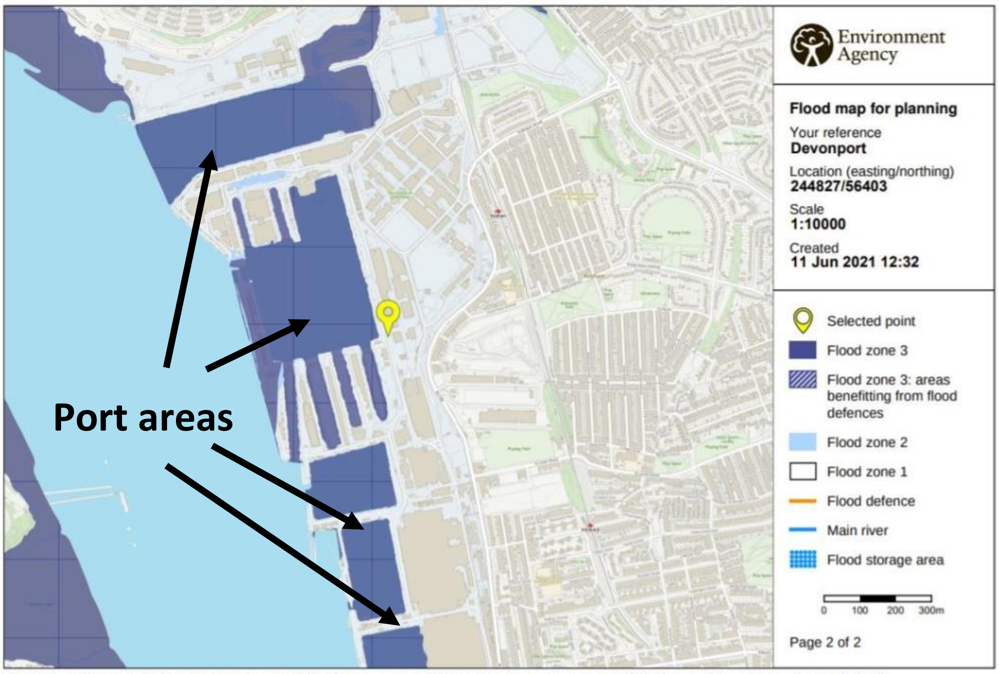

Figure 2.2. Flood zones of Devonport according to Environment Agency (2021). Published under an Open Government Licence (LINK).

3. SEA-LEVEL RISE

3.1 History of sea-level rise

Sea-levels have been rising world-wide for hundreds of years in response to natural changes in our environment. Historic sea-levels can be measured using a range of methods, such as through salt marsh deposits, archaeology, corals, geology and sediments. More recently, changes to sea-levels have been measured through tide gauges and, in the last few decades, these have been supplemented by satellite data.

Global mean sea-levels have risen at 1.4mm/yr from 1901 to 1990, 2.1mm/yr from 1970-2015 and 3.2mm/yr from 1993 to 2015 (Oppenheimer et al. 2019). The time periods of measurements overlap to show non-linear changes and also due to the more recent measurements from satellites. Sea-levels have varied for centuries, but it has only been in the last approximately 140 years (approximately since pre-industrial times) that scientists have been increasingly concerned that sea-level rise has also been anthropogenically driven. Since 1970, sea-level rise is thought to be predominantly driven by anthropogenic factors, rather than natural changes (Slangen et al. 2016).

The Permanent Service for Mean Sea Level is the global data bank for long-term sea-level information, particularly that recorded by tide gauges (Holgate et al. 2013; Permanent Service for Mean Sea Level, 2021). The tide gauges closest to Coulport / Faslane (Millport), Barrow-in-Furness (Heysham), and Devonport (Plymouth) are presented in Figure 3.1.

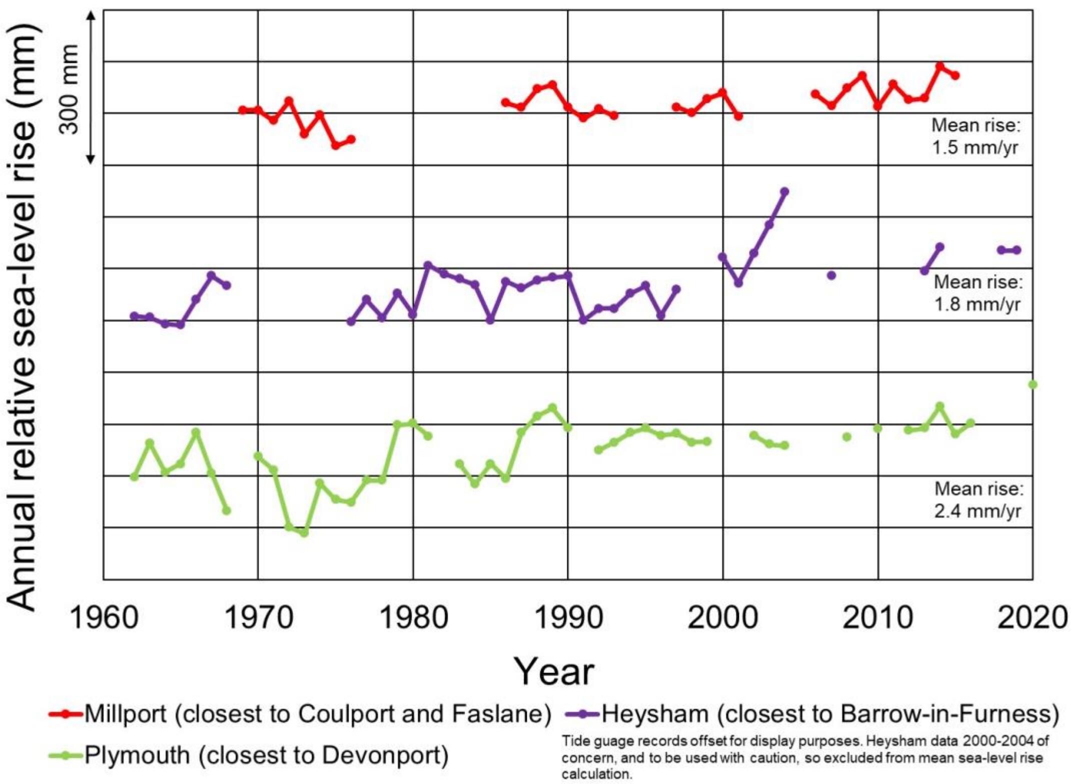

Figure 3.1. Historical tide gauges records from Millport, Heysham and Plymouth. Extracted from Holgate et al. (2013) and Permanent Service for Mean Sea Level (2021).

A linear trend was used to calculate the rate of historical *relative* sea-level rise. This indicated that Millport reported 1.5 mm/yr from 1969 to 2015, Heysham experienced 1.8 mm/yr from 1962 to 2019, and Plymouth experienced 2.4mm/yr from 1962 to 2020. Note that these are *relative* values, i.e. that they include changes in both land level (see Section 3.2) and ocean volume (eustatic sea-level).

This indicates that relative sea-level rise in Scotland is lower than that experienced in the south of England. This is largely due to changes in land level. Shennan and Horton (2002) report that in central and western Scotland land is raising by approximately 1.6mm/yr, whereas in the south-west maximum subsidence is approximately 1.2mm/yr, with updated science (Shennan et al. 2009) agreeing with these broad trends.

3.2 Components of relative sea-level rise

Relative sea-level rise comprises of two components. Firstly, the volume of water in the oceans. This is known as eustatic sea-level rise. This comprises:

(i) Thermal expansion of oceanic water as it warms;

(ii) Contributions from ice sheets – large expanses of ice in Greenland and Antarctica;

(iii) Contributions from glaciers and ice caps – tongue shaped ice in the world's mountainous regions;

(iv) Human action related to water storage.

Secondly, change in land level. This comprises:

(i) Changes to the Earth's crust; (ii)

Local soil compaction.

Thermal expansion raises the height of the water column as water warms. As thermal expansion is dependent on temperature, heat uptake in warmer regions has a larger impact on the sea-level than in colder regions (Oppenheimer et al., 2019). This creates areas of sea-level rise that are less or more than the global average. Scientists take account of these areas (known as patterns) when projecting future sea-level rise. Patterns are also modified by other processes, such as ice melt and oceanic and atmospheric effects (e.g. local temperature, salinity, pressures). As oceans are large and deep, the effects of the warming water and thermal expansion can take many decades to be realised, so that there is a time delay mechanism between the cause of atmospheric temperature rise, the absorption of heat into the ocean and an increase in sea-levels. This time delay is known as the commitment to sea-level rise and is extremely important, as it means that the effects of global mean temperature rise now will be felt for decades. Thus, sea-levels have the potential to keep rising over several centuries, even if there were to be substantial climate change mitigation (see Section 4.5).

Greenland and Antarctica contain expansive ice sheets that store significant amounts of freshwater, and are major potential contributors to sea-level rise. Ice sheets lose mass by melting whilst simultaneously gaining mass from precipitation. Ice sheets are physically difficult to get to and, therefore, measure without the use of remote observations (Oppenheimer et al., 2019). This makes modelling the contribution of sea-level rise from ice sheets very challenging. One of the main concerns is that, with rising temperatures, instabilities could develop and these could cause a sudden loss of mass from the ice sheets, leading to significant increases in sea-level rise towards the end of this century or beyond (see Section 4.5).

Glaciers and ice caps, typically found in mountainous areas, contribute smaller volumes of ice. However, due to their relatively small size compared with ice sheets, they are relatively sensitive to warming temperatures (Oppenheimer et al., 2019). Over the past century they have contributed more melting ice to the oceans than the large ice sheets of Greenland and Antarctica (Gregory et al., 2013). There is high confidence that glaciers will continue to lose substantial volumes of ice throughout this century (Hock et al. 2019). Modelling suggests that collectively, thermal expansion and the melting of ice sheets will make a greater contribution than from glaciers and ice caps.

Human water resource management is increasingly recognised as having an impact on sea-levels. However, this is relatively small compared with other global factors contributing to sea-level rise. The main mechanisms affecting sea-levels are from groundwater pumping (e.g. for human consumption or agriculture) and from storage of water in reservoirs and dams (e.g. for water management or hydropower). In the first part of the 20th century, the construction of reservoirs led to a very small decrease in the world's sea-levels. However, in recent decades, water abstraction has started to contribute to sea-level rise (Chao et al. 2008; Oppenheimer et al., 2019; Wada et al., 2017).

During periods of glaciation the Earth's crust is locally deformed under the weight of ice. After the ice has melted, the land can take many thousands of years to recover. Subsequently, the land very slowly rises where the ice was thickest, and in adjacent areas it can subside. This process known as glacial isostatic adjustment. Consequently, land in Scotland is generally rising while towards the south of England it is sinking (Shennan et al. 2009). This phenomenon explains some of the variability in relative sea-level rise across the UK.

Locally, relative sea-levels can also change due to soil compaction. This may be due to natural causes or sedimentation, or by tectonics, especially in delta regions. This is unlikely to be a major factor in the four sites studies here.

Collectively, the components outlined above indicate that understanding sea-level rise is a complex process, and dependent on many factors, both global and local. As noted, glacial isostatic adjustment is an important influence on the magnitude of relative sea-level rise throughout the UK. Large uncertainties remain due to the contribution from thermal expansion and the melting of ice sheets. The latter has implications over centennial scales (see Section 4.5).

4. FUTURE SEA-LEVEL RISE AND THREATS

4.1 Scenarios

Whilst it is certain that global temperatures are rising, the future rate of rise and the ultimate extent of the increase remain unclear. Hawkins and Sutton (2009) acknowledge that uncertainty is due to both not knowing the magnitude of greenhouse gas emissions (known as scenario uncertainty), and also the uncertainty in their interaction with other processes leading to a rise in global mean temperatures (known as model uncertainty), which will ultimately lead to a rise in sea-levels.

This means that scenarios are needed to project future change. A scenario is 'a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces … and relationships' (IPCC 2018). Scenarios may be globally, regionally or locally driven. The main climate change scenarios are called the Representative Concentration Pathways (RCP). A RCP describes a time series of emissions and concentrations of a full suite of greenhouse gases and aerosols and chemically active gases, and land cover (IPCC, 2018; Moss et al., 2008). Many RCPs project future change at global and regional levels (e.g. sub-continental scales), but there are local scenarios too, including in the UK, generated as part of the UK Climate Projections programme. Each scenario also has a range of uncertainty, represented through different percentiles. For instance, when a scenario indicates a 5th percentile of a projection, it indicates that 5% of model projections fall below the level indicated, and 95% of the projections are greater than that. A central estimate indicates the 50th percentile projection (Howard et al. 2019).

4.2 Global sea-level rise

Globally, a range of sea-level rise scenarios have been generated. These have been formulated to respond to science and policy needs, and also consider high-end low probability assessments.

Oppenheimer et al. (2019) stated that a low sea-level rise following RCP2.6 has a likely range of 0.43m (and uncertainty of 0.29m to 0.59m) by 2100 with respect to 1986-2005. At the higher end of this family of scenarios is RCP8.5, with a likely range of 0.84 (and uncertainty of 0.61m to 1.10m) by 2100, relative to 1986-2005.

In response to the Paris Agreement (United Nations, 2015), the legally binding international treaty on climate change, scientists produced new sets of sea-level rise scenarios to track the policy needs of reaching a rise in 1.5°C and 2.0°C in temperature – lower than the RCP2.6 scenario. These indicated that by 2100, sea-levels could rise in the range of 0.26–0.77 m and 0.35–0.93 m for 1.5°C and 2°C respectively (ranges indicate the 17% to 85% confidence interval). This indicates that sea-levels could be 0.04–0.16 m higher in a 2°C warmer world compared to a 1.5°C (Hoegh-Guldberg et al. 2018). However, as sea-level will keep on rising regardless of climate change mitigation, even with the most stringent mitigation scenarios, multi-metre sea-level rise could be experienced over multiple centuries (Oppenheimer et al. 2019; Hoegh-Guldberg et al. 2018).

In recent years there remains debate into how much sea-levels could rise, in particular due to the stability of ice sheets. For example, DeConto et al. (2021) suggests a jump in the contribution from

Antarctica after 2060, which could contribute approximately 5mm/yr of sea-level rise equivalent by 2100. This could happen if the emissions targets set out in the Paris Agreement are exceeded.

Given the longevity and safety issues surrounding nuclear operations and the long-term use of port facilities, it is important to consider rises in sea-level beyond 2100, with many experts supporting the use of sea-level rise scenarios exceeding 2m during the 21st century for planning purposes (Bamber et al. 2019). A number of expert surveys have been carried out with respect to sea-level rise. One such survey is Horton et al. (2020) who asked 106 scientists to make informed expert projections. They suggest possible rises of 0.54m to 2.15m by 2300 for a climate change mitigation scenario (RCP2.6) and 1.67m to 5.61m by 2300 for a non-mitigation scenario (RCP8.5). Other projections to 2300 indicate rises of 0.59m to 1.55m under a 1.5°C mitigation scenario and between 2.76m to 6.87m under a non-mitigation scenario (RCP8.5) (Goodwin et al. 2018). Oppenheimer et al. (2019) found that in the 22nd century, the rate of sea-level rise could exceed several centimetres per year. Hence, sea-levels are potentially projected to rise faster in the 21st century than the 20th century (i.e. an acceleration from previous centuries), with large uncertainties in the magnitude of future sea-level rise, even under climate change mitigation.

4.3 Methods in generating scenarios from the UK Climate Projections programme

The UK Climate Projections Programme 2019 (UKCP18) is a climate analysis tool that allows stakeholders to determine how the future climate may change at local levels (Met Office, 2019). Climate change projections are available for a range of RCP scenarios, including both with mitigation and without mitigation. The marine projections, which cover sea-level rise, have a geographical resolution of 12km (Met Office, 2019) situated on the open coast, including near to Coulport, Faslane, Barrow-in-Furness and Devonport. The main set of projections considers future sea-level rise up to 2100, and a longer term outlook up to 2300 (see Section 4.5).

To derive the sea-level rise scenarios to 2100, UKCP18 scientists followed the methodology developed by the Intergovernmental Panel on Climate Change's 5th Assessment Report (IPCC, 2013) and updated using methodology from Levermann et al. (2014). In their sea-level rise scenarios, they included contributions from thermal expansion, glaciers and ice caps, ice sheets and water contribution from land storage of water. Due to the number of parameters they considered, there is a wide range of uncertainty associated with these projections. As the local scenarios are downscaled from global projections, they do not consider the full probabilistic range of uncertainties (Lowe et al. 2018; Palmer et al. 2018). However, they remain excellent projections and ideal to determine local levels of sea-level rise around the UK.

To derive sea-level rise scenarios post 2100, exploratory scenarios were used (Palmer et al. 2018; Howard et al. 2019). These were generated by making simple assumptions of stabilising emission concentrations or constant emissions after 2100, including the use of a simple two-layer energy balance model. These results were compared against more complex models, with favourable results.

4.4 Outlook to 2100

Figure 4.1 presents relative sea-level rise scenarios closest data to the localities of Coulport / Faslane, Barrow-in-Furness and Plymouth. Three different scenarios are shown: RCP2.6 (climate change mitigation), RCP8.5 (non-mitigation), and RCP4.5 (intermediate pathway). The figure illustrates three levels of uncertainty representing the 50th percentile, and the lower (5th percentile) and upper (95th percentile) uncertainties. Table A1.1 lists the relative sea-level rise data presented in Figure 4.1.

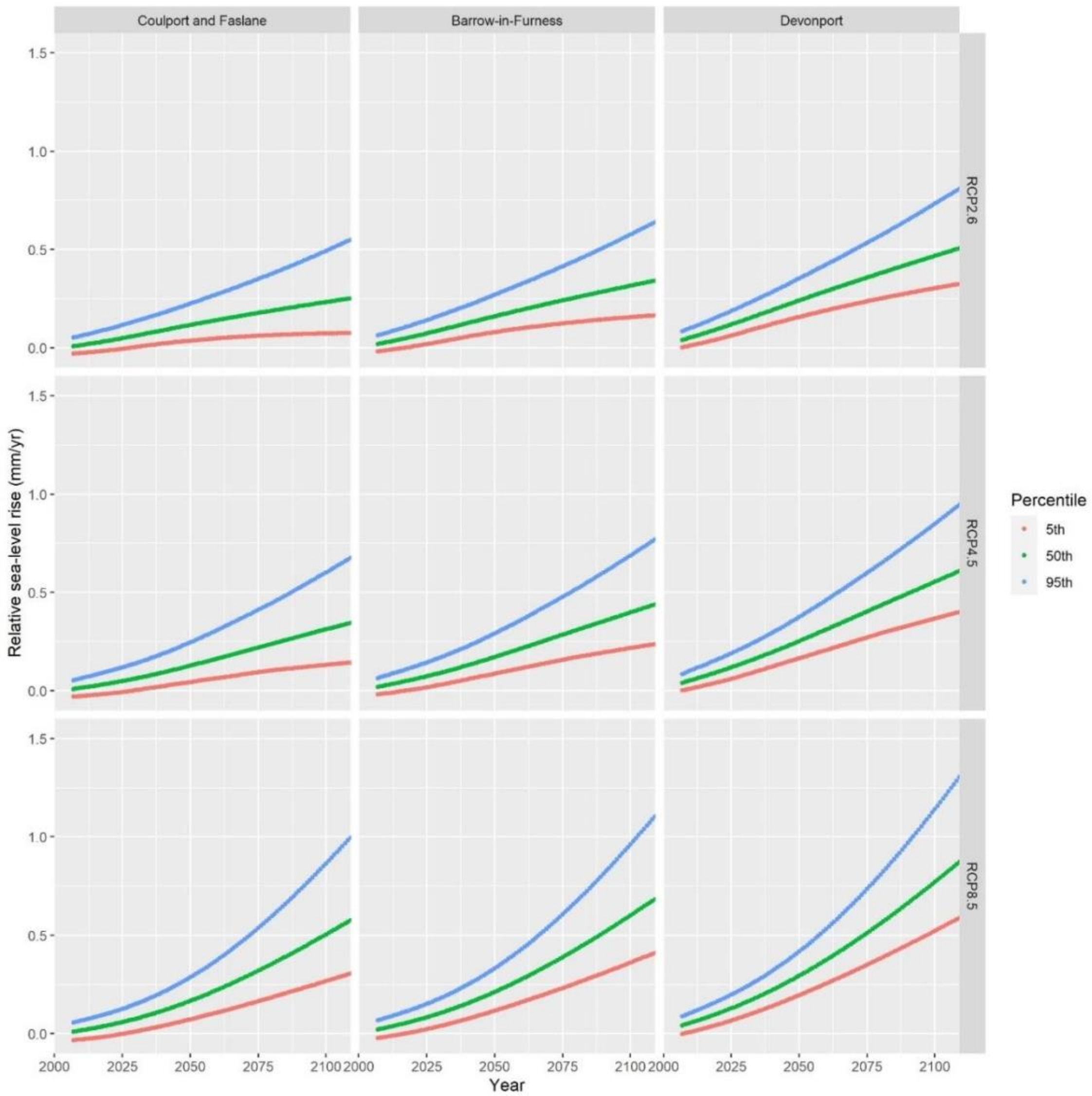

Figure 4.1. Relative sea-level rise projections to 2100 with respect to 1981-2000 for the closest 12km grid squares to Coulport / Faslane (55.94N, -4.92E), Barrow-in-Furness (54.17N, -3.25E) and Devonport (50.28N, -4.25E). Scenarios indicate RCP2.6 (red lines), RCP4.5 (green lines) and RCP8.5 (blue lines) for the 5th, 50th and 95th percentiles of uncertainty (Met Office, 2019). Data downloaded under the Open Government Licence (LINK).

Coulport and Faslane indicate the lowest relative sea-level rise with 0.12m (0.03m-0.22m) projected in 2050 and 0.23m (0.07m-0.49m) in 2100 under a RCP2.6 (mitigation) scenario. Under the same scenario, Barrow-in-Furness reports 0.16m (0.08m-0.27m) in 2050 and 0.32m (0.16m-0.58m) in 2100, whilst Devonport projects higher values of 0.24m (0.16m-0.35m) in 2050 and 0.47m (0.30m-0.73m) in 2100.

With the intermediate scenario of RCP4.5, Coulport and Faslane indicate a rise of 0.13m (0.04m0.24m) in 2050 and 0.31m (0.13m-0.60m) in 2100. Barrow-in-Furness projects 0.17m (0.09m-0.29m) in 2050 and 0.40m (0.22m-0.69m) in 2100, whilst Devonport projects higher values of 0.25m (0.16m0.37m) in 2050 and 0.55m (0.37m-0.85m) in 2100.

When considering a non-mitigation scenario (RCP8.5), Coulport and Faslane project 0.17m (0.07m-0.28m) in 2050 and 0.50m (0.27m-0.84m) in 2100, with Barrow-in-Furness reporting 0.21m (0.12m0.33m) in 2050 and 0.60m (0.36m-0.96m) in 2100, whilst Devonport projects higher values of 0.29m (0.19m-0.42m) in 2050 and 0.77m (0.52m-1.14m) in 2100.

These results indicate that until 2050, the relative sea-level rise scenarios per location are fairly similar, with a relatively small uncertainty range. As the century progresses, the scenarios diverge and the rate of sea-level rise increases. This is due to the commitment to sea-level rise, as past warming is now realised. Importantly, these rises continue beyond 2100.

Table 4.1 indicates the projected relative sea-level rise in 2060, a period of time that broadly coincides with the end of the Dreadnought (replacement Vanguard / Trident) programme. For each location, the scenario's 50th percentile projection has a lower overall uncertainty range that the uncertainty within the projection. Hence, regardless of the emission path taken between now and 2060, there is a greater certainty of the potential magnitude of sea-level rise compared with the end of the century.

Table 4.1. Relative sea-level rise in 2060. with respect to 1981-2000 for the closest 12km grid squares to Coulport / Faslane (55.94N, -4.92E), Barrow-in-Furness (54.17N, -3.25E) and Devonport (50.28N, -4.25E). Scenarios indicated RCP2.6, RCP4.5 and RCP8.5 for the 5th, 50th and 95th percentiles of uncertainty. (Met Office, 2019). Data downloaded under the Open Government Licence (LINK).

Location	RCP	Relative sea-level rise (m) in 2060 with respect to 1981-2000		
		5th	50th	95th
Coulport & Faslane	RCP8.5	0.11	0.22	0.37
Coulport & Faslane	RCP4.5	0.06	0.16	0.31
Coulport & Faslane	RCP2.6	0.05	0.14	0.27
Barrow-in-Furness	RCP8.5	0.16	0.28	0.43
Barrow-in-Furness	RCP4.5	0.12	0.22	0.36
Barrow-in-Furness	RCP2.6	0.10	0.19	0.33
Devonport	RCP8.5	0.25	0.37	0.53
Devonport	RCP4.5	0.21	0.31	0.46
Devonport	RCP2.6	0.19	0.29	0.42

4.5 Outlook to 2300

Crucially, beyond 2060 when the Trident replacement could potentially end, including at the turn of the century, sea-levels are expected to keep rising even under a climate change mitigation scenario (RCP2.6). Figure 4.2 presents relative sea-level rise scenarios closest to Coulport / Faslane, Barrow-inFurness and Plymouth up to 2300. As with Figure 4.1, three different scenarios are shown: RCP2.6 (climate change mitigation), RCP8.5 (non-mitigation), and RCP4.5 (intermediate pathways). The figure illustrates three levels of uncertainties representing the 50th percentile, and the lower and upper uncertainties that represent the 5th and 95th percentiles. Table A1.2 lists the relative sea-level rise data presented in Figure 4.2.

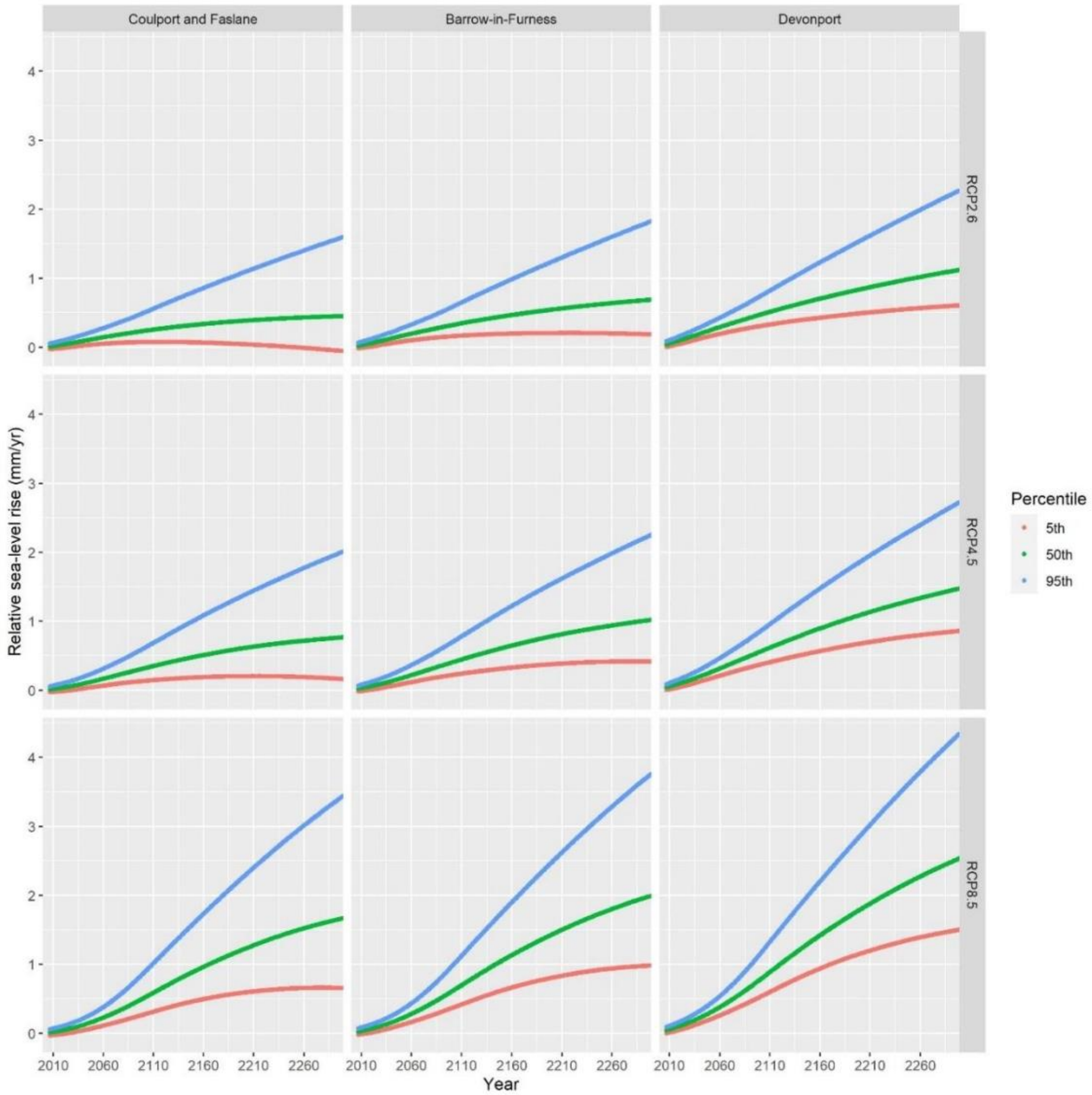

Figure 4.2. Sea-level rise projections to 2300 with respect to 1981-2000 for the closest 12km grid squares to Coulport / Faslane (55.94N, -4.92E), Barrow-in-Furness (54.17N, -3.25E) and Devonport

(50.28N, -4.25E). Scenarios indicated RCP2.6 (red lines), RCP4.5 (green lines) and RCP8.5 (blue lines) for the 5th, 50th and 95th percentiles of uncertainty. (Met Office, 2019). Data downloaded under the Open Government Licence (LINK).

Results indicate that the level of relative sea-level rise projected for Coulport / Faslane could, under the worst case scenario, be in excess of 3m by 2300. Under the most optimistic scenario, the rate of sea-level rise may stabilise leading to a negligible increase in relative sea-level rise. At Barrow-in-Furness, relative sea-level rise is projected, under a non-mitigation scenario, to be 3.8m, and at Devonport 4.35m. However, there are large uncertainties around these numbers. What is important to recognise here is that sea-levels will keep rising for hundreds of years. Hence, existing, and some of the newly installed infrastructure and facilities, will need protected from sea-level rise in decades and centuries to come.

4.6 Other threats

The main driver of future coastal hazards at the locations studied is likely to be from sea-level rise. However, changes to storm surges and the effects of waves could also cause damage to infrastructure at the sites. As the sites are situated within estuaries or lochs there is a natural degree of protection compared with the open coast. Additionally, the use of breakwaters in ports offers protection to the effects of waves.

For many years, there have been discussions as to whether there will be an increase in the frequency and/or the severity of storms and, therefore, the height of storm surges associated with extreme water levels. It is also suggested that there will be a decrease in return period so that extreme events happen more frequently. It is these extreme events caused by a combination of storm surges, often coinciding with high tides, that lead to the greatest flood impacts in a given location. From assessing regionally downscaled models and an analysis of 'high end' projections, Palmer et al. (2018) indicated that throughout the UK (based on results from the UKCP18), there is a 'best estimate of zero additional contribution' from changes in surges. There may be projected changes in the skew surge (the difference between the maximum predicted tide and the maximum observed sea-level), but this remains highly uncertain (Palmer et al. 2018). Although small regional variations of surges could occur, within the period of up to 2060 that is considered in this report, these are considered minor. Other studies consider that there may be regional differences (Arns et al. 2017).

5. ADAPTATION

5.1 UK overview

World-wide adaptation is needed to reduce risks from rising sea-levels. Adaptation in human systems is defined as 'the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities' (IPCC, 2018). For Coulport / Faslane, Barrow-in-Furness and Devonport this means considering potential flood risk and how to reduce flooding, most likely through protective means. This includes all infrastructure both on site and connected to the site, and secondary or cascading consequences and effects.

The UK Climate Change Act of 2008 has a remit to 'make provision about adaptation to climate change' (HM Government, 2008). This means that all organisations, including ports, need to consider the impact of climate change on their surroundings and activities, and plan for change. The Paris Agreement (United Nations, 2015) also requires nations to report on progress on adaptation. In response to both of these frameworks, the UK government has been reporting on adaptation through its National Adaptation Programme – a five year cycle of reporting, that feeds into the UK's Climate Change Risk Assessment (DEFRA, 2018). In 2017, it identified that flooding and coastal change was a priority area that needed further action within the next five years. Ports were also highlighted as being particularly susceptible to flooding (Environment Agency, 2020a) and require additional investment to reduce potential damage.

5.2 How sea-level rise could threaten coastal infrastructure including ports

Rising sea-levels and extreme water levels at ports could, through flooding, affect cargo, energy generation, on-site operations and associated infrastructure (Flegg, 2018). Very often, commercial ports react to events, rather than taking an anticipatory approach (Flegg, 2018). However, for ports at high-risk of flooding and where consequences would be high, one might expect to find a more precautionary approach.

This could mean the raising of sea walls and/or the protection of individual port facilities such as cranes and buildings and other infrastructure. This may affect the locations specifically discussed within this report, but also surrounding link roads. In the case of Coulport, for example, the B833 Shore Road to the south of the site is at low elevation alongside the loch and may need to be protected or raised. Adaptation would need to consider the impact of climate effects, which may be slow onset (such as sea-level rise) or fast onset (such as a storm leading to an extreme water level event). The impacts could include equipment damage and write-off, contamination, delays and, of course, their financial effects (Popovic et al., 2014), as well as back-up plans, such as alternative access or generators. Adaptation could include the development and deployment of flood risk management plans, updated regulations or operating procedures, protection of power supplies (e.g. back-up provision) and improvements to infrastructure, such as land raising and alternative access routes. Adaptation could happen in the immediate future, or in the long term when the risks are more certain. Alternatively, they could be timed to coincide with other infrastructure upgrades. Whatever the timing, it is important that any adaptation should consider both the short-term and long-term risks, so that short-term benefits are not outweighed by long-term costs.

5.3 Local implications

It is clear that some infrastructure improvements are being implemented. For instance, a dry dock in Devonport will be upgraded from 2021 with standards sufficient to withstand significant earthquakes, high winds and high tides (Navy Lookout, 2020). There are also claims that sea walls will be built higher to prevent flooding from rising sea-levels (Telford, 2020). In Faslane, a Freedom of Information request (DOI Secretariat, 2020) indicated a climate change risk assessment has been undertaken in the Clyde, which considered a 0.70m sea-level rise by the end of the century, with another assessment indicating a 0.47m rise by 2080. When land level rise is taken into account, the latter value is a few centimetres higher than the latest values considered in this present report. No publicly available information was found for Coulport or Barrow-in-Furness.

The Environment Agency (2020b) indicates allowances for the effects of climate change to reduce flood and coastal risk in projects and protection schemes. This indicates that projects should consider the RCP8.5 scenario using the 70th percentile of change as the design allowance, but also consider the 95th percentile for planning for more severe climate impacts (the data set used in this report – see Table A1.2). It also advises users to consider high impact, low probability events (known as a H++ scenario) based on the UK Climate Projections of 2009. This indicates an allowance of between 0.93m to 1.9m of sea-level rise by 2100 (Lowe et al. 2009). These allowances would need to be added to present day extreme sea-levels, that take account of the astronomical tide levels and surges (Environment Agency, 2020b). Thus, given the assets exposed to rising sea-levels, it would be expected that at least the RCP8.5 (95th percentile) would be used to factor in sea-level rise. Given the use and nature of the localities presented, it is extremely likely that they would be in use beyond 2060 (i.e. beyond the lifetime of the Trident replacement, even if it were for a different purpose). Therefore, it is anticipated that the value of sea-level rise to at least 2100 would be considered.

The Office for Nuclear Regulation (2018a,b) states that facilities should be able to withstand a design basis event (i.e. 1:10,000 year event), and where this is not possible a dry site concept, including external barriers such as levees and seawalls. Hence, climate change and sea-level rise mean an evolving base line and regular reassessment using the latest science for protection of new and existing sites, particularly considering the opportunities for adaptive management to high impact low probability (H++) events. Tsunamis are also considered a potential flood hazard, so adaptation to these events should be occurring too. Importantly, clearly communicating the standards of protection against present and future flooding, accounting for sea-level rise in climate change adaptation risk assessments, would be welcomed.

5.4 Other climate effects

Although this report has focused on sea-level rise, other climate change impacts, such as warming temperatures, changes to humidity, high winds / gusts, change in frequency and duration of precipitation causing pluvial flooding may also have an adverse effect on coastal localities. In port areas, this could cause greater disruption to day-to-day operations through power disruptions, inaccessibility, vessel damage, and damage to cranes and other equipment (Flegg, 2018). Extreme weather events rarely occur in isolation (Wisner et al. 2004), which can lead to interlinking pressures that could be more severe to contend with. Adaptation would need to consider the wider effects of climate change, not just sea-level rise in isolation, to ensure effective and safe working of Trident-type sites over many decades to come.

6. CONCLUSION

Sea-level rise presents a major long-term hazard for naval nuclear facilities located on the UK's coast. These include four sites - Coulport, Faslane, Barrow-in-Furness and Devonport – with heavy involvement in the manufacture, arming and deployment of the Dreadnought class submarines that, starting in the 2030s, will replace the ageing Trident boats. At risk are protective engineered features, such as seawalls, and infrastructure such as port operating equipment and buildings.

Changes in sea-level are caused by a range of processes and there are significant uncertainties in the rate and magnitude of future rise, especially when projecting to timescales of 100 years and more. By 2060, the UK Climate Projections programme suggests a relative sea-level rise of between 0.05m to 0.37m for Coulport and Faslane, 0.10m to 0.43m for Barrow-in-Furness and 0.19m to 0.53m for Devonport. This takes account of a range of climate change scenarios and percentiles of uncertainty. One of the main reasons that there are geographical differences is changes to relative land levels, as Scotland is rising, whereas the south of England is subsiding.

Regardless of any measures taken to curb greenhouse gas emissions, sea-levels are projected to keep rising beyond 2100. Therefore, it is important to consider the long-term effects of sea-level rise in these locations. This could be in the range of multiple-metre of sea-level rise over the centuries. Planned engineering work needs to look beyond the time span of the Trident replacement programme to consider the long-term impacts of sea-level rise on flood risk, and consider the benefits of adaptation. This means potentially considering high impact, low probability events, such as the H++ scenario (up to 1.9m of sea-level rise by 2100) as a credible maximum. Adaptation includes the possibility of raising of sea walls, associated port operating infrastructure and also buildings, all of which require long-term monitoring and planning to mitigate the effects of extreme weather events and rising sea-levels. Communicating risks and methods to adapt to changing risks at high-risk sites would be welcomed.

7. REFERENCES

Arns, A., Dangendorf , S., Jensen, J., Talke, S., Bender, J. and Pattiaratchi, C. (2017). Sea-level rise induced amplification of coastal protection design heights. *Scientific Reports*. 7, 40171, doi: 10.1038/srep40171

Bamber, J.L., Oppenheimer, M., Kopp, R.E., Aspinall, W.P. and Cooke, R.M. (2019). Ice sheet contributions to future sea-level rise from structured expert judgement. *Proceedings of the National Academy of Sciences of the United States of America*, 116 (23) 11195-11200. doi: 10.1073/pnas.1817205116

Chao, B.F., Wu, Y.H., Li, Y.S. (2008). Impact of artificial reservoir water impoundment on global sea level. *Science*, 320 (5873), 212-214.

Chhetri, P., Cocoran, J., Gekara, V., Corbitt, B., Wickramsinghe, N., Jayatilleke, G., Basic, F., Scott, H., Manzoni, A. and Maddox, C. (2013) *Functional resilience of port environs in a changing climate - assets and operations*. Work Package 2 of Enhancing the resilience of seaports to a changing climate.

DeConto, R.M., Pollard, D., Alley, R.B., Velicogna, I., Gasson, E., Gomez, N., Sadai, S., Condron, A., Gilford, D.M., Ashe, E.L., Kopp, R.E. Li, D. and Dutton, A. (2021). The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* 593, 83–89. doi: 10.1038/s41586-021-03427-0

Defence Nuclear Organisation and Ministry of Defence (2020). The United Kingdom's future nuclear deterrent: the 2020 update to Parliament. https://www.gov.uk/government/publications/theunited-kingdoms-future-nuclear-deterrent-the-2020-update-to-parliament/the-unitedkingdoms-future-nuclear-deterrent-the-2020-update-to-parliament#introduction Accessed 20th May 2021.

Defence Nuclear Organisation and Ministry of Defence (2021). The UK's nuclear deterrent: what you need to know. https://www.gov.uk/government/publications/uk-nuclear-deterrencefactsheet/uk-nuclear-deterrence-what-you-need-to-know Accessed 20th May 2021.

DEFRA (2018). The National Adaptation Programme and the Third Strategy for Climate Adaptation Reporting. Making the country resilient to a changing climate.. DEFRA, London. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/727252/national-adaptation-programme-2018.pdf Accessed 10th June 2021.

DOI Secretariat (2020). Climate Impact Risk Assessment Annex A - Estate and Climatic Information HM Naval Base Clyde. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/878527/20200116-FOI13198.pdf Accessed 11th June 2020

Environment Agency (2015). Flood map for planning risk http://apps.environmentagency.gov.uk/wiyby/cy/151263.aspx Accessed 11th June 2021.

Environment Agency (2020a). National flood and coastal erosion risk management Strategy for England https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_dat a/file/920944/023_15482_Environment_agency_digitalAW_Strategy.pdf Accessed 10th June 2021.

Environment Agency (2020b) Flood and coastal risk projects, schemes and strategies: climate change allowances https://www.gov.uk/guidance/flood-and-coastal-risk-projects-schemes-andstrategies-climate-change-allowances Accessed 11th June 2021.

Environment Agency (2021). Flood map for planning. https://flood-map-for-planning.service.gov.uk/ Accessed 11th June 2021.

Flegg, E.F. (2018). *UK ports, extreme events and climate change: legislative and adaptive perspectives*. PhD thesis, University of Southampton.

Goodwin, P., Brown, S., Haigh, I.D., Nicholls, R. J., and Matter, J.M. (2018). Adjusting mitigation pathways to stabilize climate at 1.5 and 2.0°C rise in global temperatures to year 2300. *Earth's Future*. 6, 601– 615. doi: 10.1002/2017EF000732

Gregory, J.M., White, N. J., Church, J. A., Bierkens, M. F. P., Box, J. E., van den Broeke, M. R., Cogley, J. G., Fettweis, X., Hanna, E., Huybrechts, P., Konikow, L. F., Leclercq, P. W., Marzeion, B., Oerlemans, J., Tamisiea, M. E., Wada, Y., Wake, L. M. and van de Wal, R. S. W. (2013). Twentiethcentury global-mean sea level rise: Is the whole greater than the sum of the parts? *Journal of Climate*, 26(13), 4476–4499. doi: 10.1175/JCLI-D-12-00319.1.

Hawkins, E. and Sutton, R. (2009). The potential to narrow uncertainty in regional climate projections. *Bulletin of the American Meteorological Society*, 90(8), 1095-1108.

HM Government (2008). Climate Change Act 2008. https://www.legislation.gov.uk/ukpga/2008/27/introduction Accessed 9th June 2021.

Hock, R., Rasul, G., Adler, C., Cáceres, B., Gruber, S., Hirabayashi, Y., Jackson, M., Kääb, A., Kang, S., Kutuzov, S., Milner, A., Molau, U., Morin, S., Orlove, B., and Steltzer, H. (2019). *High Mountain Areas*. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Pörtner, H.O.., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N.M. (eds.)).

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K.L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S.I., Thomas, A., Warren, R. and Zhou, G., (2018). *Impacts of 1.5ºC global warming on natural and human systems.* In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M. and Waterfield, T. (eds.)).

Holgate, S.J., Matthews, A., Woodworth, P.L., Rickards, L.J., Tamisiea, M., Bradshaw, E., Foden, P.R., Gordon, K.M., Jevrejeva, S. and Pugh, J. (2013) New data systems and products at the Permanent

Service for Mean Sea Level. *Journal of Coastal Research*, 29, 3, 493-504. doi:10.2112/JCOASTRESD-12-00175.1.

Horton, B.P., Khan, N.S., Cahill, N., Cahill, N., Lee, J.S.H., Shaw, T.A., Garner, A.J., Kemp, A.C., Engelhart, S.E. and Rahmstorf, S. (2020). Estimating global mean sea-level rise and its uncertainties by 2100 and 2300 from an expert survey. *npj Climate and Atmospheric Science*, 3, 18. doi: 10.1038/s41612-020-0121-5

Howard, T., Palmer, M., Guentchev, G. and Krijnen, J. (2019). Exploratory sea level projections for the UK to 2300. https://assets.publishing.service.gov.uk/media/60378c448fa8f5048f78a5cf/Exploratory_sea_level_projections_for_the_UK_to_2300_-_report.pdf Accessed 9th June 2021.

IPCC (2013) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2018). *Annex I: Glossary* [Matthews, J.B.R. (ed.)]. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [MassonDelmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)].

Levermann, A., Winkelmann, R., Nowicki, S., Fastook, J. L., Frieler, K., Greve, R., Hellmer, H. H., Martin, M. A., Meinshausen, M., Mengel, M., Payne, A. J., Pollard, D., Sato, T., Timmermann, R., Wang, W. L., and Bindschadler, R. A., (2014). Projecting Antarctic ice discharge using response functions from SeaRISE ice-sheet models. *Earth System Dynamics*, 5, 271-293. doi: 10.5194/esd-5-271-2014

Lowe, J.A., Bernie, D., Bett, P.E., Bricheno, L., Brown, S., Calvert, D., Clark, R.T., Eagle, K.E., Edwards, T., Fosser, G., Fung, F., Gohar, L., Good, P., Gregory, J., Harris, G.R., Howard, T., Kaye, N., Kendon, E.J., Krijnen, J., Maisey, P., McDonald, R.E., McInnes, R.N., McSweeney, C.F., Mitchell, J.F.B., Murphy, J.M., Palmer, M., Roberts, C., Rostron, J.W., Sexton, D.M.H., Thornton, H.E., Tinker, J., Tucker, S., Yamazaki, K., and Belcher, S. (2018). UKCP18 Science Overview report. Met Office, Exeter.

Lowe, J.A., Howard, T.P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake, J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. and Bradley, S. (2009). UK Climate Projections science report: Marine and coastal projections. Met Office Hadley Centre, Exeter, UK.

Met Office (2019). UK Climate Projections: Headline Findings. Version 2. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp-headline-findings-v2.pdf Accessed 26th May 2021.

Moss, R.H., Nakicenovic, N. and O'Neill, B.C. (2008). *Towards new scenarios for analysis of emissions, climate change, impacts, and response strategies*. Technical Summary. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland, 25 pp.

Navy Lookout (2020). Upgrading the Royal Navy's nuclear submarine support facilities. https://www.navylookout.com/upgrading-the-royal-navys-nuclear-submarine-supportfacilities/ Accessed 10th June 2021.

Office for Nuclear Regulation (2018a). Nuclear safety technical assessment guide. NS-TAST-GD-013 Revision 8. Office for Nuclear Regulation. https://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-013.pdf Accessed 25th June 2021.

Office for Nuclear Regulation (2018b). Nuclear safety technical assessment guide. NS-TAST-GD-013 Annex 3 Revision 1. Office for Nuclear Regulation. https://www.onr.org.uk/operational/tech_asst_guides/ns-tast-gd-013-annex-3.pdf Accessed 25th June 2021.

Oppenheimer, M., Glavovic, B.C., Hinkel, J., van de Wal, R., Magnan, A.K., Abd-Elgawad, A., Cai, R., Cifuentes-Jara, M., DeConto, R.M., Ghosh, T., Hay, J., Isla, F., Marzeion, B., Meyssignac, B. and Sebesvari, Z. (2019). *Sea level rise and implications for low-lying islands, coasts and communities*. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., Petzold, J., Rama, B. and Weyer, N.M., (eds.)).

Ordnance Survey (2020a). OS MasterMap, 1:1,250. British National Grid. EPSG:27700. August 2020.

Ordnance Survey (2020b). OS VectorMap Local Raster, 1:5000. British National Grid. EPSG:27700. October 2020.

Ordnance Survey (2021). Ordnance Datum Newlyn - 100 years old today https://www.ordnancesurvey.co.uk/newsroom/blog/ordnance-datum-newlyn-100-years-oldtoday Access 11th June 2021.

Palmer, M., Howard, T., Tinker, J., Lowe, J., Bricheno, L. Calvert, D., Edwards, T., Gregory, J., Harris, G., Krijnen, J., Pickering, M., Roberts, C. and Wolf, J. (2018). https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-marine-report-updated.pdf Accessed 9th June 2021.

Permanent Service for Mean Sea Level (2021).Tide gauge data, retrieved 17th May 2021 https://www.psmsl.org/ Accessed 20th May 2021.

Popovic, R., Kulovic, M. and Stanivuk, T. (2014) Meteorological safety of entering eastern Adriatic Ports. Transactions on Maritime Science. 1, 53-60.

Scottish Environmental Protection Agency (2021). Flood maps https://map.sepa.org.uk/floodmap/map.htm Access 11 June 2021.

Shennan, I. and Horton, B. (2002). Holocene land- and sea-level changes in Great Britain. Journal of *Quaternary Science*., 17 (5-6).511-526.

Shennan, I., Milne, G., Bradley, S. (2009). Late Holocene relative land- and sea-level changes: Providing information for stakeholders. *GSA Today*, 19 (9), 52-53.

Slangen, A., Church, J., Agosta, C., Fettweis, X., Marzeion, B. and Richter, K. (2016). Anthropogenic forcing dominates global mean sea-level rise since 1970. *Nature Climate Change.* 6, 701–705 doi: 10.1038/nclimate2991

Telford, W. (2020). Huge redevelopment project planned for UK's largest dockyard https://www.business-live.co.uk/manufacturing/huge-redevelopment-project-planned-uks18087657 Accessed 20th June 2021.

Townend, I.H. and Burgess, K.A. (2001). Methodology for assessing the impact of climate change upon coastal defence structures. ASCE, 29th International Conference on Coastal Engineering, 3953-3966.

United Nations (2015). The Paris Agreement. https://unfccc.int/sites/default/files/english_paris_agreement.pdf Accessed 26th May 2021.

Wada, Y., Reager, J.T., Chao, B.F., Wang, J., Lo, M.-H., Song, C., Li, Y. and Gardner, A.S. (2017). Recent changes in land water storage and its contribution to sea level variations. *Surveys in Geophysics*, 38, (1), 131–152.

Wisner, B., Blaikie, P., Cannon, T. and Davis, I. (2004) At Risk: Natural hazards, people's vulnerability and disasters. Routledge, Abingdon, 496 pp.

APPENDIX 1

Table A1.1. Relative sea-level rise projections to 2100 with respect to 1981-2000 for the closest 12km grid squares to Coulport / Faslane (55.94N, -4.92E), Barrow-in-Furness (54.17N, -3.25E) and Devonport (50.28N, -4.25E). Scenarios indicated RCP2.6, RCP4.5 and RCP8.5 for the 5th, 50th and 95th percentiles of uncertainty. Data presented every five years. (Met Office, 2019). Data downloaded under the Open Government Licence (LINK).

Location	Year	RCP	Relative sea-level rise (m) with respect to 1981-2000		
			5th	50th	95th
Devonport	2010	RCP8.5	0.01	0.06	0.11
Devonport	2015	RCP8.5	0.03	0.08	0.13
Devonport	2020	RCP8.5	0.04	0.10	0.16
Devonport	2025	RCP8.5	0.07	0.13	0.20
Devonport	2030	RCP8.5	0.09	0.16	0.23
Devonport	2035	RCP8.5	0.11	0.19	0.27
Devonport	2040	RCP8.5	0.14	0.22	0.32
Devonport	2045	RCP8.5	0.17	0.26	0.37
Devonport	2050	RCP8.5	0.19	0.29	0.42
Devonport	2055	RCP8.5	0.22	0.33	0.47
Devonport	2060	RCP8.5	0.25	0.37	0.53
Devonport	2065	RCP8.5	0.29	0.42	0.60
Devonport	2070	RCP8.5	0.32	0.46	0.66
Devonport	2075	RCP8.5	0.35	0.51	0.73
Devonport	2080	RCP8.5	0.38	0.56	0.81
Devonport	2085	RCP8.5	0.42	0.61	0.89
Devonport	2090	RCP8.5	0.45	0.66	0.97
Devonport	2095	RCP8.5	0.49	0.72	1.05
Devonport	2100	RCP8.5	0.52	0.77	1.14
Devonport	2010	RCP4.5	0.01	0.05	0.10
Devonport	2015	RCP4.5	0.03	0.07	0.13
Devonport	2020	RCP4.5	0.04	0.10	0.16
Devonport	2025	RCP4.5	0.06	0.12	0.19

Devonport	2030	RCP4.5	0.08	0.14	0.22
Devonport	2035	RCP4.5	0.10	0.17	0.26
Devonport	2040	RCP4.5	0.12	0.20	0.29
Devonport	2045	RCP4.5	0.14	0.22	0.33
Devonport	2050	RCP4.5	0.16	0.25	0.37
Devonport	2055	RCP4.5	0.19	0.28	0.42
Devonport	2060	RCP4.5	0.21	0.31	0.46
Devonport	2065	RCP4.5	0.23	0.34	0.51
Devonport	2070	RCP4.5	0.25	0.37	0.55

Location	Year	RCP	Relative sea-level rise (m) with respect to 1981-2000		
			5th	50th	95th
Devonport	2075	RCP4.5	0.27	0.40	0.60
Devonport	2080	RCP4.5	0.29	0.43	0.65
Devonport	2085	RCP4.5	0.31	0.46	0.70
Devonport	2090	RCP4.5	0.33	0.49	0.75
Devonport	2095	RCP4.5	0.35	0.52	0.80
Devonport	2100	RCP4.5	0.37	0.55	0.85
Devonport	2010	RCP2.6	0.01	0.05	0.10
Devonport	2015	RCP2.6	0.03	0.07	0.13
Devonport	2020	RCP2.6	0.04	0.10	0.16
Devonport	2025	RCP2.6	0.06	0.12	0.19
Devonport	2030	RCP2.6	0.08	0.14	0.22
Devonport	2035	RCP2.6	0.10	0.17	0.25
Devonport	2040	RCP2.6	0.12	0.19	0.28
Devonport	2045	RCP2.6	0.14	0.22	0.32
Devonport	2050	RCP2.6	0.16	0.24	0.35
Devonport	2055	RCP2.6	0.17	0.26	0.39
Devonport	2060	RCP2.6	0.19	0.29	0.42
Devonport	2065	RCP2.6	0.21	0.31	0.46
Devonport	2070	RCP2.6	0.22	0.33	0.50

Devonport	2075	RCP2.6	0.24	0.36	0.53
Devonport	2080	RCP2.6	0.25	0.38	0.57
Devonport	2085	RCP2.6	0.26	0.40	0.61
Devonport	2090	RCP2.6	0.28	0.42	0.65
Devonport	2095	RCP2.6	0.29	0.45	0.69
Devonport	2100	RCP2.6	0.30	0.47	0.73
Barrow-in-Furness	2010	RCP8.5	-0.02	0.03	0.08
Barrow-in-Furness	2015	RCP8.5	0.00	0.05	0.10
Barrow-in-Furness	2020	RCP8.5	0.01	0.06	0.13
Barrow-in-Furness	2025	RCP8.5	0.02	0.08	0.15
Barrow-in-Furness	2030	RCP8.5	0.04	0.10	0.18
Barrow-in-Furness	2035	RCP8.5	0.06	0.13	0.21
Barrow-in-Furness	2040	RCP8.5	0.08	0.15	0.25
Barrow-in-Furness	2045	RCP8.5	0.10	0.18	0.29
Barrow-in-Furness	2050	RCP8.5	0.12	0.21	0.33
Barrow-in-Furness	2055	RCP8.5	0.14	0.24	0.38
Barrow-in-Furness	2060	RCP8.5	0.16	0.28	0.43
Barrow-in-Furness	2065	RCP8.5	0.18	0.31	0.49
Barrow-in-Furness	2070	RCP8.5	0.21	0.35	0.54

Location	Year	RCP	Relative sea-level rise (m) with respect to 1981-2000		
			5th	50th	95th
Barrow-in-Furness	2075	RCP8.5	0.23	0.39	0.61
Barrow-in-Furness	2080	RCP8.5	0.26	0.43	0.67
Barrow-in-Furness	2085	RCP8.5	0.28	0.47	0.74
Barrow-in-Furness	2090	RCP8.5	0.31	0.51	0.81
Barrow-in-Furness	2095	RCP8.5	0.33	0.56	0.89
Barrow-in-Furness	2100	RCP8.5	0.36	0.60	0.96
Barrow-in-Furness	2010	RCP4.5	-0.01	0.03	0.08
Barrow-in-Furness	2015	RCP4.5	0.00	0.04	0.10
Barrow-in-Furness	2020	RCP4.5	0.01	0.06	0.12

Barrow-in-Furness	2025	RCP4.5	0.02	0.07	0.14
Barrow-in-Furness	2030	RCP4.5	0.03	0.09	0.17
Barrow-in-Furness	2035	RCP4.5	0.04	0.11	0.20
Barrow-in-Furness	2040	RCP4.5	0.06	0.13	0.23
Barrow-in-Furness	2045	RCP4.5	0.07	0.15	0.26
Barrow-in-Furness	2050	RCP4.5	0.09	0.17	0.29
Barrow-in-Furness	2055	RCP4.5	0.10	0.19	0.33
Barrow-in-Furness	2060	RCP4.5	0.12	0.22	0.36
Barrow-in-Furness	2065	RCP4.5	0.13	0.24	0.40
Barrow-in-Furness	2070	RCP4.5	0.14	0.26	0.44
Barrow-in-Furness	2075	RCP4.5	0.16	0.28	0.48
Barrow-in-Furness	2080	RCP4.5	0.17	0.31	0.52
Barrow-in-Furness	2085	RCP4.5	0.18	0.33	0.56
Barrow-in-Furness	2090	RCP4.5	0.19	0.35	0.60
Barrow-in-Furness	2095	RCP4.5	0.21	0.38	0.64
Barrow-in-Furness	2100	RCP4.5	0.22	0.40	0.69
Barrow-in-Furness	2010	RCP2.6	-0.01	0.03	0.08
Barrow-in-Furness	2015	RCP2.6	0.00	0.04	0.10
Barrow-in-Furness	2020	RCP2.6	0.01	0.06	0.12
Barrow-in-Furness	2025	RCP2.6	0.02	0.07	0.14
Barrow-in-Furness	2030	RCP2.6	0.03	0.09	0.17
Barrow-in-Furness	2035	RCP2.6	0.04	0.11	0.19
Barrow-in-Furness	2040	RCP2.6	0.06	0.13	0.22
Barrow-in-Furness	2045	RCP2.6	0.07	0.14	0.24
Barrow-in-Furness	2050	RCP2.6	0.08	0.16	0.27
Barrow-in-Furness	2055	RCP2.6	0.09	0.18	0.30
Barrow-in-Furness	2060	RCP2.6	0.10	0.19	0.33
Barrow-in-Furness	2065	RCP2.6	0.11	0.21	0.35
Barrow-in-Furness	2070	RCP2.6	0.12	0.23	0.38

Location	Year	RCP	Relative sea-level rise (m) with respect to 1981-2000		

			5th	50th	95th
Barrow-in-Furness	2075	RCP2.6	0.12	0.24	0.41
Barrow-in-Furness	2080	RCP2.6	0.13	0.26	0.44
Barrow-in-Furness	2085	RCP2.6	0.14	0.27	0.48
Barrow-in-Furness	2090	RCP2.6	0.14	0.29	0.51
Barrow-in-Furness	2095	RCP2.6	0.15	0.30	0.54
Barrow-in-Furness	2100	RCP2.6	0.16	0.32	0.58
Coulport & Faslane	2010	RCP8.5	-0.03	0.02	0.07
Coulport & Faslane	2015	RCP8.5	-0.02	0.03	0.08
Coulport & Faslane	2020	RCP8.5	-0.01	0.04	0.10
Coulport & Faslane	2025	RCP8.5	0.00	0.06	0.13
Coulport & Faslane	2030	RCP8.5	0.01	0.08	0.15
Coulport & Faslane	2035	RCP8.5	0.03	0.10	0.18
Coulport & Faslane	2040	RCP8.5	0.04	0.12	0.21
Coulport & Faslane	2045	RCP8.5	0.06	0.14	0.25
Coulport & Faslane	2050	RCP8.5	0.07	0.17	0.29
Coulport & Faslane	2055	RCP8.5	0.09	0.19	0.33
Coulport & Faslane	2060	RCP8.5	0.11	0.22	0.37
Coulport & Faslane	2065	RCP8.5	0.13	0.25	0.43
Coulport & Faslane	2070	RCP8.5	0.15	0.29	0.48
Coulport & Faslane	2075	RCP8.5	0.16	0.32	0.54
Coulport & Faslane	2080	RCP8.5	0.18	0.35	0.60
Coulport & Faslane	2085	RCP8.5	0.20	0.39	0.66
Coulport & Faslane	2090	RCP8.5	0.22	0.43	0.73
Coulport & Faslane	2095	RCP8.5	0.25	0.47	0.79
Coulport & Faslane	2100	RCP8.5	0.27	0.50	0.86
Coulport & Faslane	2010	RCP4.5	-0.03	0.02	0.06
Coulport & Faslane	2015	RCP4.5	-0.02	0.03	0.08
Coulport & Faslane	2020	RCP4.5	-0.01	0.04	0.10
Coulport & Faslane	2025	RCP4.5	-0.01	0.05	0.12
Coulport & Faslane	2030	RCP4.5	0.00	0.06	0.14

Coulport & Faslane	2035	RCP4.5	0.01	0.08	0.16
Coulport & Faslane	2040	RCP4.5	0.02	0.09	0.19
Coulport & Faslane	2045	RCP4.5	0.03	0.11	0.22
Coulport & Faslane	2050	RCP4.5	0.04	0.13	0.25
Coulport & Faslane	2055	RCP4.5	0.05	0.15	0.28
Coulport & Faslane	2060	RCP4.5	0.06	0.16	0.31
Coulport & Faslane	2065	RCP4.5	0.07	0.18	0.34
Coulport & Faslane	2070	RCP4.5	0.08	0.20	0.38

Location	Year	RCP	Relative sea-level rise (m) with respect to 1981-2000		
			5th	50th	95th
Coulport & Faslane	2075	RCP4.5	0.09	0.22	0.41
Coulport & Faslane	2080	RCP4.5	0.10	0.24	0.45
Coulport & Faslane	2085	RCP4.5	0.11	0.26	0.48
Coulport & Faslane	2090	RCP4.5	0.12	0.28	0.52
Coulport & Faslane	2095	RCP4.5	0.12	0.29	0.56
Coulport & Faslane	2100	RCP4.5	0.13	0.31	0.60
Coulport & Faslane	2010	RCP2.6	-0.03	0.01	0.06
Coulport & Faslane	2015	RCP2.6	-0.02	0.03	0.08
Coulport & Faslane	2020	RCP2.6	-0.01	0.04	0.10
Coulport & Faslane	2025	RCP2.6	0.00	0.05	0.12
Coulport & Faslane	2030	RCP2.6	0.00	0.06	0.14
Coulport & Faslane	2035	RCP2.6	0.01	0.08	0.16
Coulport & Faslane	2040	RCP2.6	0.02	0.09	0.18
Coulport & Faslane	2045	RCP2.6	0.03	0.10	0.20
Coulport & Faslane	2050	RCP2.6	0.04	0.12	0.23
Coulport & Faslane	2055	RCP2.6	0.04	0.13	0.25
Coulport & Faslane	2060	RCP2.6	0.05	0.14	0.27
Coulport & Faslane	2065	RCP2.6	0.05	0.15	0.30
Coulport & Faslane	2070	RCP2.6	0.06	0.17	0.32
Coulport & Faslane	2075	RCP2.6	0.06	0.18	0.35
Coulport & Faslane	2080	RCP2.6	0.07	0.19	0.38

Coulport & Faslane	2085	RCP2.6	0.07	0.20	0.40
Coulport & Faslane	2090	RCP2.6	0.07	0.21	0.43
Coulport & Faslane	2095	RCP2.6	0.07	0.22	0.46
Coulport & Faslane	2100	RCP2.6	0.07	0.23	0.49

Table A1.2. Relative sea-level rise projections to 2300 with respect to 1981-2000 for the closest 12km grid squares to Coulport / Faslane (55.94N, -4.92E), Barrow-in-Furness (54.17N, -3.25E) and Devonport (50.28N, -4.25E). Scenarios indicated RCP2.6, RCP4.5 and RCP8.5 for the 5th, 50th and 95th percentiles of uncertainty. Data presented every fifty years. (Met Office, 2019). Data downloaded under the Open Government Licence (LINK).

Location	Year	RCP	Relative sea-level rise (m) with respect to 1981-2000		
			5th	50th	95th
Devonport	2050	RCP8.5	0.19	0.29	0.42
Devonport	2100	RCP8.5	0.52	0.77	1.14
Devonport	2150	RCP8.5	0.87	1.32	2.03
Devonport	2200	RCP8.5	1.15	1.79	2.86
Devonport	2250	RCP8.5	1.36	2.20	3.64
Devonport	2300	RCP8.5	1.50	2.54	4.35
Devonport	2050	RCP4.5	0.16	0.25	0.37
Devonport	2100	RCP4.5	0.37	0.55	0.85
Devonport	2150	RCP4.5	0.54	0.84	1.37
Devonport	2200	RCP4.5	0.67	1.09	1.86
Devonport	2250	RCP4.5	0.78	1.30	2.31
Devonport	2300	RCP4.5	0.86	1.48	2.73
Devonport	2050	RCP2.6	0.16	0.24	0.35
Devonport	2100	RCP2.6	0.30	0.47	0.73
Devonport	2150	RCP2.6	0.41	0.67	1.15
Devonport	2200	RCP2.6	0.49	0.84	1.54
Devonport	2250	RCP2.6	0.55	0.99	1.92
Devonport	2300	RCP2.6	0.61	1.12	2.28
Barrow-in-Furness	2050	RCP8.5	0.12	0.21	0.33

Barrow-in-Furness	2100	RCP8.5	0.36	0.60	0.96
Barrow-in-Furness	2150	RCP8.5	0.62	1.05	1.74
Barrow-in-Furness	2200	RCP8.5	0.80	1.43	2.48
Barrow-in-Furness	2250	RCP8.5	0.92	1.74	3.16
Barrow-in-Furness	2300	RCP8.5	0.98	1.99	3.77
Barrow-in-Furness	2050	RCP4.5	0.09	0.17	0.29
Barrow-in-Furness	2100	RCP4.5	0.22	0.40	0.69
Barrow-in-Furness	2150	RCP4.5	0.31	0.61	1.13
Barrow-in-Furness	2200	RCP4.5	0.38	0.78	1.54
Barrow-in-Furness	2250	RCP4.5	0.41	0.91	1.91
Barrow-in-Furness	2300	RCP4.5	0.42	1.02	2.26
Barrow-in-Furness	2050	RCP2.6	0.08	0.16	0.27
Barrow-in-Furness	2100	RCP2.6	0.16	0.32	0.58
Barrow-in-Furness	2150	RCP2.6	0.19	0.44	0.92
Location	**Year**	**RCP**	**Relative sea-level rise (m) with respect to 1981-2000**		
			5th	**50th**	**95th**
Barrow-in-Furness	2200	RCP2.6	0.20	0.54	1.24
Barrow-in-Furness	2250	RCP2.6	0.20	0.62	1.54
Barrow-in-Furness	2300	RCP2.6	0.18	0.69	1.83
Coulport & Faslane	2050	RCP8.5	0.07	0.17	0.29
Coulport & Faslane	2100	RCP8.5	0.27	0.50	0.86
Coulport & Faslane	2150	RCP8.5	0.46	0.89	1.59
Coulport & Faslane	2200	RCP8.5	0.59	1.21	2.27
Coulport & Faslane	2250	RCP8.5	0.65	1.47	2.89
Coulport & Faslane	2300	RCP8.5	0.65	1.67	3.44
Coulport & Faslane	2050	RCP4.5	0.04	0.13	0.25
Coulport & Faslane	2100	RCP4.5	0.13	0.31	0.60
Coulport & Faslane	2150	RCP4.5	0.18	0.48	1.00
Coulport & Faslane	2200	RCP4.5	0.20	0.61	1.37
Coulport & Faslane	2250	RCP4.5	0.19	0.70	1.71
Coulport & Faslane	2300	RCP4.5	0.16	0.77	2.01

Coulport & Faslane	2050	RCP2.6	0.04	0.12	0.23
Coulport & Faslane	2100	RCP2.6	0.07	0.23	0.49
Coulport & Faslane	2150	RCP2.6	0.07	0.32	0.80
Coulport & Faslane	2200	RCP2.6	0.04	0.38	1.08
Coulport & Faslane	2250	RCP2.6	0.00	0.42	1.35
Coulport & Faslane	2300	RCP2.6	-0.06	0.45	1.60